UNCERTAINTIES OF THE NEUTRONIC CALCULATIONS AT CORE LEVEL DETERMINED BY THE KARATE CODE SYSTEM AND THE KIKO3D CODE

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ABSTRACT

Nowadays, there is a tendency to use best estimate plus uncertainty methods in the field of nuclear energy. This implies the application of best estimate code systems and the determination of the corresponding uncertainties. For the latter one an OECD NEA benchmark was set up. The objective of the OECD NEA Uncertainty Analysis in Best-Estimate Modeling (UAM) LWR benchmark is to determine the uncertainties of the coupled reactor physics/thermal hydraulics LWR calculations at all stages.

In this paper the uncertainties of the neutronic calculations at core level - originating from the uncertainties of the basic nuclear data - are presented. The investigations have been made for a VVER-1000 core (Kozloduy-6) defined in the frame of the UAM benchmark. In the first part of the paper, the uncertainties of the effective multiplication factor, the assembly-wise radial power distribution, the axial power distribution and the rod worth are shown. After that the preliminary evaluation of the uncertainties of the neutron kinetic calculations are presented for a rod movement transient at HZP state, where the uncertainties of the time dependent core and assembly powers and the dynamic reactivity were evaluated.

In both cases, we will see that the most important quantities - at core level and at HZP state - have a considerable uncertainty which is originating from the uncertainties of the basic cross section library in these investigations.

1. INTRODUCTION

In the frame of the OECD NEA UAM benchmark [1] there has been a large activity to determine the uncertainties of coupled reactor physics/thermal hydraulics LWR calculations at all stages. In order to perform this large task, 3 phases were defined in the benchmark and these phases include the survey of the uncertainties of the stand alone neutronics (Phase I), the time dependent neutronics, stand alone thermo-hydraulics, the fuel behavior calculations (Phase II) and the system phase, as well.

In this paper we concentrate on the determination of uncertainties of “core physics” (Phase I, Exercise I-3) and partially on the determination of uncertainties of the “Time-Dependent Neutronics” (Phase II, Exercise II-2). It is important to note that only the uncertainties of the cross sections were taken into account in our investigations. In the following we are giving the content of the paper.

In Chapter 2 the applied codes (MULTICELL [2, 3] for the preparation of cross section, and KIKO3D [4-7] for the static and kinetic core calculations) and the used statistical methods are presented. The modeling of the VVER-1000 (Kozloduy-6) core - based on the VVER-1000 coolant transient benchmark [11] and used in UAM benchmark - and some special assumptions are discussed in Chapter 3. The results for the Kozloduy-6 core, namely steady state results at HZP (UAM benchmark Exercise I-3) are given in the next Chapter. In this section the uncertainties of the effective multiplication factor, the assembly-wise radial power distribution, the axial power distribution and the rod worth are shown. It follows the preliminary assessment of the uncertainties of kinetic calculations originating from the uncertainties of XS. In this chapter, the uncertainties of the neutron kinetic calculations are presented for a rod movement transient at HZP state, where the uncertainties of the time dependent core and assembly powers and the dynamic reactivity were evaluated. Finally the conclusions are given.

2. THE APPLIED CODES AND THE USED STATISTICAL METHOD

The two group assembly homogenized Xs generations were done by the MULTICELL [2, 3] spectral code. The main features of the MULTICELL code can be given as follows:

- This code is a part of KARATE code system developed at Centre for Energy Research, Hungarian Academy of Sciences (further on EK)
- Multi group spectral code
- Applying 70 energy groups (based on ENDF/B-VI library)
- For the solution of the neutron transport equation, the method of collision probabilities is used
- The code is able to calculate the neutron physical properties of a cell with its neighborhood or it is able to calculate higher region (e.g. an assembly in 2 D geometry)
- MULTICELL is usually used for preparing the few group cross section libraries for the higher level of KARATE [2, 3] code system

The core calculations (both steady state and transient) were performed by the KIKO3D [4, 5, 6, 7] code.

The main features of the KIKO3D code can be given as follows:

- KIKO3D is a three-dimensional reactor dynamics code for stand alone and coupled (KIKO3D/ATHLET) neutronic/thermo-hydraulics calculations
- It is a nodal code, where the nodes are the fuel assemblies subdivided into axial layers
- The code solves the 2 group diffusion equation and the unknowns are the scalar flux integrals on the node boundaries.
- The time dependent nodal equations are solved by using the Improved Quasi Static factorization method.
- The code was developed at EK, and validated against many benchmark problems (e.g. experiment at the V-1000 zero power facility of the Kurchatov institute, VALCO EU-5 project [8], this is used in UAM benchmark for VVER-1000 case)

The applied statistical method is based on Monte Carlo sampling and the method consists of four steps. In case of considering only the uncertainties of cross-section libraries these are:

Step 1: Monte Carlo sampling from covariance matrices of the basic cross sections based on the 44GROUPV6REC covariance library originating from the SCALE code

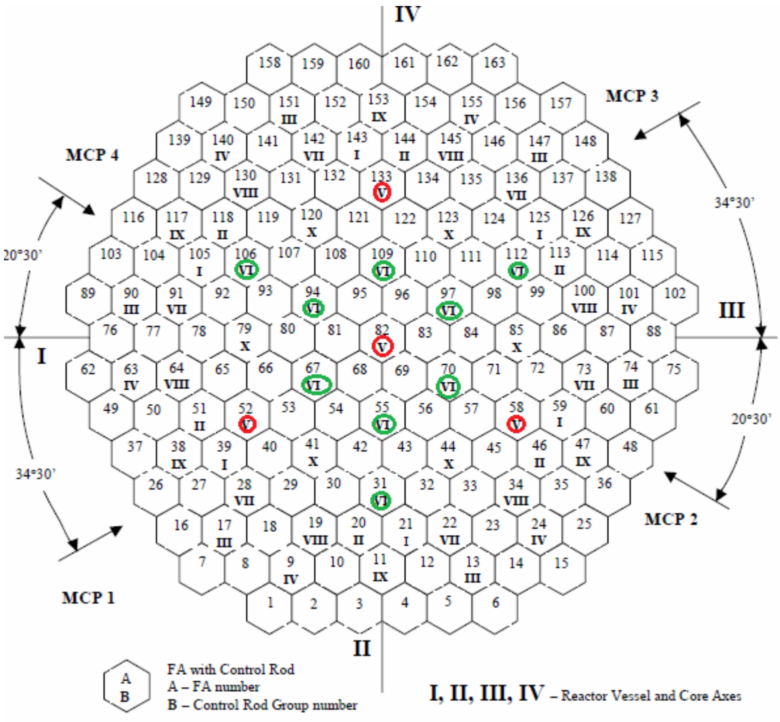
Step 2: Using the results of Step 1, 1000 (or 100) samples ('basic libraries') of XS are generated. Using the perturbed basic libraries 1000 (or 100) assembly homogenized KIKO3D input libraries (including different materials) are generated by the MULTICELL code.

Step 3: 1000 (100) KIKO3D calculations are to be performed. It should be mentioned that our methodology corresponding to the case that in each KIKO3D run the uncertainties are propagated through the full calculation chain (cell-assembly-core).

Step 4: The uncertainty of the selected output quantities (e.g. Keff, power distributions, etc.) are evaluated by calculating the standard deviations (and/or correlation matrices) from the results of 1000 calculations. In Case of 100 runs upper and lower bounds are determined with 0.95/0.963 probabilities according to the Wilks' theorem [9, 10], as well

3. MODELING OF THE VVER-1000 (KOZLODUY-6) CORE AND SOME SPECIAL ASSUMPTIONS

In the UAM benchmark the VVER-1000 core model is based on the VVER-1000 coolant transient benchmark [11]. The VVER-1000 (Kozloduy-6) core and the control rod arrangements used in the UAM benchmark are shown in Figure 1. Note, that this core arrangement is the same used in the VVER-1000 coolant transient benchmark. It can be seen that in same cases, due to special arrangement of control rods in group V and VI, there can be only 120 degree symmetry in this core and in our case this is the situation (see Fig. 2).



Bank	No. of rods	Purpose
I	6	Safety
II	6	Safety
III	6	Safety
IV	6	Safety
V	4	Part-length
VI	9	Safety
VII	6	Safety
VIII	6	Safety
IX	6	Safety
X	6	Regulating

Figure 1: Control rod arrangements reproduced from [1]

Number	T-H conditions	Control rod positions
0	HZP	Groups 1-3 ARO[1] Group 4 – 57.3% wd (227 cm) Group 5 ARO Groups 6-10 ARI[2]
1	HP	Groups 1-9 ARO Group 10 – 36% wd

1. ARO – all rods out.
2. ARI – all rods inserted.

Figure 2: Control rod positions according to [1] and reproduced from [11]

As it can be seen from Fig. 2, a lot of control rods are inserted in the core due to the HZP state.

In accordance with the newest UAM specification [1], we had to do some special assumptions in the modeling:

- In the VVER-1000 CT benchmark - according to [11]– the burnup is not exactly zero, in the present calculations only fresh fuel assemblies were assumed
- The boron concentration is not given for the HZP case for the VVER-1000 CT benchmark [11]. According to [1] 6.4 g/kg was used in these investigations
- Other problem is the radial reflector model. In the VVER-1000 CT benchmark the reflector model (compositions, geometry) is not detailed, in the UAM benchmark the VVER-1000 reflector is defined in 1D

So the reflector model was modeled in 1D and only one type of reflector is modeled both radially and axially. The results of the 1D model used in the MULTICELL calculations are demonstrated in Fig. 3.

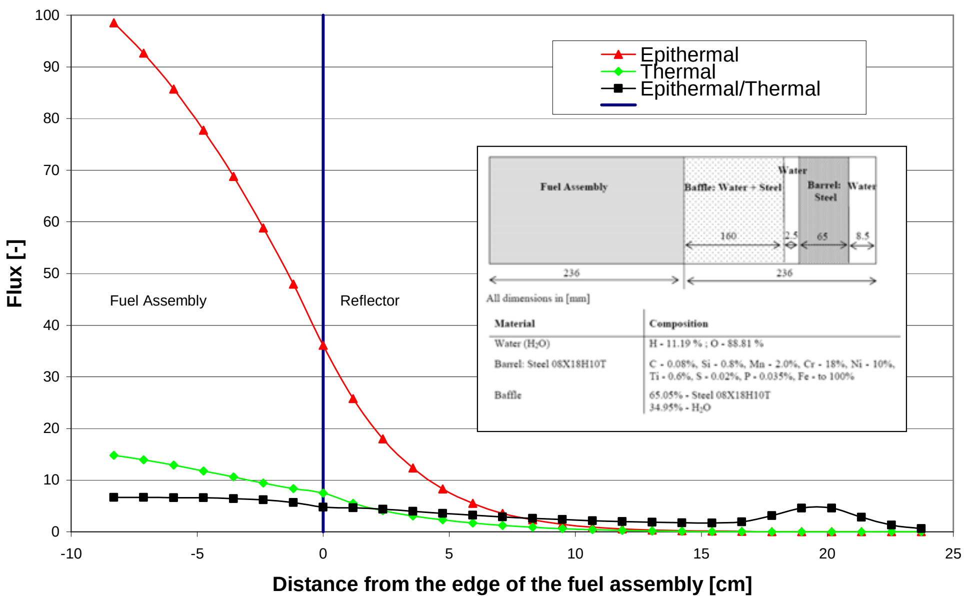


Figure 3: Epithermal and thermal fluxes and the ratio of the fluxes

The VVER-1000 core was modeled by the KIKO3D code. Table 1 and Figure 4 shows the materials applied for the VVER-1000 core model.

Materials (No.)	Description of assemblies
1	2% enrichment without absorber
2	3% enrichment without absorber
3	3.3% enrichment without absorber
4	3.3% enrichment without absorber (profiled assembly)
5	2% enrichment with absorber
6	3% enrichment with absorber
7	Reflector

Table 1: Materials used in the KIKO3D model

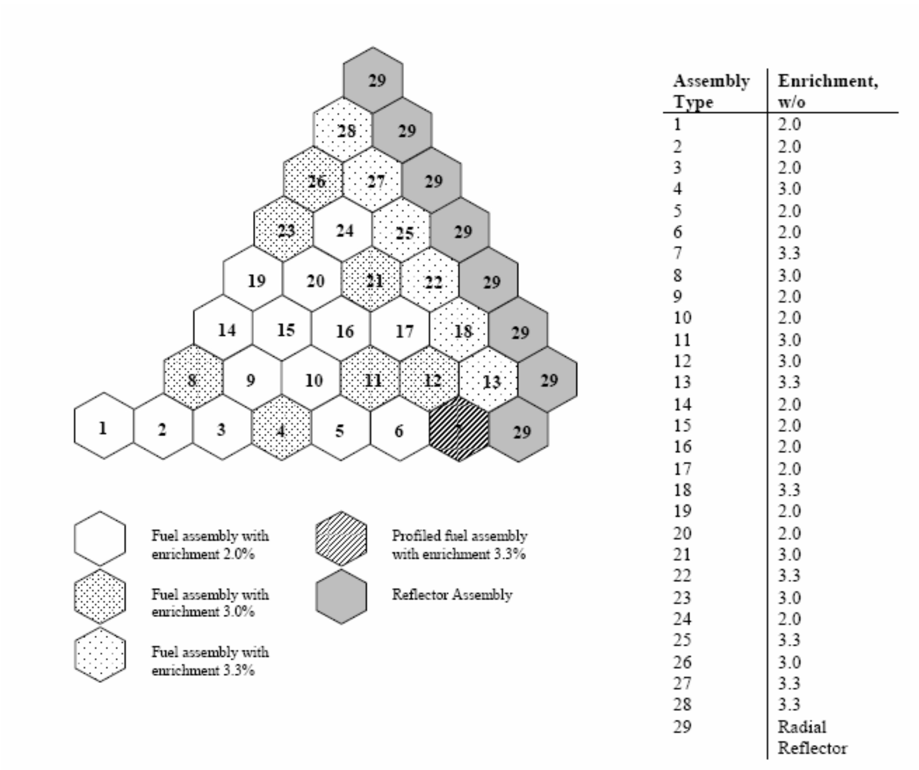


Figure 4: Materials in 60 degree of the core reproduced from [1]

4. STEADY STATE RESULTS FOR THE VVER-1000 CORE

The results for the Kozloduy-6 core, namely steady state results at HZP (UAM benchmark Exercise I-3) are given in this section. In the followings the uncertainties of the effective multiplication factor, the assembly-wise radial power distribution, the axial power distribution and the rod worth are shown.

In Table 2, the effective multiplication factor and its uncertainty are given. It can be stated that the uncertainty of the k_{eff} is similar to the former results calculated by the MULTICELL code for cell and assembly problems [12].

Keff	1.00102
Sigma	555.4 pcm
Relative sigma	0.555%

Table 2: Effective multiplication factor and its uncertainty

Figure 5 and Table 3 shows the axial power distribution and its uncertainties (relative sigma's) in the modeled VVER-1000 core at HZP state, and Table 4 shows the empirical correlation matrix of the axial power. It can be seen that the relative uncertainty (σ) of the axial power is approx. 1% at the maximum and 4% at the minimum. The empirical correlation shows that approx. the first half of the core is in an opposite phase than the second half. This is due to the normalization of the power and possibly due to the control rod insertion.

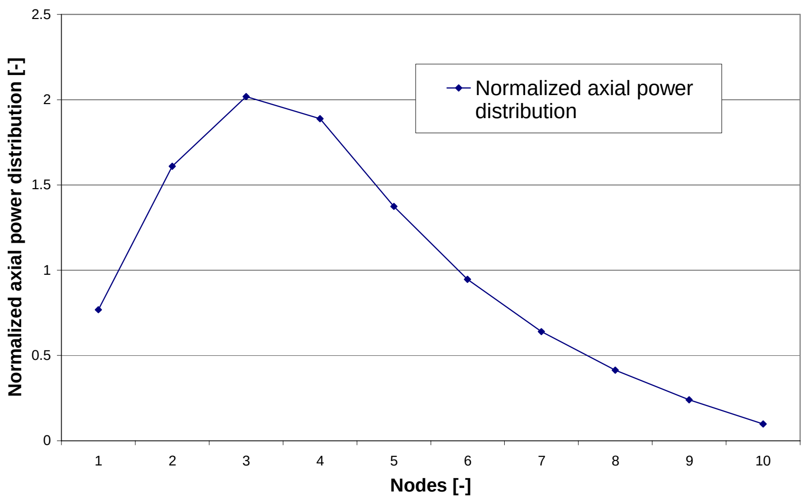


Figure 5: The axial power distribution

Power distribution	0.768	1.61	2.018	1.888	1.375	0.947	0.64	0.415	0.241	0.098
Relative sigma [%]	1.091	1.161	0.966	0.499	0.366	1.313	2.173	2.914	3.501	4.011

Table 3: Axial power distribution and its uncertainties

Node	1	2	3	4	5	6	7	8	9	10
1	1.00	0.98	0.98	0.96	-0.99	-0.98	-0.98	-0.98	-0.98	-0.97
2	0.98	1.00	1.00	1.00	-1.00	-1.00	-1.00	-1.00	-1.00	-1.00
3	0.98	1.00	1.00	1.00	-0.99	-1.00	-1.00	-1.00	-1.00	-1.00
4	0.96	1.00	1.00	1.00	-0.98	-0.99	-1.00	-1.00	-1.00	-1.00
5	-0.99	-1.00	-0.99	-0.98	1.00	1.00	1.00	0.99	0.99	0.99
6	-0.98	-1.00	-1.00	-0.99	1.00	1.00	1.00	1.00	1.00	1.00
7	-0.98	-1.00	-1.00	-1.00	1.00	1.00	1.00	1.00	1.00	1.00
8	-0.98	-1.00	-1.00	-1.00	0.99	1.00	1.00	1.00	1.00	1.00
9	-0.98	-1.00	-1.00	-1.00	0.99	1.00	1.00	1.00	1.00	1.00
10	-0.97	-1.00	-1.00	-1.00	0.99	1.00	1.00	1.00	1.00	1.00

Table 4: Empirical correlation matrix of the axial power

The axial offset is defined as $AO = \frac{P_{upper} - P_{lower}}{P_{upper} + P_{lower}} * 100\%$. Its uncertainty is given in Table 5.

AO	-53.186 %
Relative sigma	1.909 %

Table 5: Axial offset and the corresponding uncertainty

In the followings the uncertainties and correlations of the normalized power distribution is given. Figure 6 shows the normalized radial power distribution and the corresponding uncertainties (relative sigma in %). This figure shows that there is a large tilt in the core. Additionally it can be seen there is only 120 degree symmetry in the core due to the control rod arrangement. The uncertainties (σ) of the power distribution [%] are shown in Fig 7, as well. It can be stated that at the centre the uncertainty is large approx. 5% due to the low power, but at high powers it is also relevant: 1.4%.

Figure 8 shows the correlation coefficient between assembly No 158 and the other ones, and Fig. 9 shows the correlation coefficient between assembly No 82 and the other ones. It can be seen that the outer assemblies are positively correlated strongly with each other, and the outer ones and the inner ones are correlated negatively. It is due to the normalization of the power and the fact that the neighboring assemblies are in a similar environment.

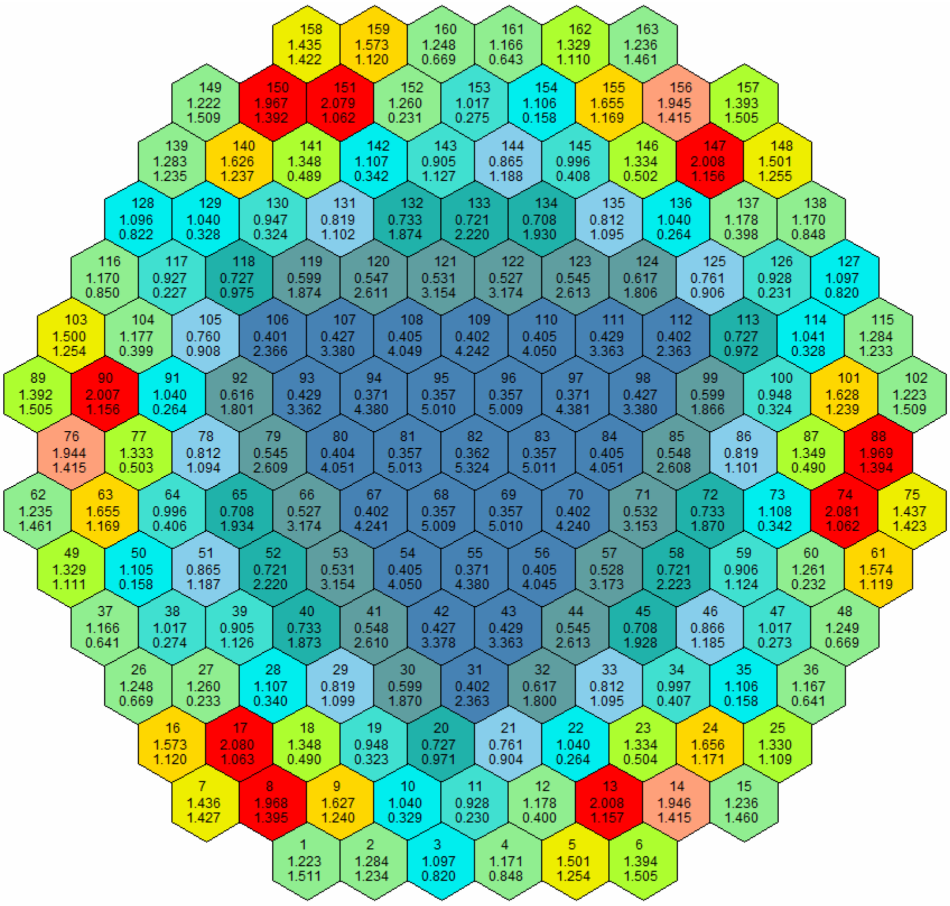


Figure 6: Normalized radial power distribution and corresponding uncertainties (relative sigma in %)

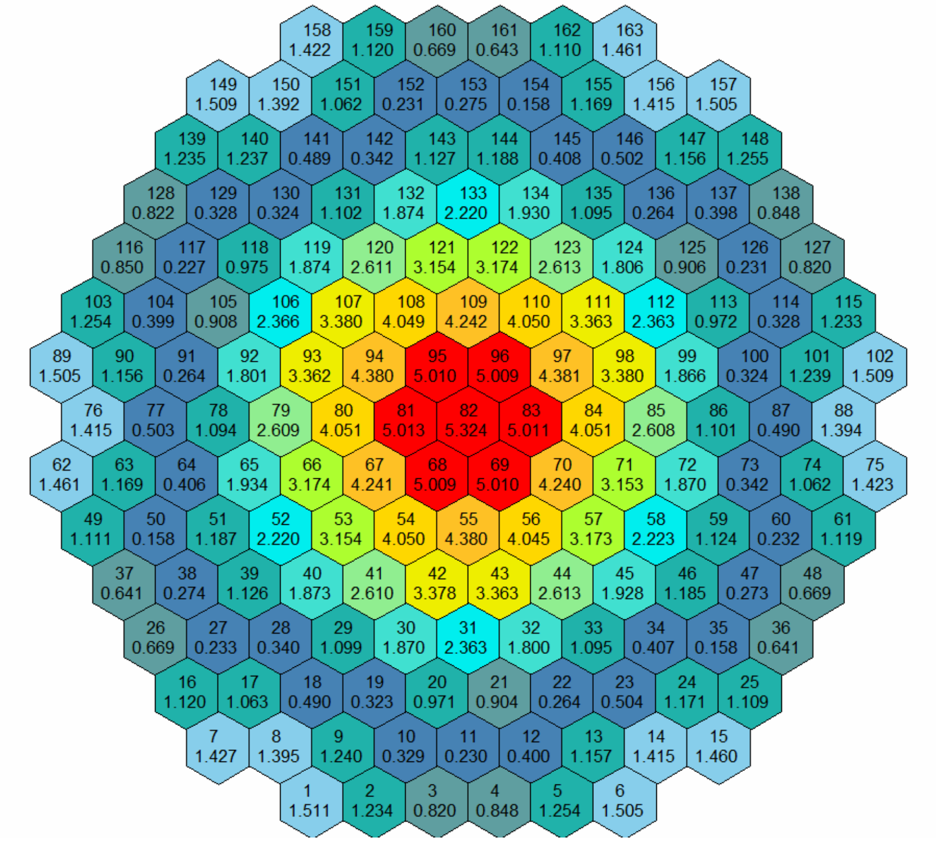


Figure 7: Uncertainties (σ) of the power distribution [%]

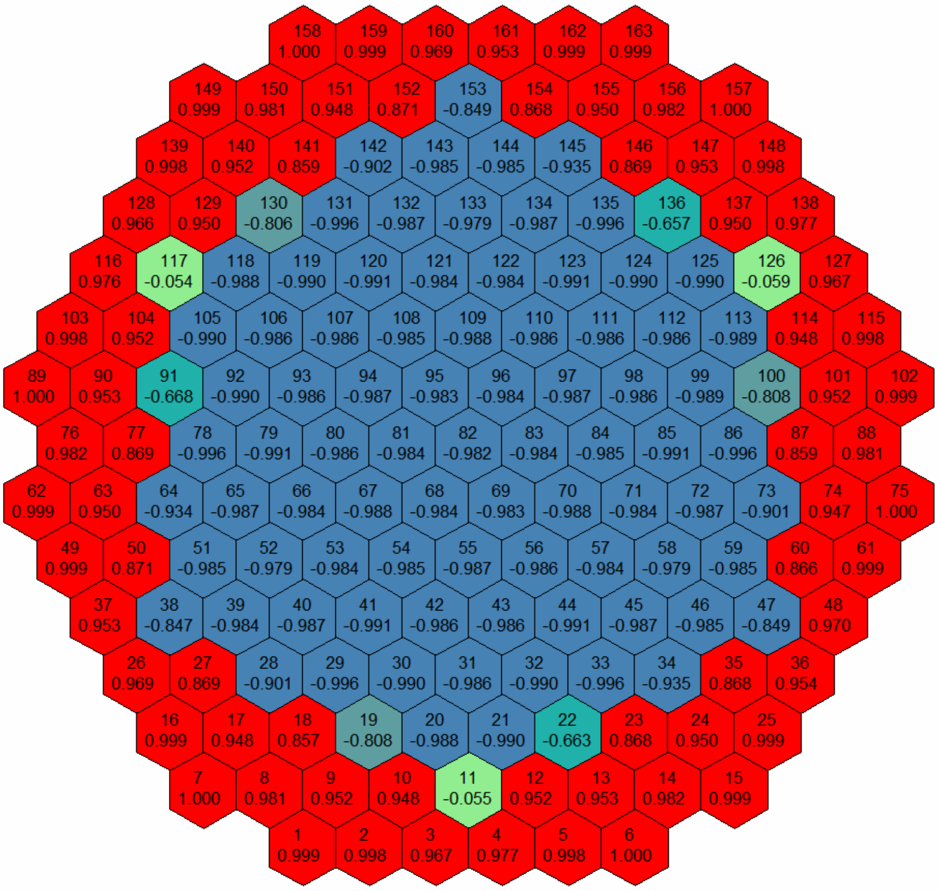


Figure 8: Correlation coefficient between assembly No 158 and the other ones

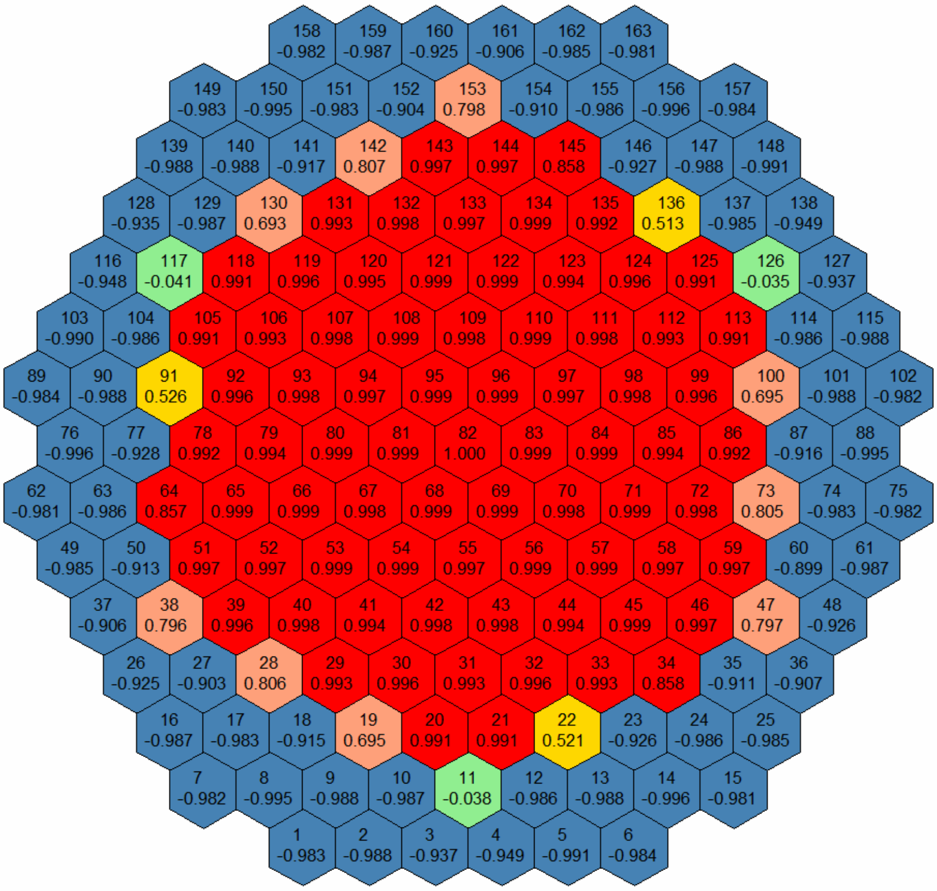


Figure 9: Correlation coefficient between assembly No 82 and the other ones

In the followings the uncertainties of the rod worth are given. The rod worth can be given as $\rho = \frac{1}{k_2} - \frac{1}{k_1}$, where in the unrodded case $k_{eff}=k_1$, and in the rodded case $k_{eff}=k_2$. In the followings two possible but equivalent methods can be used for the calculation of the uncertainty of the rod worth. First one is the use of the statistics of the differences (ρ values). The second one is the determination of the standard deviations (e.g. empirical standard deviations) of $\frac{1}{k_2}$(X) and $\frac{1}{k_1}$(Y) variables, and in this case the uncertainty can be given as $\sigma_\rho = \sqrt{X^2 + Y^2 - 2 * X * Y * corr(X,Y)}$. Here corr (X,Y) is the correlation of X and Y, which can be approximated by the calculation of the empirical correlation coefficient

According to our experiences, the above discussed two methods give the same value even at large correlation of X and Y, e.g. for the case given at Table 6.

Rod worth	0.0807 % (80.7 pcm)
σ	0.0047 % (4.7 pcm)
Relative σ	5.86 %

Table 6: Rod worth and the corresponding uncertainties of one element (assembly No 79) of group X, **corr(X,Y)=0.9999651 !!!**

It is important that X and Y are very close to each other, if we set corr(X,Y)=1.0 artificially, then the relative σ=1.21% instead of 5.86%. The following questions can be raised: Is it enough 1000 samples of ρ to determine of the uncertainty of rod worth or not? What is the uncertainty of σ in this case? At this moment, we can state that the uncertainty of the rod worth is not greater then 5.86%.

In the followings (Table 7-9) we give some other values for the uncertainties of rod worth.

Rod worth	0.0632% (63.2 pcm)
σ	0.0014 % (1.4 pcm)
Relative σ	2.24%

Table 7: Rod worth and the corresponding uncertainties of one element (assembly No 147) of group III

Rod worth	0.4031% (403.1 pcm)
σ	0.0220% (22 pcm)
Relative σ	5.45%

Table 8: Rod worth and the corresponding uncertainties of the group X

Rod worth	3.7675% (3767.5 pcm)
σ	0.0281% (28.1 pcm)
Relative σ	0.75%

Table 9: Rod worth and the corresponding uncertainties of SCRAM

5. PRELIMINARY ASSESSMENT OF THE UNCERTAINTIES OF KINETIC CALCULATIONS

In this section we give the preliminary assessment of the uncertainties of kinetic calculations. The used special assumptions can be summarized as follows:

- The transient was similar to the experiment carried out on the V-1000 zero power facility of the Kurchatov institute [8] (VALCO EU-5 project, one Case in the UAM benchmark)
- However, the Kozloduy-6 core was used instead of the Kurchatov one
- The transient was a rod movement (one element (assembly No 147) of the control group III)
- The absorber rod was inserted in the time period of 16-69 s, and it was withdrawn at 800-837 s
- Before the transient the reactor was in a mild supercritical state (25 pcm)
- Only the Xs uncertainties were taken into account (e.g. the uncertainties of beta effective was not considered in this study)
- Only 100 KIKO3D runs were performed, we have calculated both the standard deviations and the upper and lower limits (95%/96.3%) according to the Wilks' theorem

Figure 10 shows the reactivites for the 100 runs, and in Figure 11 the mean, upper and lower bounds, and results of the basic run are given. The relative uncertainties of the reactivity is given in Fig 12 and it can be stated that the estimated maximal relative uncertainty (σ) of the time dependent reactivity is approx. 4% (the lower and upper bounds at 95%/96.3% are -13%

and 8% respectively). Note that in the more precise static case the corresponding value was 2.4% was.

In case of core powers the Figure 13 shows mean, upper and lower bounds, and the results of basic run, and the relative uncertainties of the core power are given in Figure 14. The estimated maximal relative uncertainty (σ) of the time dependent power is 11% (the lower and upper bounds at 95%/96.3% are 22% and 42% respectively.

Figure 15 shows the powers in the assembly where the rod movement happened for two cases. In the left part of the figure our results are presented and in right part of the figure the results of the VALCO project [8]. It can be stated that the uncertainties of the powers originating from the uncertainty of Xs is similar to the uncertainties originating from the use of different codes.

Figure 16 shows the uncertainties of the powers in the assembly where the rod movement happened. These results are similar to the results given by Fig. 14.

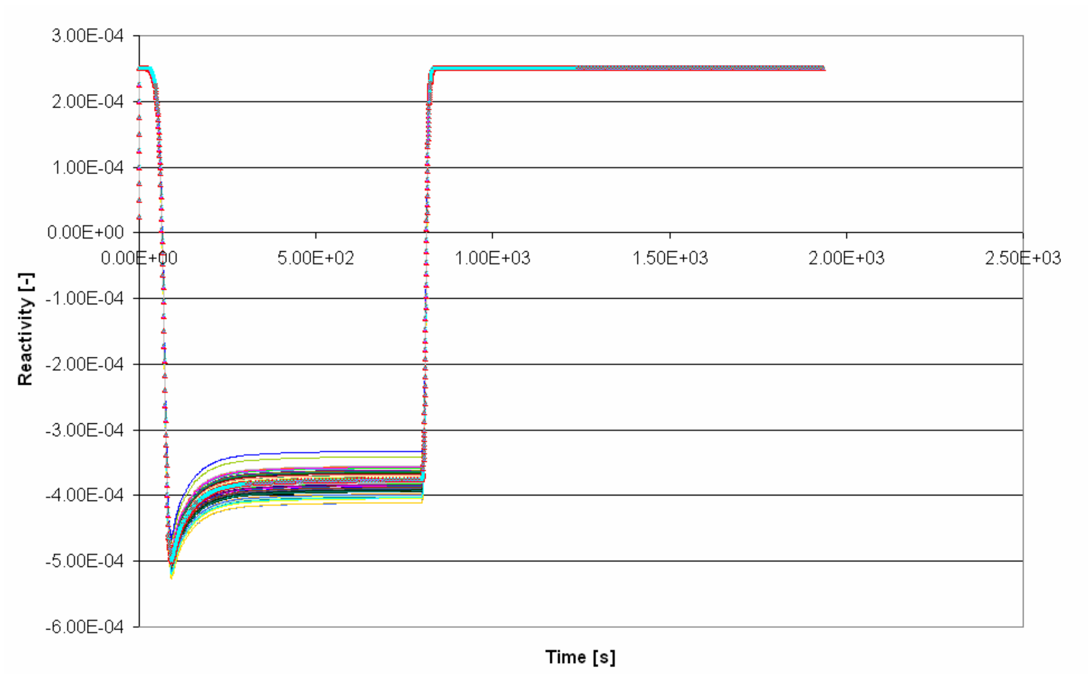


Figure 10: Reactivites for the 100 runs

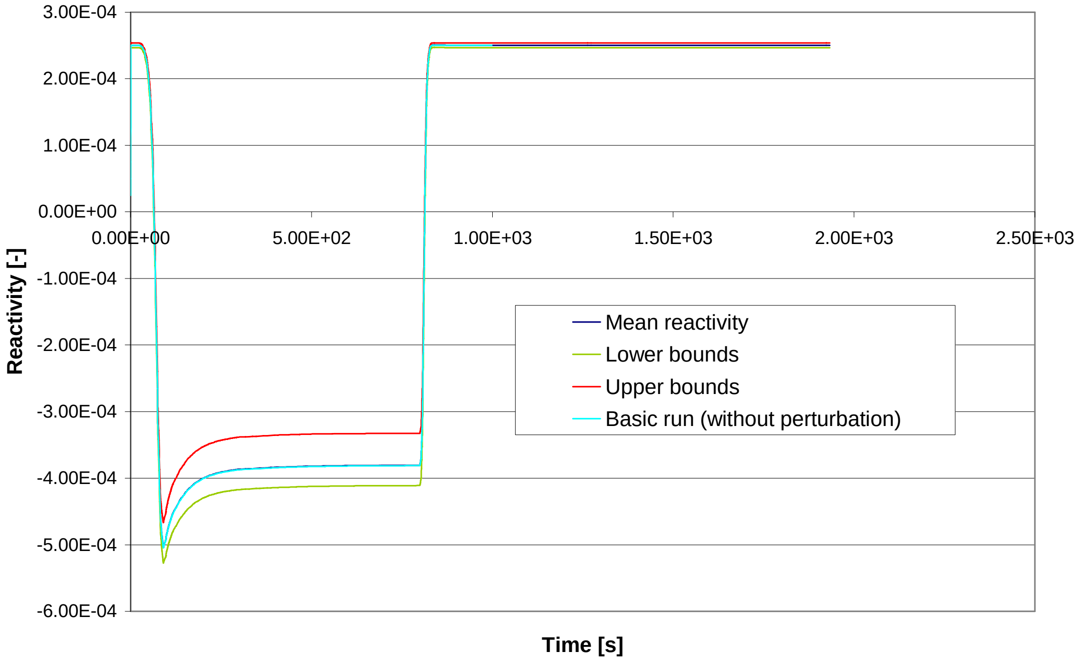


Figure 11: Reactivites, mean, upper and lower bounds, basic run

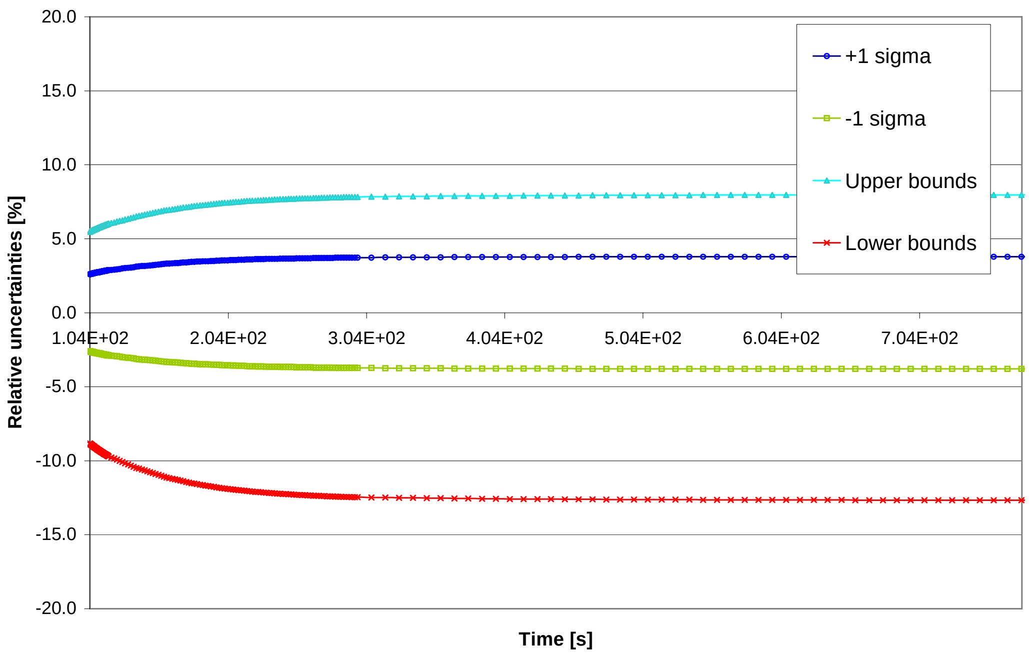


Figure 12: Relative uncertainties of the reactivity

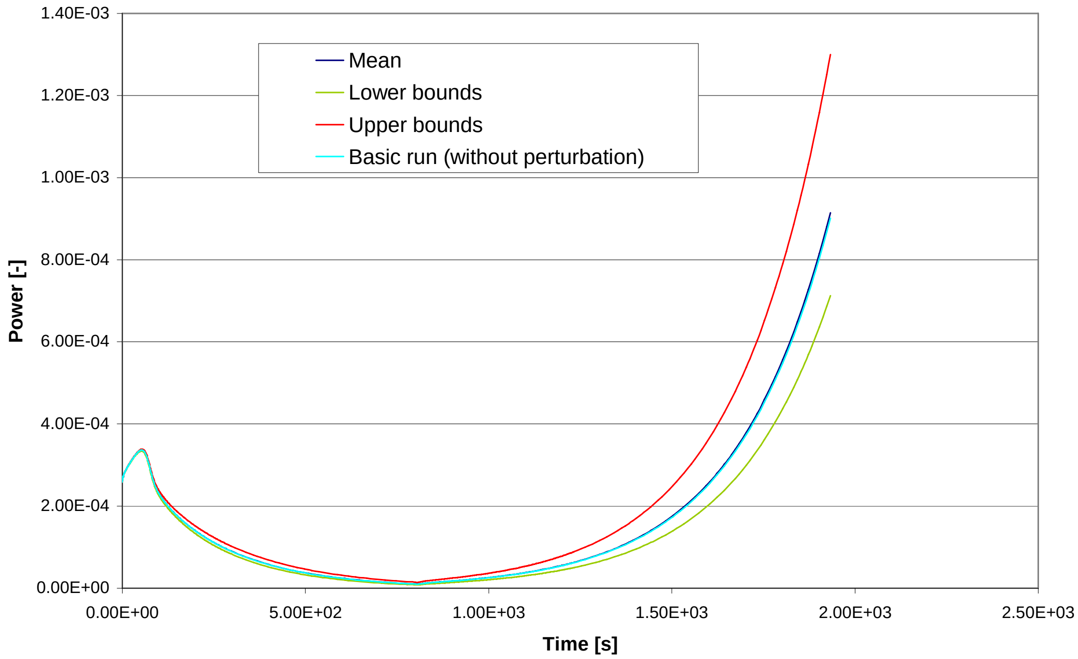


Figure 13: Core powers, mean, upper and lower bounds, basic run

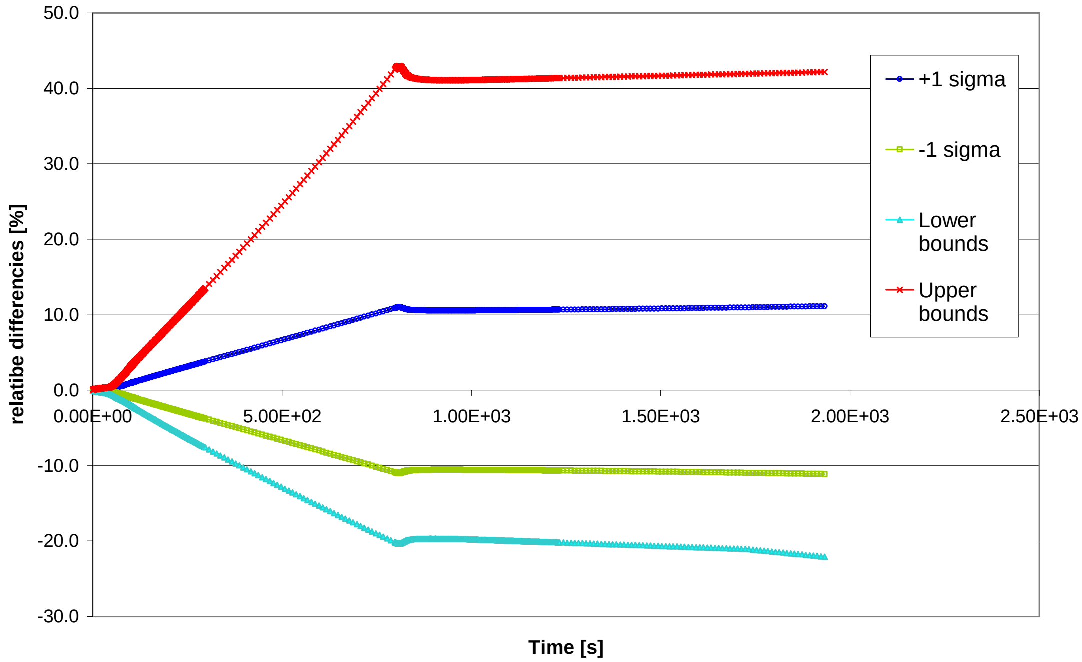


Figure 14: Relative uncertainties of the core power

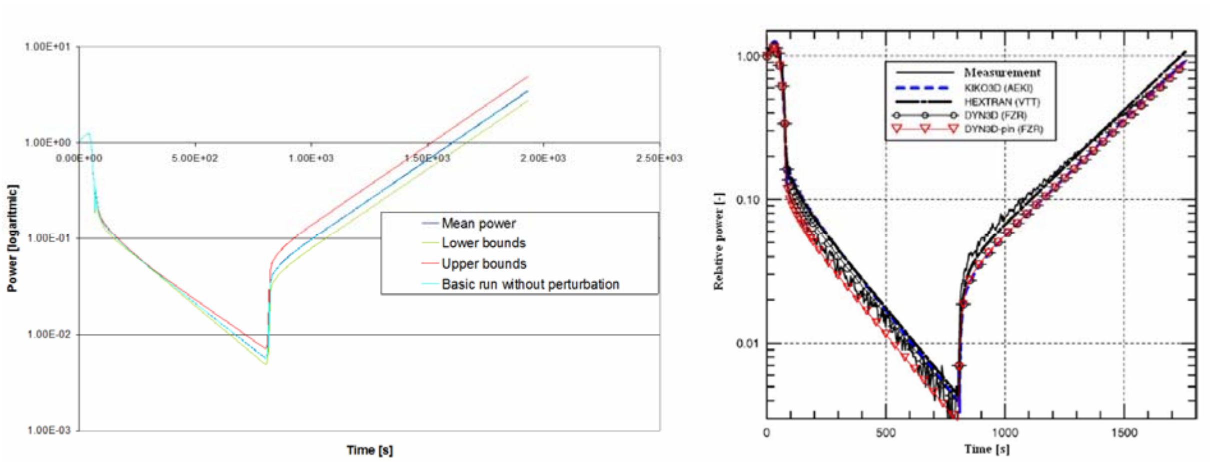


Figure 15: Powers in the assembly where the rod movement happened, UAM (left figure) and in the VALCO project [8] (right figure)

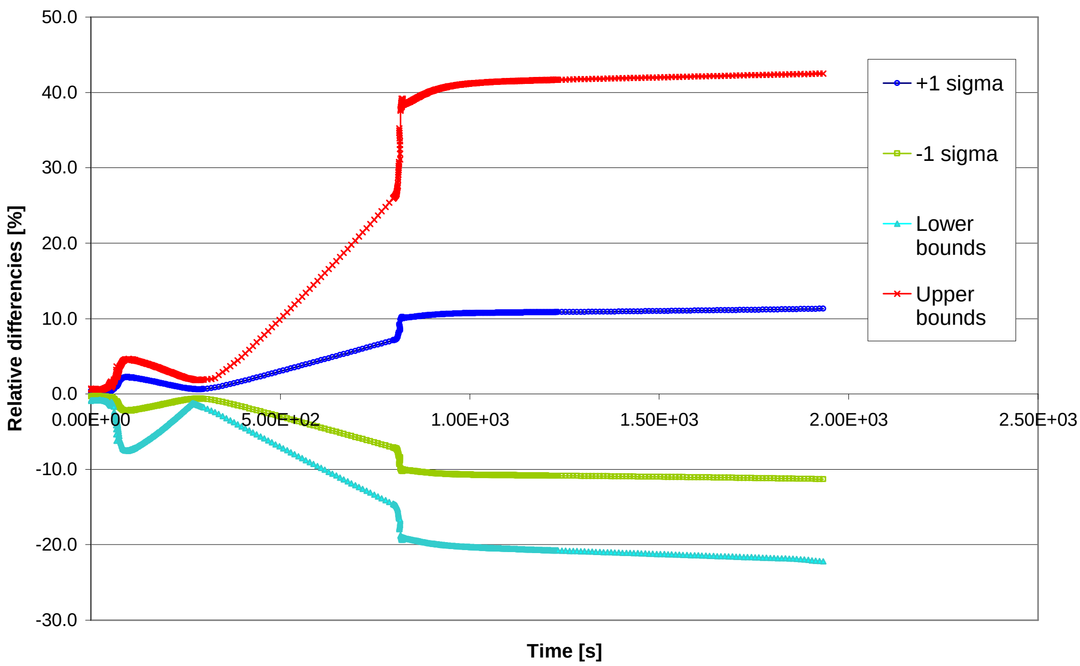


Figure 16: Uncertainties of the powers in the assembly where the rod movement happened

6. SUMMARY

Using the MULTICELL and KIKO3D codes the determination of the uncertainties of the neutronic calculations at core level - originating from the uncertainties of the basic nuclear data - are presented. It can be stated that the relative uncertainty of the effective multiplication factor is similar (0.56%) to the results of the assembly and cell calculations [12].

The relative uncertainties of rod worth are depending on the corresponding state (rod position) and they are between 0.75-5.86%. The maximum relative uncertainty (σ) of the assembly-wise power is 5.3%, the corresponding value is 1.4% at the maximum power.

According to the preliminary kinetic calculation the estimated maximal relative uncertainty (σ) of the time dependent reactivity is approx. 4% (the lower and upper bounds at 95%/96.3% are -13% and 8% respectively). The estimated maximal relative uncertainty (σ) of the time dependent power is 11% (the lower and upper bounds at 95%/96.3% are 22% and 42% respectively.

It can be stated that the most important quantities - at core level and at HZP state - have a considerable uncertainty which is originating from the uncertainties of the basic cross section library in these investigations.

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