RESULTS OF REACTOR CORE SYMMETRY MEASUREMENTS AT BOHUNICE AND MOCHOVCE NPPs

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ABSTRACT

Reactor core symmetry measurement is carried out as one of the reload start-up physics tests at the Bohunice and Mochovce NPPs. The paper deals with the symmetry measurement results obtained in the Bohunice and Mochovce NPPs since the Gd-2 fuel has been applied in core loads. At first, the symmetry measurement procedure and evaluation method is presented. Then, measurements results from reactor cores loaded with Gd-2 fuel at Bohunice Units 3&4 and Mochovce Units 1&2 are summarized. The results obtained from the Mochovce Unit 1, the 9-th fuel cycle are analysed in detail, because these results did not met their acceptance criterion. The procedures applied in the case of the acceptance criterion non-fulfilment together with possible reasons of the acceptance criterion non-fulfilment are described in the paper.

1. INTRODUCTION

Reactor core symmetry measurement is carried out as one of the reload start-up physics tests at the Bohunice and Mochovce NPPs. This paper deals with the symmetry measurement results obtained at the Bohunice Units 3&4 and Mochovce Units 1&2 in the years 2006÷2008, which are the first 3 years of the Gd-2 fuel application in reactor core loads. Altogether, 12 symmetry measurements results, which were measured at these 4 units during the years 2006÷2008, are presented in this paper.

2. SYMMETRY MEASUREMENT PROCEDURE AND EVALUATION

Reactor core symmetry measurement at Bohunice and Mochovce NPPs is carried out after reactor criticality achievement and after check of control assemblies and drive coupling. As reactor core load and the placement of individual control assemblies (CAs) in its group are designed in 60° symmetry, theoretically individual CAs of the same group should have the

same worth. The measured differences of individual CAs worth are caused by either neutron flux asymmetry or by differences of CAs absorption characteristics.
During the symmetry measurement, the individual CAs are inserted into the core down to the same position to measure their worth, see chap. 2.1 and 2.2. The symmetry coefficients are calculated from the differences of individual CA worth in the group, see chap. 2.3. At the end, the measured symmetry coefficients are evaluated by the acceptance criterion, see chap. 2.4.

2.1 Worth measurement of individual CAs from group 1 ÷ 5

The measurement of individual CAs is carried out separately for each group. In initial state of the measurement reactivity is stabilized at zero value. The measured CA number *i* from group number *m* is individually inserted from the top of the reactor core to the bottom. The reactivity changes introduced by insertion of the measured CA are compensated by withdrawal of CA group 6 from its initial position (IP) to its midst position (MP). After reactivity is stabilized at zero value, measured CA is withdrawn from the bottom to the top of reactor core. The reactivity changes introduced by withdrawal of the measured CA are compensated by insertion of CA group 6 from its midst position to its final position (FP) and reactivity is stabilized at zero value.

Worth of *i*-th CA from group *m* is evaluated from the CA group 6 position changes by the expression

$$\rho_{i,m} = \frac{\rho(IP) + \rho(FP) - 2 * \rho(MP)}{2} \tag{2.1.1}$$

where

- $\rho_{i,m}$ - worth of *i*-th CA from group *m*
- $\rho(X)$ - function value of integral worth of group 6 in the position X
- *IP* - initial position of CA group 6, when measured CA is at the top of reactor core,
- *MP* - midst position of CA group 6, when measured CA is at the bottom of reactor core,
- *FP* - final position of CA group 6, when measured CA is at the top of reactor core,
- *m* - number of measured group, *m* = 1,2, ...,5,
- *i* - sequence number of measured CA in measured group, *i* = 1,2, ...,6.

2.2 Worth measurement of individual peripheral CAs from group 6

In the beginning, initial reactivity is stabilized at value ρ_i^I close to zero. Then a peripheral CA number *i* is individually inserted into the core down about 50 cm. After CA insertion and after reactivity stabilization, the value of reactivity ρ_i^M is registered. Then measured CA is withdrawn to its initial position. After reactivity stabilization the stabilized value ρ_i^F is registered. Then the worth of CA number *i* is evaluated by the expression

$$\rho_{i,6} = \frac{\rho_i^I + \rho_i^F - 2 * \rho_i^M}{2} \tag{2.2.1}$$

where

$\rho_{i,6}$ - worth of CA (number *i*) corresponding to measured section,

ρ_i^I - reactivity of initial state before insertion of CA number *i*,

ρ_i^M - reactivity after insertion of CA number *i* into the core down about 50 cm,

ρ_i^F - reactivity of final state after withdrawal of CA number *i* to its initial position.

2.3 Calculation of symmetry coefficients

After measurement of all CA worth in the group number *m*, the mean value of worth for the CA from group *m* is calculated as

$$\bar{\rho}_m = \frac{1}{6}\sum_{i=1}^{6} \rho_{i,m} \tag{2.3.1}$$

Then the symmetry coefficients $k_{i,m}$ are calculated as

$$k_{i,m} = \sqrt{\frac{\rho_{i,m}}{\bar{\rho}_m}} \tag{2.3.2}$$

where $k_{i,m}$ - symmetry coefficient of CA number *i* from the group number *m* (*i*, *m*=1,2,...,6).

2.4 Acceptance criterion for symmetry measurement

Relative deviations between measured $k_{i,m}$ and theoretical $k_{i,m}^{theor}$ symmetry coefficients are defined as

$$\varepsilon_{i,m} = \frac{k_{i,m} - k_{i,m}^{theor}}{k_{i,m}^{theor}} \cdot 100\% \quad , \tag{2.4.1}$$

Note: If reactor core is loaded symmetrically then $k_{i,m}^{theor}$ = 1.

Acceptance criterion for symmetry measurement is

$$\left|\varepsilon_{i,m}\right| \leq 7\,\%\,. \qquad (2.4.2)$$

The acceptance criterion ±7 % was designed by VUJE on the basis of statistical processing of deviations between measured and theoretical symmetry coefficients obtained at Bohunice Units 3&4 [L2]. Value ±7 % represents 2,5 σ, where σ is standard deviation

$$\sigma = \sqrt{\left(\frac{1}{n}\sum_{i=1}^{n}\left(\varepsilon_i - \bar{\varepsilon}\right)^2\right)}\ , \qquad (2.4.3)$$

where

ε_i - is relative deviation between measured and theoretical value for i-th symmetry coefficient

$\bar{\varepsilon}$ - is mean value of the deviations ε_i

n - number of measured symmetry coefficients.

3. SYMMETRY MEASUREMENT RESULTS

Measurements results from reactor cores loaded with Gd-2 fuel at Bohunice Units 3&4 and Mochovce Units 1&2 in the years 2006÷2008 are summarized in Table 1. Minimum and maximum deviations between measured and theoretical symmetry coefficients and the number of reactor core section where the minimum and maximum were measured are shown in the table. If the reactor core was loaded asymmetrically, the theoretical symmetry coefficients were calculated by BIPR-7. The reactor core sections are displayed in the Fig. 1.

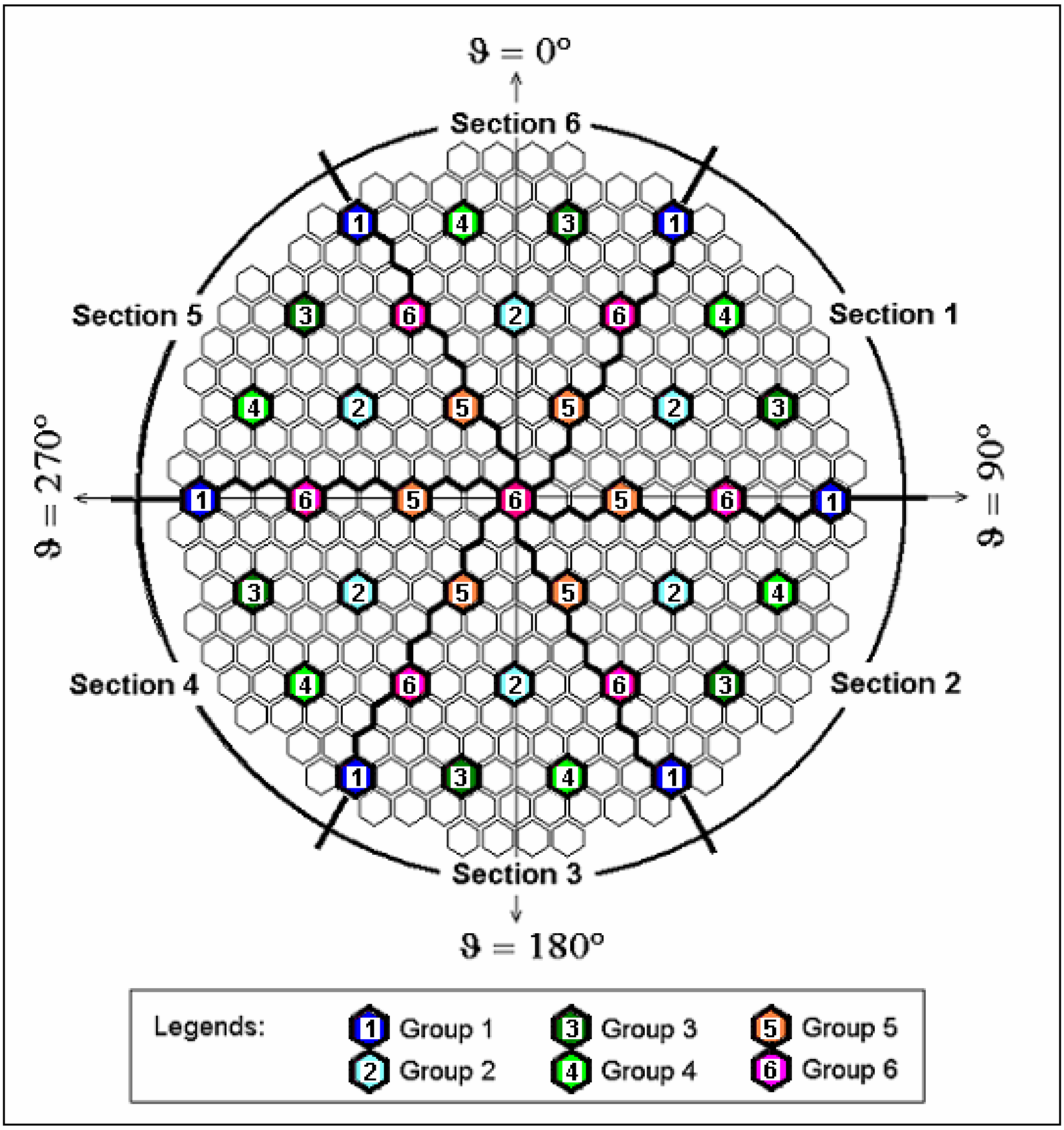

Fig. 1 Placement of individual control assemblies in reactor core, definition of azimuth angle and reactor core dividing into 6 sections

Table 1 Minimum and maximum values of deviations between measured and theoretical symmetry coefficients of reactor core loaded with Gd-2 fuel

NPP	Unit	Cycle	Range of deviations between measured and theoretical symmetry coefficients			
			Minimum	Core Section	Maximum	Core Section
EMO	1	8	-2,2	2	2,9	4
		9	**-7,8**	1	**7,7**	4
		10	-3,5	5	3,3	4
EMO	2	7	-6,2	5	5,7	2
		8	-3,3	5	3,3	4
		9	-1,8	5	1,8	2
EBO	3	23	-1,9	6	2,4	5
		24	-5,4	1	4,8	5
		25	-3,3	4	3,3	2
EBO	4	22	-3,6	3	4,2	1
		23	-2,8	1	3,3	3
		24	-4,1	2	4,6	6

From the Table 1 it is seen that the results obtained from the Mochovce Unit 1, the 9-th cycle did not meet the acceptance criterion ±7 %. Therefore the symmetry measurement results of Mochovce Unit 1, Cycle 9, are presented in more detail.

3.1 Symmetry measurement results at the Mochovce Unit 1, the 9-th cycle

As the core load was designed symmetric, the theoretical symmetry coefficients were equal to value 1.

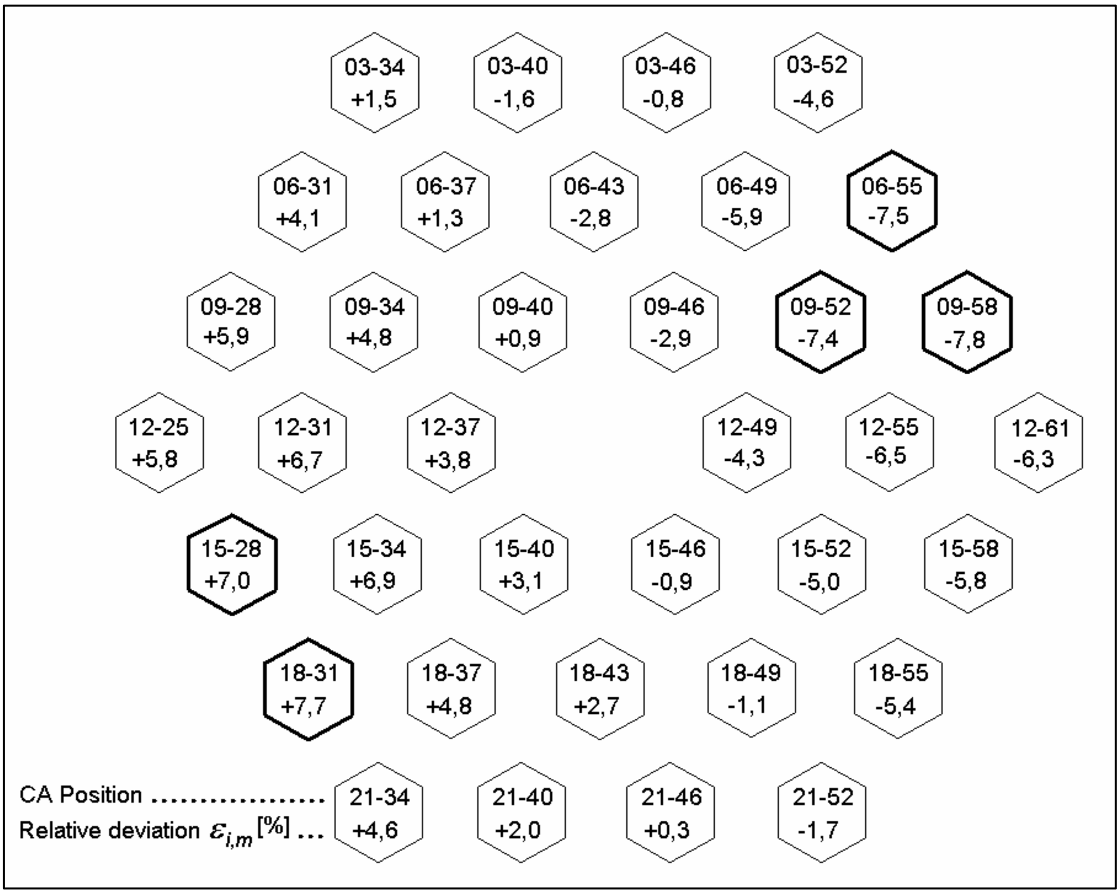

Fig. 2 Distribution of relative deviations between measured and theoretical values of symmetry coefficients at the Mochovce Unit 1, Cycle 9

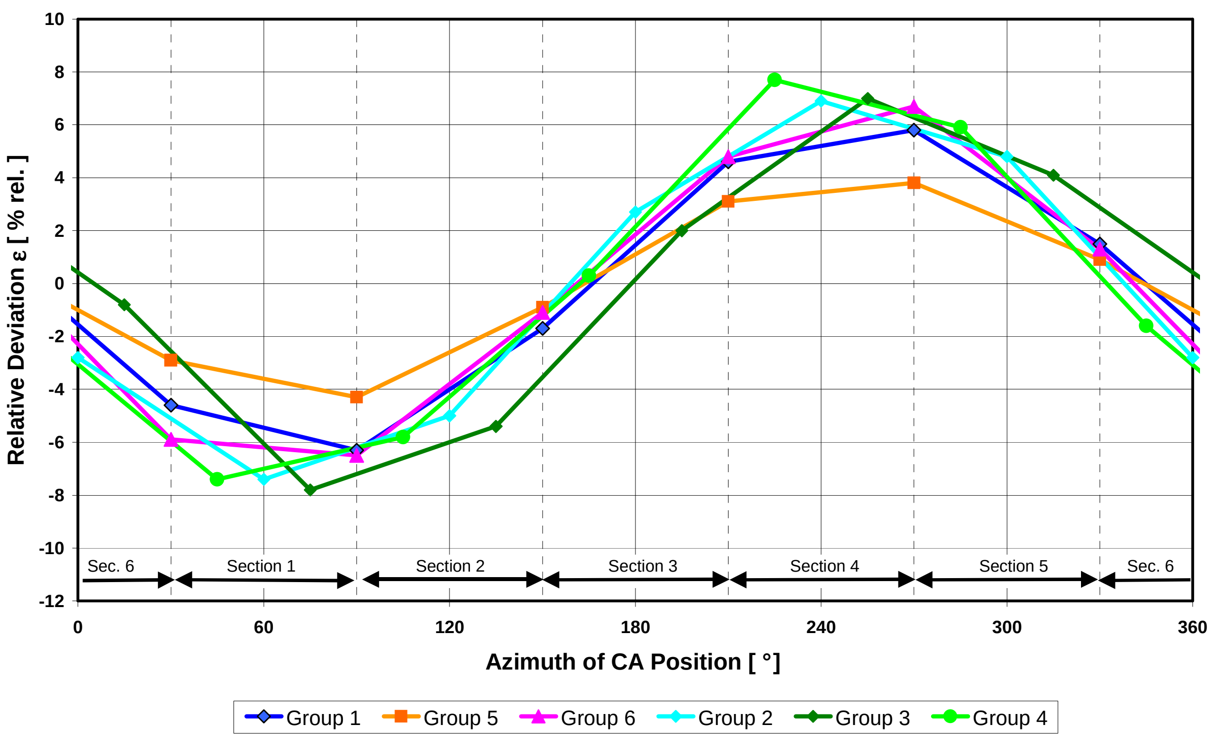

Fig. 3 Azimuthal distribution of relative deviations between measured and theoretical symmetry coefficients from the Mochovce Unit 1, Cycle 9

The relative deviations between measured and theoretical values of symmetry coefficients are displayed in Fig. 2 and Fig. 3. In Fig. 2 the deviations are displayed in form of reactor core cartogram. Azimuthal distribution of the deviations is displayed in Fig. 3. From the Fig. 2 and 3 it is seen that the minimum of deviations was measured in the Section 1 and the maximum of deviations in the opposite Section 4. Five measured deviations for CAs with positions 06-55, 09-52, 09-58, 15-28 and 18-31 did not meet the acceptance criterion ±7 %.
As the acceptance criterion was not met, the procedure in the case of the acceptance criterion non-fulfilment had to be applied:

- All measured input data and measurement procedure were reviewed.
- Initial conditions and operations sequence were reviewed on the basis of the records in the Physics Start-up Diary.
- Differences between the initial and the final reactor state had to be explainable.
- The reactor core symmetry measurement by Group 4 was repeated and this measurement confirmed the previous measurement.
- Possible reasons for acceptance criterion non-fulfilment was analysed, see Table 2.
- All measured and evaluated data were immediately delivered to the supplier of theoretical neutron-physics characteristics for the Mochovce NPP.
- Loading of fuel assembly (FA) with incorrect enrichment into the reactor core was theoretically simulated , see chap. 3.2.
- An extra operative programme was carried out at reactor power 55 % and 90 % of rated power, see [L3]. These measurements confirmed power distribution asymmetry similar to the asymmetry measured at physics start-up. The asymmetry measured by in-core thermometric system had its minimum -5,5% in the Sector 1 and its maximum +7,2% in the Sector 4. The core load symmetry results measured at the physics start-up were independently confirmed.

3.2 Theoretical simulation of incorrect loading at Mochovce Unit 1, Cycle 9

One of the reasons, which could cause a core asymmetry, was incorrect loading of fuel assembly. The aim of the theoretical simulation was to simulate such incorrect loading, which could cause the core asymmetry similar to the asymmetry measured at the Mochovce Unit 1, Cycle 9. Therefore, two cases of incorrect loadings were calculated by BIPR-7 by VUJE see [L4]:

1. Instead of the fresh Gd-2 fuel assembly (average enrichment 4,25 %) in the position 17-28 (the Sector 4), profiled FA (average enrichment 3,82 %) was loaded. The calculated deviations between calculated symmetry coefficients and value 1,0 are displayed in Fig. 4 and Fig. 5.
2. Instead of the fresh Gd-2 fuel assembly (average enrichment 4,25 %) in the position 17-28 (the Sector 4), unprofiled FA (average enrichment 3,6 %) was loaded. The calculated deviations between calculated symmetry coefficients and coefficients 1,0 are displayed in Fig. 6 and Fig. 7.

From the Fig. 4, 5, 6 and 7 it is seen that the positive deviations between calculated symmetry coefficients and value 1,0 in the Sector 4 approximately match the measured deviations. But the negative deviations between calculated symmetry coefficients and value 1,0 in the Sector 1 are less (in absolute values) than the measured deviations. It means that the simulated deviations are in conflict with the measured deviations, which positive and negative deviations in absolute value were approximately the same.

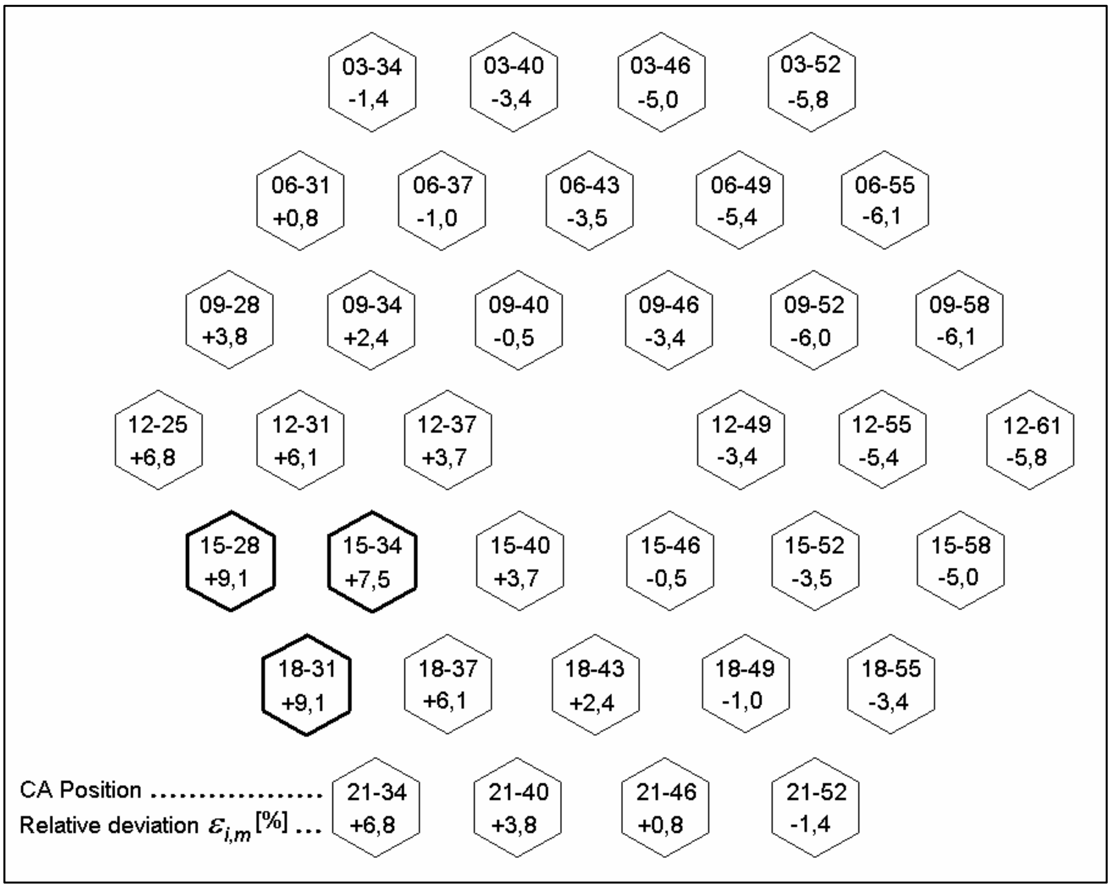

Fig. 4 Distribution of relative deviations between theoretical values of symmetry coefficients and value 1 in case of incorrect loading of profiled FA in the position 17-28

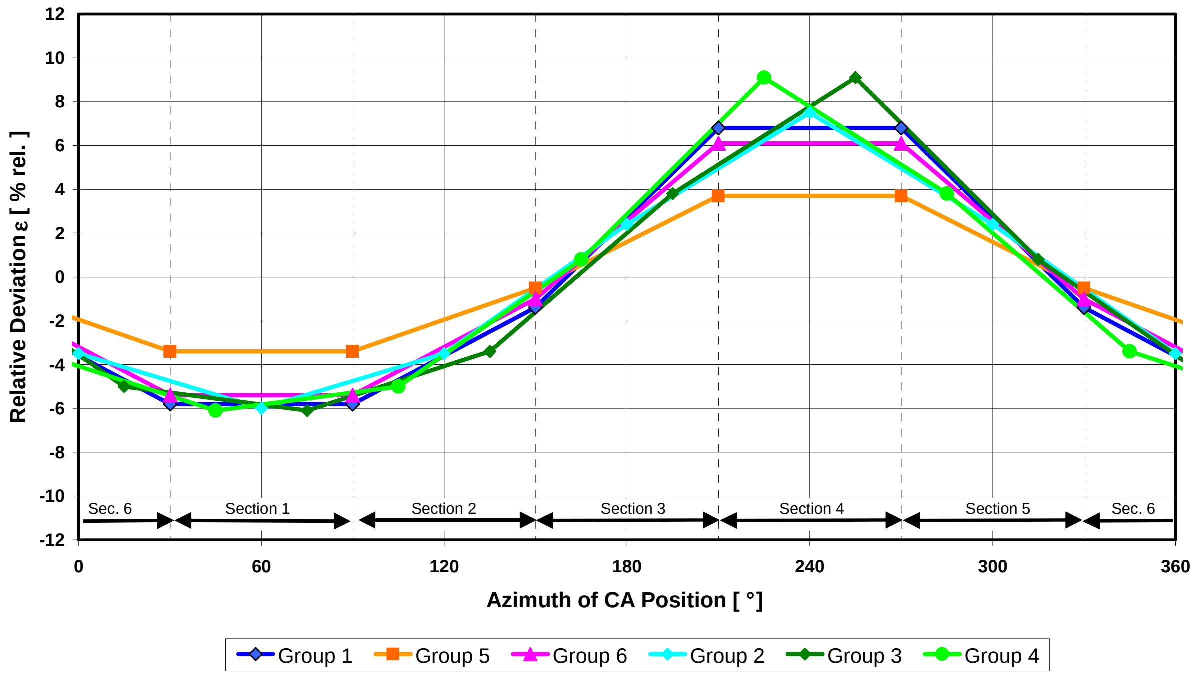

Fig. 5 Azimuthal distribution of relative deviations from Fig. 4

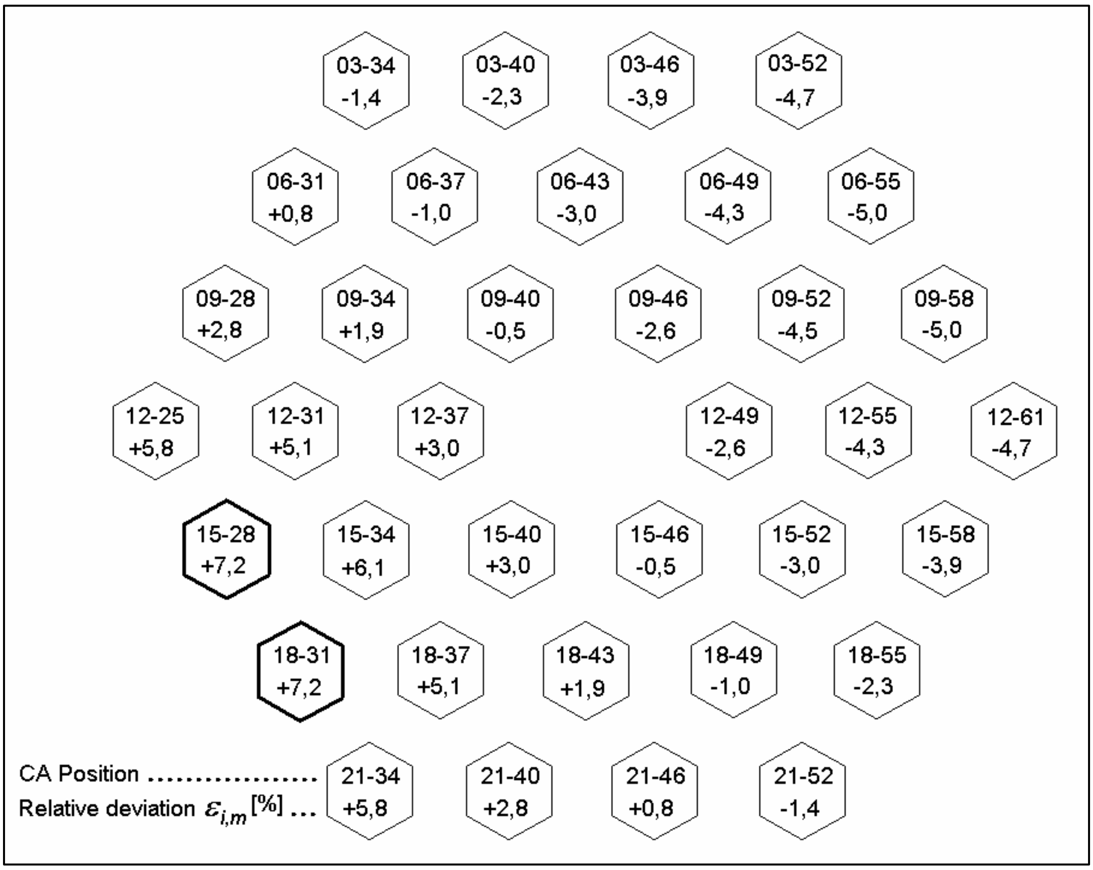

Fig. 6 Distribution of relative deviations between theoretical values of symmetry coefficients and value 1 in case of incorrect loading of unprofiled FA in the position 17-28

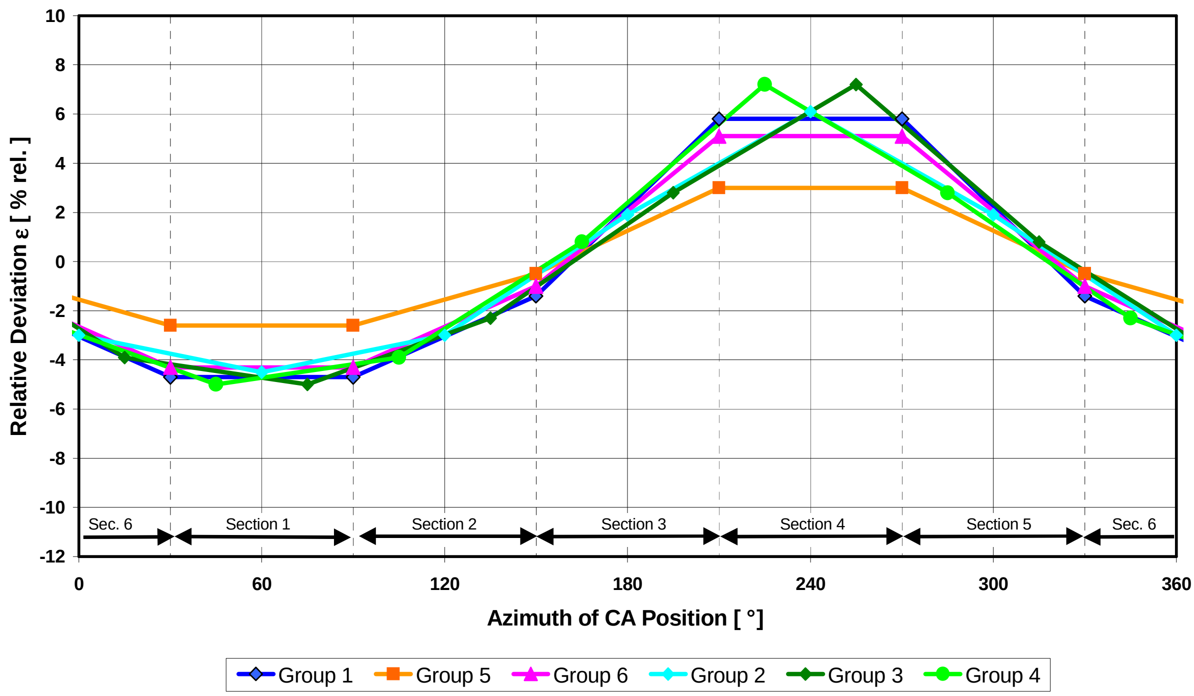

Fig. 7 Azimuthal distribution of relative deviations from Fig. 6

From the results of both simulated loadings is obvious that the asymmetry measured at the Mochovce Unit 1, Cycle 9 could not be caused by incorrect loading of one FA. Generally, if one incorrect FA would be loaded into the core, it would cause a sharp extreme of the deviations of symmetry coefficients in the core sector with the incorrect FA. And in the opposite core sector the other extreme would be more round or not so sharp.

As the maximum and the minimum of the symmetry coefficients deviations measured at the Mochovce Unit 1, Cycle 9 were almost the same in absolute values, theoretically it could be caused by two incorrect FAs loaded into core or by unintended switch of two FAs. However, as the core loading is checked by a prescribed loading procedure and also by a television camera, loading of two incorrect FAs into the core or unintended switch of two FAs is improbable.

3.3 Possible reasons for acceptance criterion non-fulfilment

Possible reasons for acceptance criterion non-fulfilment were analysed and the analysis results are summarized in Table 2.

Table 2 Analysis of possible reasons for acceptance criterion non-fulfilment

Possible reasons for acceptance criterion non-fulfilment	**Analysis results**
Mistake in measurement procedure or evaluation	Impossible
Human error	Impossible
Measurement system failure	Impossible
Influence of undesirable change of boric acid concentration or coolant temperature.	Impossible
Influence of boric acid concentration differences in reactor core sectors	Impossible
Interchange in connection of any CA drive	Impossible
Unequal coolant flow through FAs in a reactor core sector	Impossible
Unintended switch of FAs with different enrichment or burn-up	Impossible
Loading of FAs with incorrect enrichment	Impossible
Unequal worth of individual CAs in the same group 1÷5	Impossible
During the measurement some CA from group 1÷5 were partially inserted into core	Impossible
During the measurement some CAs from group 6 were in incorrect positions	Impossible
Unequal worth of individual CAs in the group 6 in frame of manufacturing tolerances	Impossible
Influence of Gd on neutron flux distribution	Probable

The symmetry measurement results obtained during Physics Start-up at the Mochovce Unit 1, Cycle 9, were independently confirmed by the power distribution measurement at 55 % and 90 % of rated power. It means that at the Mochovce Unit 1, Cycle 9 neutron flux distribution was really asymmetric.

The asymmetry at the Mochovce Unit 1, Cycle 9 was probably caused by utilization of the gadolinia. The power distributions in the reactor core are never perfectly in equilibrium or symmetrical due to a lot of perturbations. Some of asymmetrical distributions can be emphasized by the use of burnable absorber, because the depletion of the burnable absorber is different in each part of reactor core [L5].

4. CONCLUSION

The utilization of the gadolinia at the Bohunice Units 3&4 and Mochovce Units 1&2 started in 2006. The symmetry measurement results obtained at the Bohunice and Mochovce Units in the years 2006÷2008 were presented in the paper. Except the results measured at the Mochovce Unit 1, Cycle 9, all symmetry coefficients met the acceptance criterion ±7 %. The symmetry measurement results measured during Physics Start-up at the Mochovce Unit 1, Cycle 9 were in the range -7,8 % to + 7,7 %. This asymmetry was independently confirmed by the power distribution measurement at 55 % and 90 % of rated power. It means that the asymmetry measured during physics start-up was real.

Loading of one incorrect fuel assembly into the reactor core at the Mochovce Unit 1, Cycle 9 was excluded on the base of theoretical simulation calculated by BIPR-7. One of the reasons, which could cause a core asymmetry, is the utilization of the gadolinia. The power distributions in the reactor core are never perfectly in equilibrium or symmetrical due to a lot of perturbations. Some of asymmetrical distributions can be emphasized by the use of burnable absorber, because the depletion of the burnable absorber is different in each part of reactor core [L5]. The utilization of the gadolinia like a possible reason for reactor core asymmetry in Cycle 9 was confirmed by core symmetry measurement in the beginning of next Cycle 10, where the measured core symmetry coefficients met the acceptance criterion.

LITERATURE

[L1] Elko M. at al.: Physics start-up evaluation of Mochovce Unit 1, Cycle 9, VUJE, V01- 0410/4275-1/2007.8.1.1, 2007

[L2] Sedlacek M. at al.: Acceptance criterion of start-up physics tests, VUJE, 50/95, 1995

[L3] Palenik P., Urban P.: Evaluation of programme 1DOP/B0143.088/2007 „Reactor core symmetry check and power distribution measurement in case of individual CA insertion into core", SE-EMO, May 2007

[L4] Chrapciak V.: Theoretical simulations of incorrect fuel assembly loading at Mochovce Unit 1, Cycle 9, information by e-mail, VUJE, March 25, 2007

[L5] Zheng S.: Bi-content Gadolinia as Burnable Absorber in PWR to Improve the Reactor Core Behaviour, AREVA, 2007 International LWR Fuel Performance Meeting, San Francisco, California