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Comprehensive solution of the „MIDICORE" VVER-1000 Core Periphery Power Distribution Benchmark by the KARATE and MCNP code system

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Abstract - *The paper presents KARATE and MCNP solutions of the "MIDICORE" benchmark. This test problem includes a mathematical benchmark representing a simplified sector of VVER-1000 core. The exercise was defined by ŠKODA JS a.s. in cooperation with ÚJV Řež a.s. It consists of 37 fresh fuel assemblies with 4 different enrichments. The details (materials and geometry) about core basket and the radial reflector are given, too. To investigate this benchmark is valuable in many reasons. The validation of the actually applied calculational methods is necessary, as the distribution of the fuel pin power cannot be directly measured. It is worth to see how our upgraded models which were used for VVER-440 until now can be applied for VVER-1000.*

I. INTRODUCTION

The new Russian reactor AES-2006 (VVER-1200) represents the latest model currently offered for construction by Rosatom. It is an evolutionary development of the well-proven VVER-1000 with an increasing thermal power to about 3200 MWth and providing additional passive safety features [1]. A number of VVER-1200 reactors are currently being built in Russia, Turkey and Belarus [2, 3] and planned to be built in Hungary, too.

Because this new reactor is similar to the VVER-440 also, as it has -for example- hexagonal geometry too, it is appropriate to create the new code complex starting from the methods currently used very effectively for this smaller VVER reactor.

The original KARATE-440 code system applicable for the calculation of VVER-440 reactors is based on the ENDF/B-VI nuclear data library [4, 5]. The main goal of the calculation is core reload design, however, certain problems amenable to a static code can be analysed by KARATE-440. Accordingly, stationary neutron physics and thermal hydraulics models have been implemented. These models are capable of following burnup and slow Xenon transient processes but do not allow for calculating faster transients demanded in a safety analysis.

KARATE 440 involves all the libraries and computer programs, which are needed to perform fuel cycle calculations and fuel cycle design. The intra assembly power distribution is also determined. The libraries need refreshment if a new fuel type is being used or if the parameter range of an existing fuel is being extended. The calculation is grouped into 3 levels. A level is connected to the higher one through parameterised data libraries. These libraries provide a part of the input data for the higher level. A level is connected to the lower one also, usually boundary condition is provided for a "Lupe"-like calculation. The main solvers of library preparation are the 1D COLA and 2D MULTICELL transport modules.

Some major changes of the existing program system and further development in the methodology previously used are necessary to apply it for VVER-1200 reactors. The enhanced system is needed to be verified and validated.

In this paper, the verification and demonstration of the improved model named as KARATE-1200 code system is demonstrated by the solution of the MIDICORE benchmark defined in the frame of the AER ("Atomic Energy Research") collaboration. The problem has been solved by MCNP and KARATE codes [6]. Now some improvements will be presented.

II. OUTLINE OF THE MIDICORE BENCHMARK

Some information on the 2D mathematical benchmark is presented below. The details can be found in [7]. The horizontal cross section of the benchmark problem is hexagonal and it is restricted only on a small part of the core at the basket near the periphery as denoted by bold dashed lines in Figure 1. It is based on the cold state geometry of the VVER-1000 reactor vessel. The inner edge of the reactor vessel presents the outer boundary of the model in the radial direction. The core segment with the fuel assembly (FA's) names and numbering can be seen in Figure 1, too.

The reflective boundary conditions are used on the azimuthal surfaces numbered as 1 and 2; while the total absorption boundary condition (leakage to the vacuum) is used on the cylindrical outer boundary numbered as 3 (see the bold dashed lines in Fig. 1.). The reflective boundary conditions are used in axial directions.

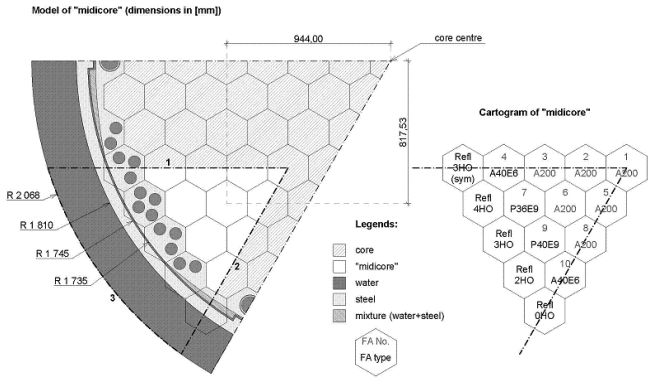

Fig. 1. The MIDICORE calculation model as a segment of horizontal cut of the VVER-1000 core (left) and the map with FA's names and numbering (right).

In our method of the nodal calculation, the reflector parts are excluded from the diffusion type calculations and represented by albedo matrices which are deduced from a set of specific calculations with different inhomogeneous boundary conditions. Such a way the detailed description of the core periphery is important in this aspect.
Due to the unusual symmetry of the problem a full core arrangement was investigated (see in Figure 2.) instead of the above given 60 degree sector. The comparison of the two arrangements reflects some weakness of the benchmark, namely the outer part of the problem is not simulated precisely. However these assemblies are not subject of the benchmark.

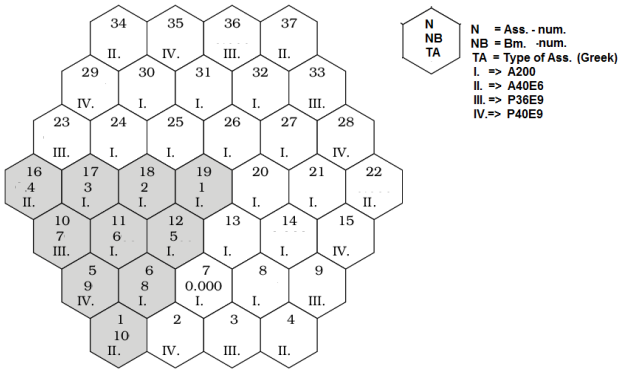

Fig. 2**.** Extended to full core of the 60 degree sector of the MIDICORE benchmark. The type of assembly is given by Roman number and the original sector of the benchmark signed by gray color. In the middle of the grey hexagon, the numbering of Benchmark is presented.

Material composition is homogeneous in axial direction, except the steel-water mixture at a small part of the reflector. On the arc of the basket there are grooves on its outer surface. That is why two different models are introduced. In the reference model a periodic steel/water structure 20/38 mm has be used, while in the standard model this structure is smeared over the volume. There are several cylindrical holes in the basket. Its diameter is 70 mm and strict position can be read from the Fig. 1. The distances of the holes center from the inner edge of basket are 75 mm and 150 mm, respectively. Finally a 3 mm water gap can be found between the edge of core basket and the edge of FA which has to be modelled, too. The reflector with the basket can be divided into with reflector hexagon. Their names are non-standard one, however the remaining FA's have standard Russian names and their details are defined in Figs. 2.a-2.d. and in [3]. The cluster control rods are not inserted into the FA's and the guide tubes are filled with water.

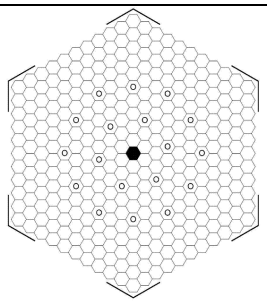

Fig. 2. a: FA of type A200

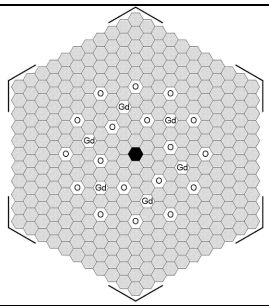

Fig. 2. b**:** FA of type A40E6

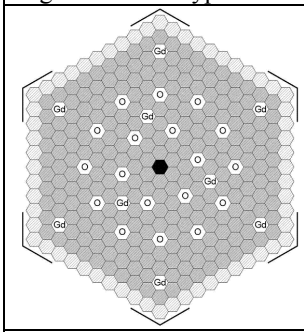

Fig. 2. c: FA of type P36E9

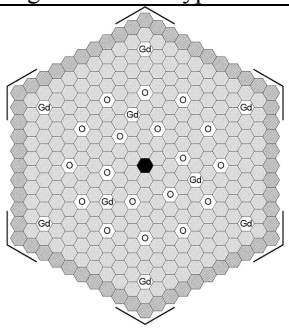

Fig. 2. d**:** FA of type P40E9

The main issue of this benchmark is to give some reference for validation of pin by pin power distribution at the periphery of the VVER-1000 core calculated by standard core calculation method using few-group diffusion approximation. In another case reflector assemblies presented in Fig. 1 have to be considered in details in the calculations. The results to be reported:

- k_{eff}
- Integral fission power of FA's No. 1-10. (normalized for the full core: 37 FA's)
- Pin by pin power distributions in FA No. 6 - 9 (normalized for the assembly: average relative pin powers equals 1 in each FA's)

III. CALCULATIONS BY THE MONTE CARLO CODE

On the basis of the benchmark specification a series of Monte Carlo calculations were carried out. All presented Monte Carlo calculations have been performed with MCNP5 ver1.40 code [8]. The ENDF/B-VI library was chosen as the basic data library (14c for uranium isotopes, .62c and .66c for the others) but for the Fe, Co and Ni isotopes the ENDF/B-V data were chosen. Possible source convergence problems were checked by increasing the number of active and passive cycles as well as the number of neutrons per cycles. No significant change of the evaluated quantities was found. It is worth to mention, that our model has been validated against VVER-1000 benchmarks with good results [9].

First, Monte Carlo calculations were used to verify our assembly calculations. In case of KARATE the few group library preparation for the nodal and pin by pin models were performed by the MULTICELL code. The calculated infinite multiplication factors for four different assemblies with our MCNP results are presented in Table I.

Table I. The calculated infinite multiplication factor

Name of FA	K_{inf} calculated by MCNP	St.Dev of MCNP	K_{inf} calculated by MULTICELL
A200	1.07861	3.9E-4	1.07167
A40E6	1.22281	4.0E-4	1.21420
P36E9	1.16005	4.0E-4	1.15152
P40E9	1.19049	4.0E-4	1.18061

The underestimation of the MULTICELL is significant in these cases. On the other hand the MULTICELL code gave rather good results against measurements containing gadolinium perturbation [11].

Secondly, the benchmark was calculated as it was specified, in the reference. Three different MCNP input decks were developed separately: Rez [7], RRC Kurchatov [12] and MTA EK. The calculated effective multiplication factors are shown in Table II.

Table II. The calculated effective multiplication factor

	k_{eff}	σ
SKODA-REZ	1.04538	0.00003
RRC Kurchatov	1.039516	-
KFKI AEKI	1.04411	0.0001

The radial power peaking factor predicted by our MCNP model and its deviation from the reference solution can be seen in Figure 3. The pin power distributions are given in Figures 4-6. The difference among the assembly integrated power distribution is less than 1.5% the average value was 0.3%. Concerning the pin power distributions the difference was less than 1%. The highest discrepancies could be found near the basket. Generally, no significant change was found.

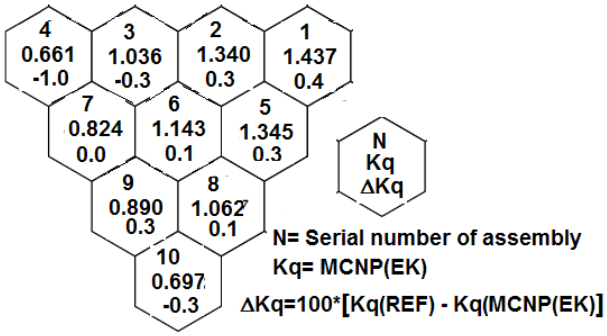

Fig. 3. Radial power peaking factor (up) and its deviation from the reference (down) calculated by our MCNP5

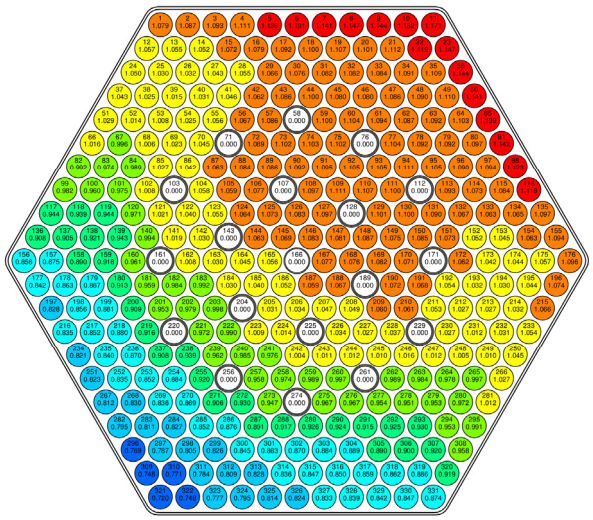

Fig. 4. Pin power distribution calculated by our MCNP5 for assembly 6 (Type: A200)

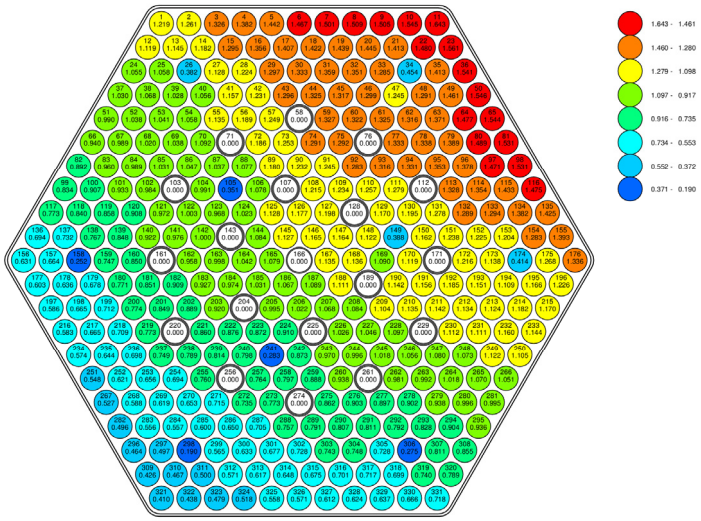

Fig. 5. Pin power distribution calculated by our MCNP5 for assembly 7 (Type: P36E9)

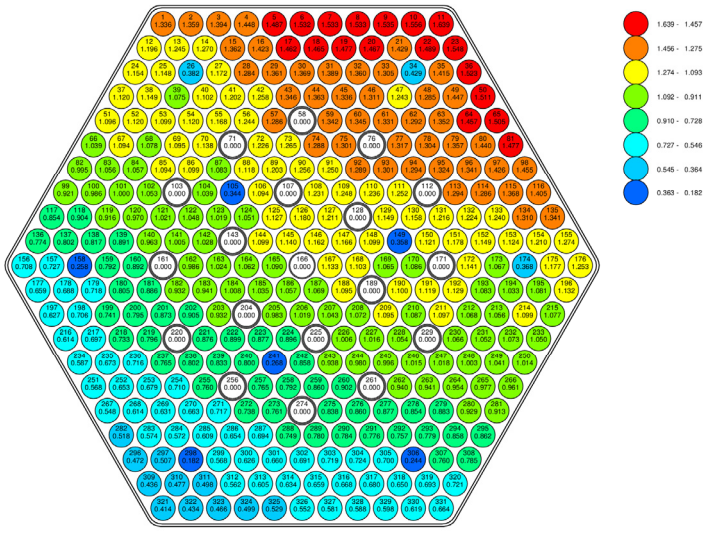

Fig. 6. Pin power distribution calculated by our MCNP5 for assembly 9 (Type: P40E9)

Another goal of the MCNP calculation is to give 2 group current at the reflector edges for preparing the reflector albedos. This task is under consideration.

IV. CALCULATIONS BY THE KARATE CODE

IV.1. Linear Pin Power Calculation Methodology in KARATE Code System

KARATE code system involves all the libraries and computer programs, which are needed to perform fuel cycle calculations and fuel cycle design. The intra assembly power distribution is also determined. The libraries need refreshment if a new fuel type is being used or if the parameter range of an existing fuel is being extended. The calculation is grouped into 3 levels. A level is connected to the higher one through parameterised data libraries. These libraries provide a part of the input data for the higher level. A level is connected to the lower one also, usually boundary condition is provided for a "Lupe"-like calculation. The levels involved in KARATE include:

- cell or assembly spectral calculation by using the 1D COLA and 2D MULTICELL transport modules,
- assembly level to provide homogenized assembly library and to calculate pin powers in selected assemblies by using a 2D 2 or 4 group diffusion calculation,
- global level to determine criticality parameters and power distributions by using a 2 group nodal method.

Core calculations are made with the GLOBUS nodal code using the homogenized few group cross sections of assemblies, then as a result of the core calculations (with flux boundary conditions) inhomogeneous type fine mesh diffusion calculations are carried out for the assembly and its vicinity with the SADR code.

As the goal of the work is the validation of the KARATE code system concerning the linear pin power calculation near the reflector, in solving the test case we applied the same methods and procedures as in case of routine power plant calculations. The difficulties of the calculations in the reflector region are as follows.

- Very complicated structure (geometry and composition data). Even the Monte-Carlo calculations can lead to different results due to the different input data created by different users. There are different technical data available. Even the Monte-Carlo calculations must be validated against measurements.
- Complicated spectral and 3D spatial effects of the neutron transport: diffusion approximation in the very heterogeneous region is not satisfactory without some special treatment. 3D effects must be taken into account. Usually core design calculations are based on the few-group diffusion approximation. Fine mesh calculations taking into account the flux tilt caused by the environment of the calculated region are usually two-dimensional.

In KARATE, the reflector parts and the control rod regions are excluded from the diffusion type calculations, and represented by albedo matrices. The elements of the albedo matrices [$\acute{\alpha}_{gg'}$] are the reflection probabilities for neutrons entering the excluded region in group g' and returning to the fuel assemblies in group g, thus for the partial current that enters the control rod from the fuel [J^+] the returning partial current [J^-] can be expressed as

$$J_g^- = \sum_{g'=1}^{2} \alpha_{gg'} J_{g'}^+ \qquad (1)$$

According to the results of the methodological investigations, the albedo matrix elements can be considered as a function of the soluble boric acid concentration [C_B] the moderator density [ρ_m] and the position of the edge.

$$\alpha_{gg'} = \alpha_{gg'}(C_B, \rho_m) \qquad (2)$$

In the KARATE calculations, first 1D multigroup transport calculations of the different coupler regions and the neighbor assemblies are performed by using the COLA module, and the obtained two-group albedo matrices are parameterized. Finally a correction factor D is determined by using MCNP 3D results.

$$J_{MCNP}^- = D\alpha_C(p) J_{MCNP}^+ \qquad (3)$$

In case of the fuel pin few group cross-section library and the fuel assembly library new calculations were necessary for the simplified fuel assembly description in the benchmark. Correspondingly new albedo matrices were developed for reflector albedos according to the specification.

IV.2. Results of the Calculations Made by KARATE Code System

Concerning our previous calculation [6] recently the library of the reflector albedo was made more precise.

The radial power peaking factor predicted by KARATE and its deviation from the reference solution can be seen in Figure 7. The discrepancies found in the preparation of the FA library (Table 1) together with the deviation of the power distributions predicted by KARATE and the reference solution (higher leakage indication of KARATE) explains the k_{eff} deviation (see Table II and MTA EK k_{eff} in Table III). It is worth to mention that the difference between the eigenvalue calculated by KARATE and MCNP can be originated from the different nuclear data and the methods.

Table III. The calculated effective multiplication factor

	k_{eff}
SKODA Moby Dick (2011)	1.0305
MTA EK	1.03435

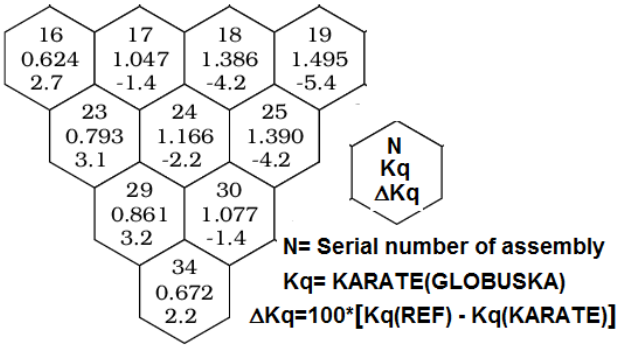

Fig. 7. Radial power peaking factor (up) and its deviation from the reference (down) given in the benchmark specification

The last nine figures present the reference solution (SKODA), the result of KARATE (SADR module) and their differences for the three assemblies prescribed by the benchmark specification, successively. The difference is given by the following formula:

$$\Delta K_x = 100 * [\Delta K_x(REFERENCE) - \Delta K_x(CALCULATED)]$$

where: x should be q (assembly power) or k (pin power).

One can see from these figures, that the discrepancies in the power distributions (K_q and K_k) are similar that it is usual in our calculations.

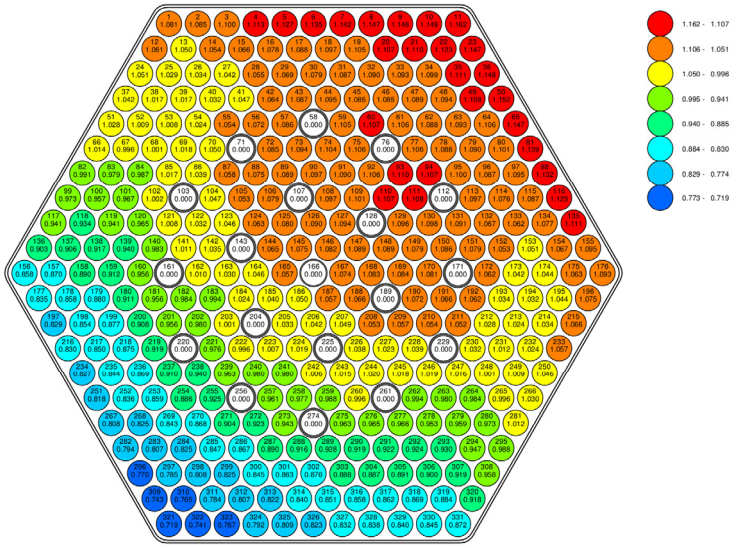

Fig. 8. Reference solution for Assembly No. 6. (Type: A200)

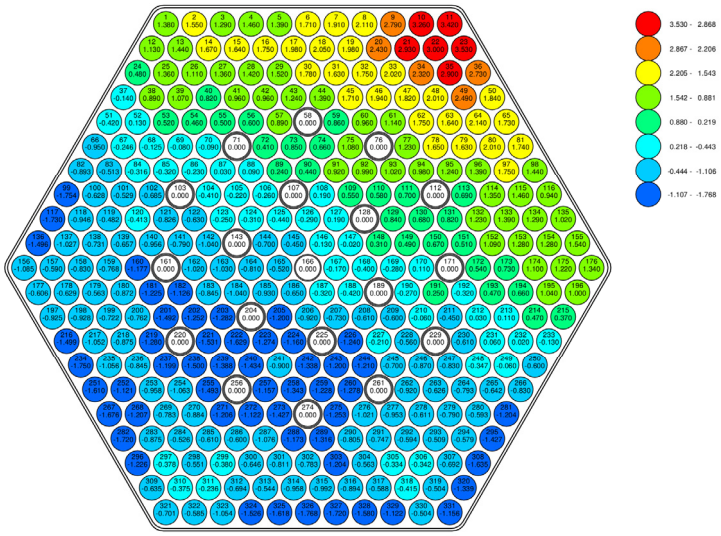

Fig. 10. Difference given by $100*[K_k(SADR)-K_k(REF)]$ for Assembly No. 6.

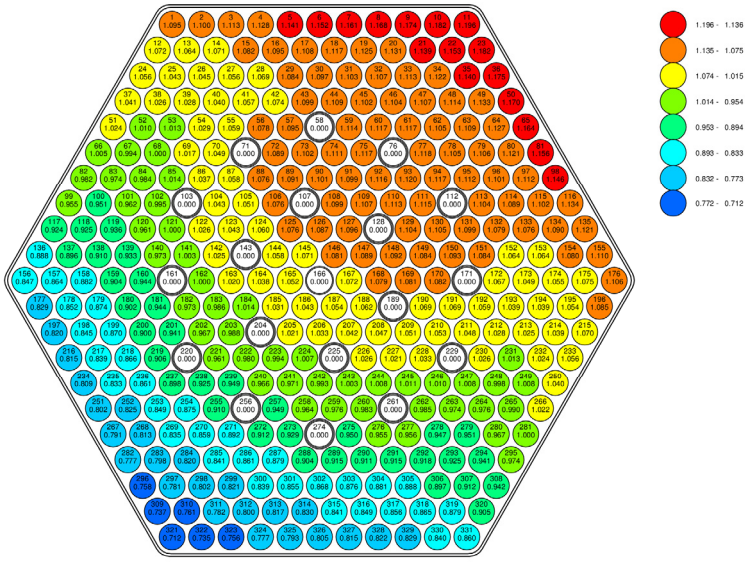

Fig. 9. Normalized pin power calculated by SADR: Assembly No. 6. (Type: A200)

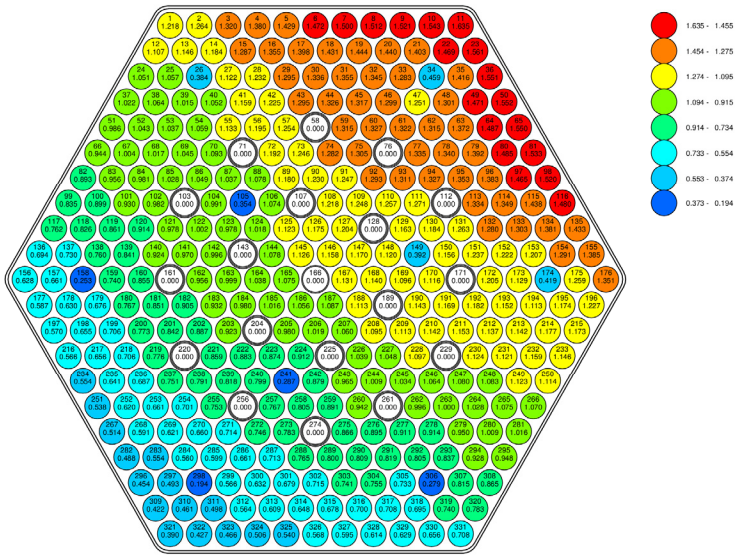

Fig. 11. Reference solution for Assembly No. 7. (Type: P36E9)

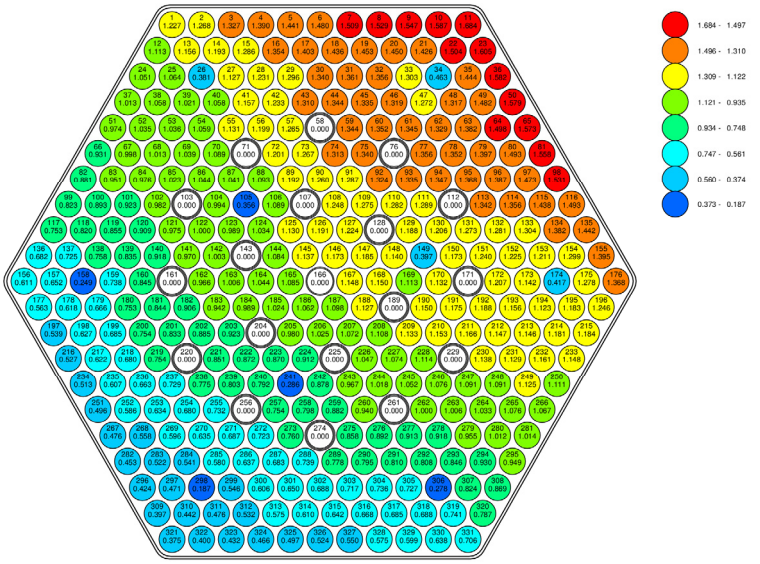

Fig. 12. Normalized pin power calculated by SADR: Assembly No. 7. (Type P36E9)

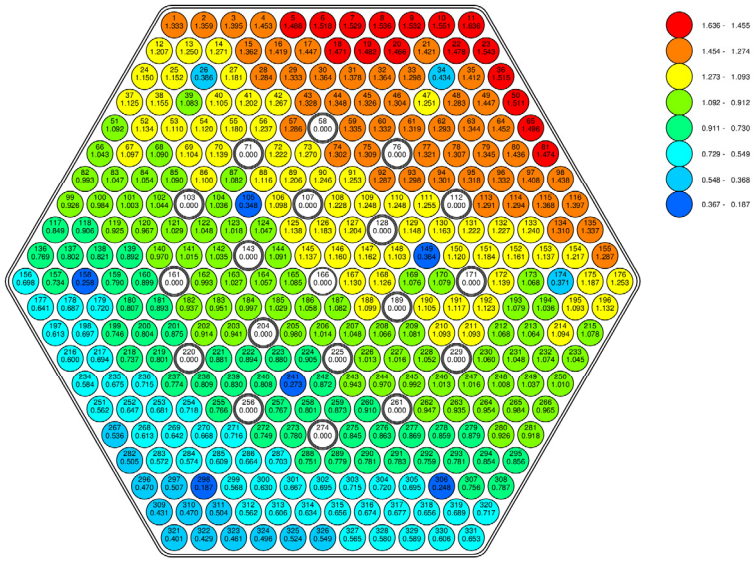

Fig. 14. Reference solution for Assembly No. 9. (Type: A40E9)

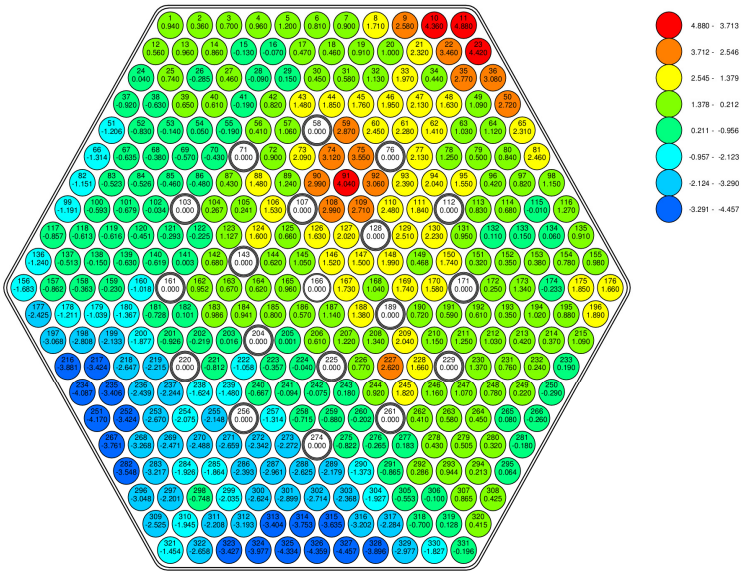

Fig. 13. Difference given by 100*[K_k(SADR)-K_k(REF)] for Assembly No. 7.

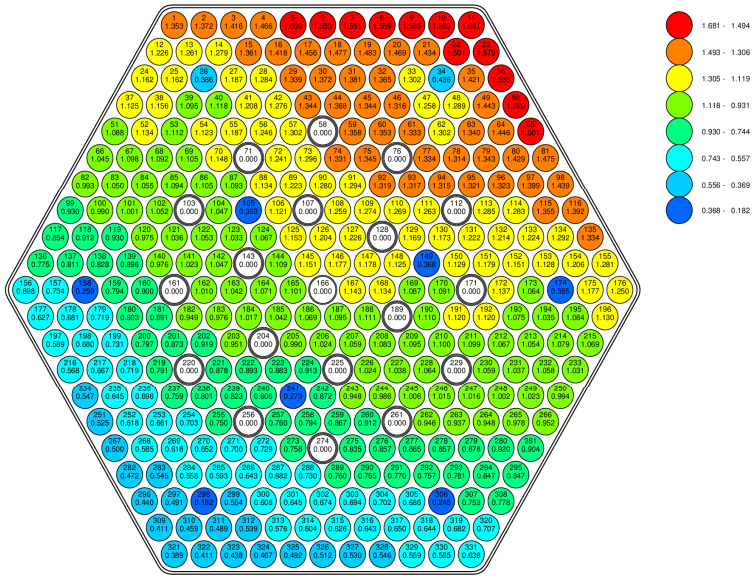

Fig. 15. Normalized pin power calculated by SADR Assembly No. 9. (Type: A40E9)

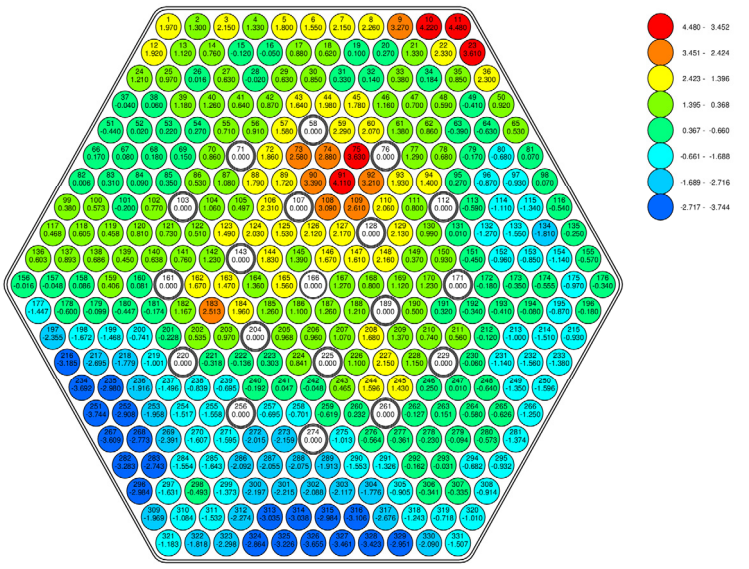

Fig. 16. Difference given by 100*[K_k(SADR)-K_k(REF)] for Assembly No. 9.

V. SUMMARY

The MIDICORE 2D mathematical benchmark was solved by the MCNP and KARATE code system. Rather good agreement was gained in case of Monte Carlo simulation comparing the results of three different data sets. In case of KARATE the same methods and approximations were used as in case of VVER-440 NPP applications. The under prediction of k_{eff} was already observed in the library preparation. In case of power distributions (K_q and K_k), the discrepancies (alterations) are similar that it is usual in our calculations.

Further investigations are necessary to understand the sources of errors in this new set of application of the KARATE code.

ACKNOWLEDGMENTS

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