Calculations and Measurements at the Training Reactor VR-1

J. Rataj, L. Sklenka

Department of Nuclear Reactors, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague

Presented by J. Rataj

Abstract. The Paper describes basic information about MCNP calculations and experimental measurements at the VR-1 reactor and their evaluation. The preparation of calculations and verification of the experiments are integral part of the VR-1 reactor operation. The neutronics calculations and analyses are often necessary condition to gain the approval to experiments realization at the reactor VR-1. The paper is focused particularly on the calculations and experiments with the LEU fuel core configuration.

1. Introduction

The training reactor VR-1 has been in operation since 1990 by the Department of Nuclear Reactors of the Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague. The reactor is a pool-type light-water reactor based on low enriched uranium (20 %) fuel IRT-4M with thermal power is up to 5kW$_{th}$. The moderator is light demineralised water, which is also used as a reflector, a biological shielding and a coolant. The pool disposition of the reactor facilitates easy access to the core, setting and removing of various experimental samples and detectors, easy and safe handling of the fuel assemblies. The integral control rods with cadmium absorber are identical, but its function is different. According to the connection to I&C are safety, compensation (shim) or control rods. The AmBe neutron source is used to start up the reactor. It ensures a sufficient level of the signal at the output of the power measuring channels from deep subcriticalities and thus it guarantees a reliable control of the reactor power during the start-up. The reactor is equipped with standard experimental instrumentations; e.g. horizontal, radial and tangential channels, instrumentation for study delay neutrons, rabbit and unique instrumentations; e.g "Hopik" for reactor dynamics studies or "Bublinky" for void coefficient studies. The reactor is successfully used for training the students of Czech universities and preparing the experts for the Czech nuclear. The reactor can be used for R&D with respecting low power of the reactor [6].

Deterministic codes WIMS and DIFER were used formerly for the neutronics calculations (criticality and neutron flux distribution calculations) of the VR-1 reactor at the Department of Nuclear Reactor. Since 1998 the calculations are performed by the statistical code MCNP [8] (version 4A, 4B, 4C and 5 now). The calculations are mainly focused on different parameters and characteristics of the new core configurations at the reactor, e.g. control rods worth, determination of reactivity excess and calculations of neutron flux distribution. A lot of MCNP simulations are focused on verification of neutron activation analysis experiments or determination of delayed neutrons parameters.

The Department of Nuclear Reactors made detailed neutronics calculations for core configurations with LEU fuel using MCNP code as well. These calculations were the necessary condition to gain the approval to operating the training reactor VR-1 with the LEU fuel IRT-4M [1], [2], [3], [4].

2. MCNP model of the reactor

Since the beginning the MCNP model of the reactor has been continuously upgraded and improved. Contemporary model of the reactor describes all significant parts of the reactor core:

- fuel assemblies IRT-4M (4-tube, 6-tube and 8-tube assemblies),
- 6-tube assemblies with control rods,
- core grid,
- fuel dummies,
- vertical channels (with the various diameter) in the fuel assembly, in the fuel dummy or in water only,
- horizontal channels (radial and tangential),
- external AmBe neutron source,
- beryllium and graphite reflectors,
- rabbit tube,
- delayed neutron measurement instrumentation.

MCNP input file (model) of the reactor VR-1 has been designed and created in order to easy use for all users even those with the small knowledge of MCNP. User can change the input file quickly and simply in order to change the core configuration and control rods position for the k_{eff} calculations. MCNP model enables to calculate neutron flux distribution in vertical channels with or without external neutron source. Some details of the VR-1 reactor MCNP model are shown in FIG. 1. and FIG. 2.

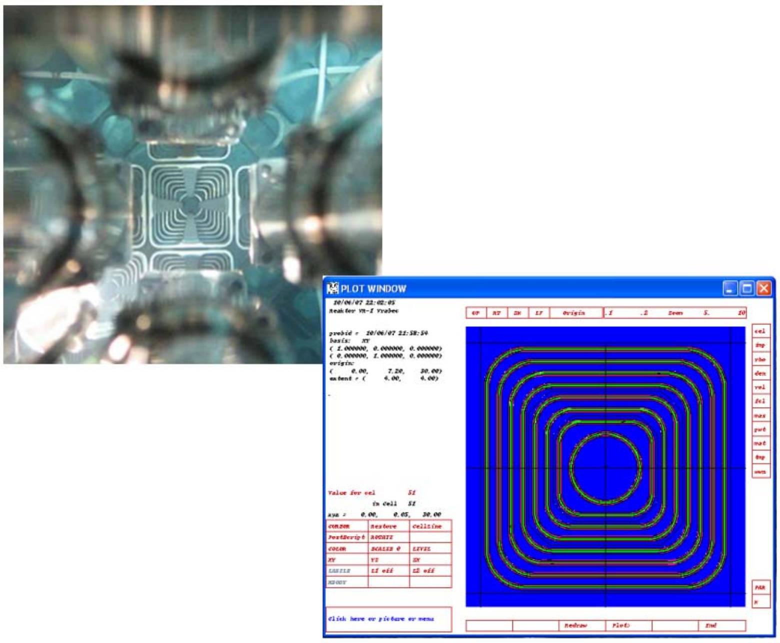

FIG. 1. Eight-tube fuel assembly IRT-4M in the reactor core and its MCNP model

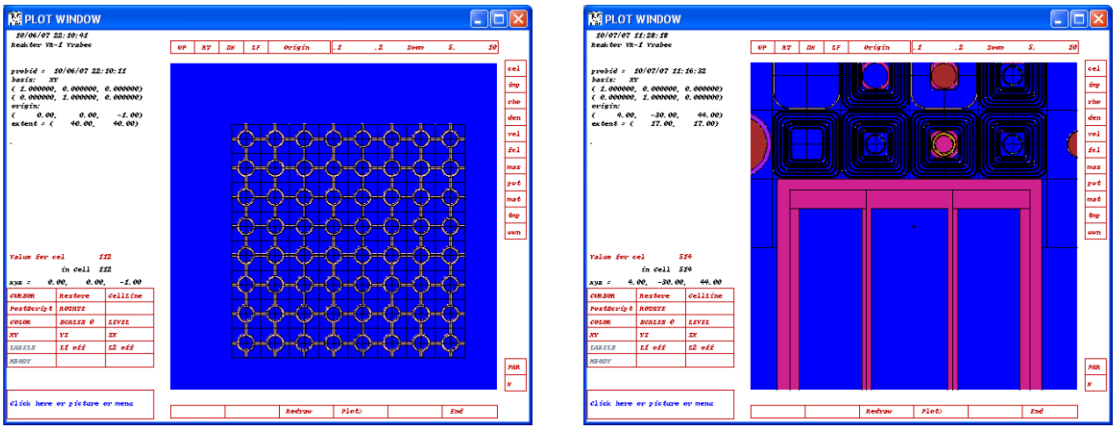

FIG. 2. model of the reactor grid (left) and radial channel (right)

3. MCNP calculations of the reactor with LEU fuel IRT-4M

In the autumn 2005 the HEU fuel IRT-3M with enrichment 36 % ^{235}U was replaced by the LEU fuel IRT-4M with enrichment 19.7 % ^{235}U at the reactor. The fuel swap at the reactor was a part of the international RERTR program [5].

Detailed criticality calculations were an essential part of the preparation of the reactor for operation with LEU fuel. Calculations were made for two intended core configurations C1 and C2 (see Fig. 3). The C1 configuration has been defined as “the essential core for education and training”. The C1 core contains nine 6-tube assemblies and eight 8-tube assemblies. The C2-configuration has been defined as “R&D core”. The C2 core contains ten 6-tube assemblies and ten 8-tube assemblies and in the center of the core is located a large graphite block.

Detailed criticality calculations for both core configurations by MCNP code were performed [1], [2], [7]. MCNP model of the C1 and C2 core configurations [FIG. 3] are shown in [FIG. 4]. As the C1 core is basic operational configuration in the reactor, its neutronics calculations were deeply studied and done in 4 four steps (1-4). For the C2 experimental core configuration the calculation was conducted in the same way as C1 core, but without last 4 step:

(1) Calculations required for the standard core license:
i.e. criticality calculations for the core with all control rods at the top positions, all control rods at the bottom positions, determination of the suitable critical state (i.e. control rod’s positions), worth of control rods and experimental channels, maximal and operational reactivity excess, shutdown margins, calibration curves of the rods.

(2) Uncertainties calculations arisen from fuel manufacture:
i.e. influence of different 235U enrichment, 235U mass, width of Al cladding, length of the assembly.

(3) Calculations of reactivity coefficients, see [Fig. 5] and [Table 1]:
i.e. Doppler effect, temperature coefficient of the moderator, void coefficient.

(4) Calculations of neutron flux density, see [Fig. 6]:
i.e. neutron flux density both in radial and axial direction.

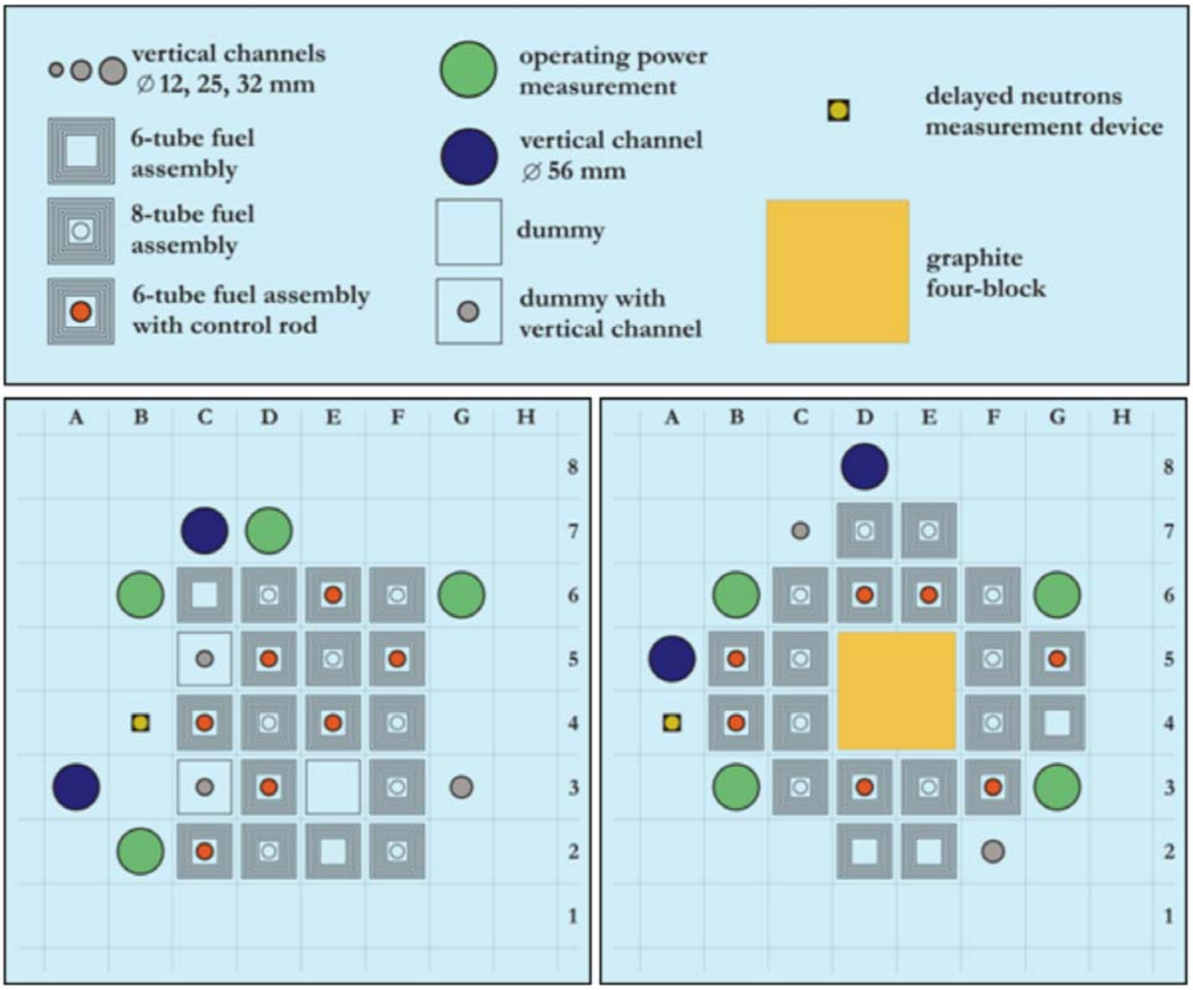

FIG. 3. Core configuration C1 and C2

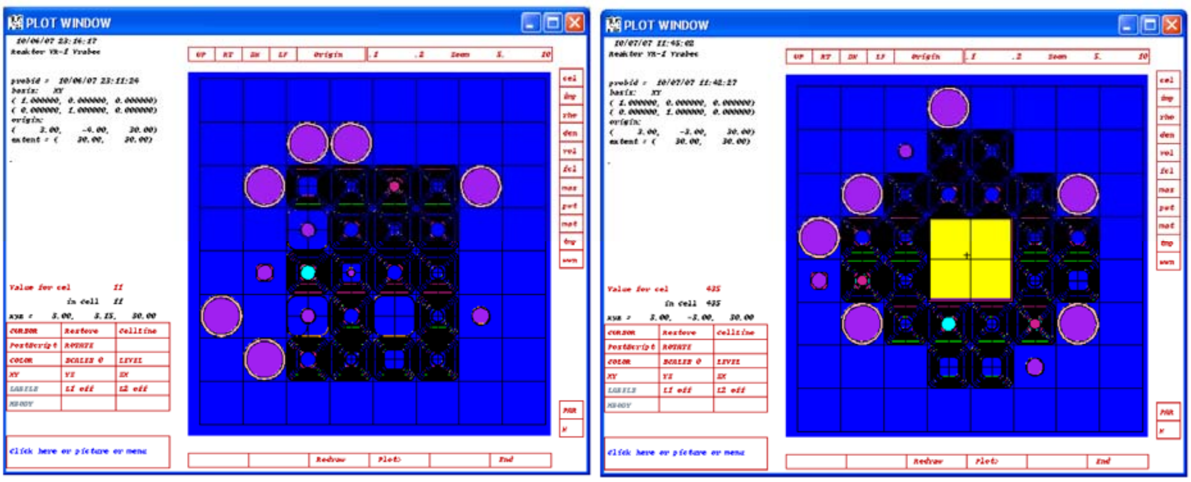

FIG. 4. MCNP model of C1 and C2 core configuration

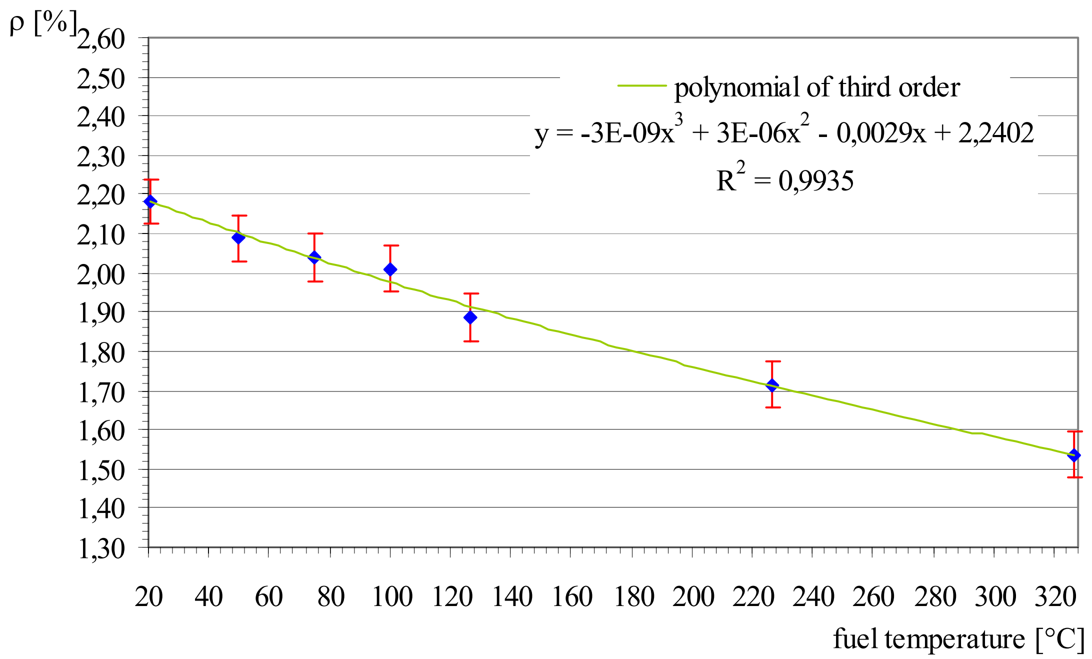

FIG. 5. Reactivity dependency on the the fuel temperature in the C1 core

Table 1. Temperature coefficients for the C1 core

parameter	value
moderator temperature reactivity coefficient, Δρ(%)/ºC	-1.38e-2
fuel temperature (Doppler) reactivity coefficient, Δρ(%)/ºC	-2.18e-3

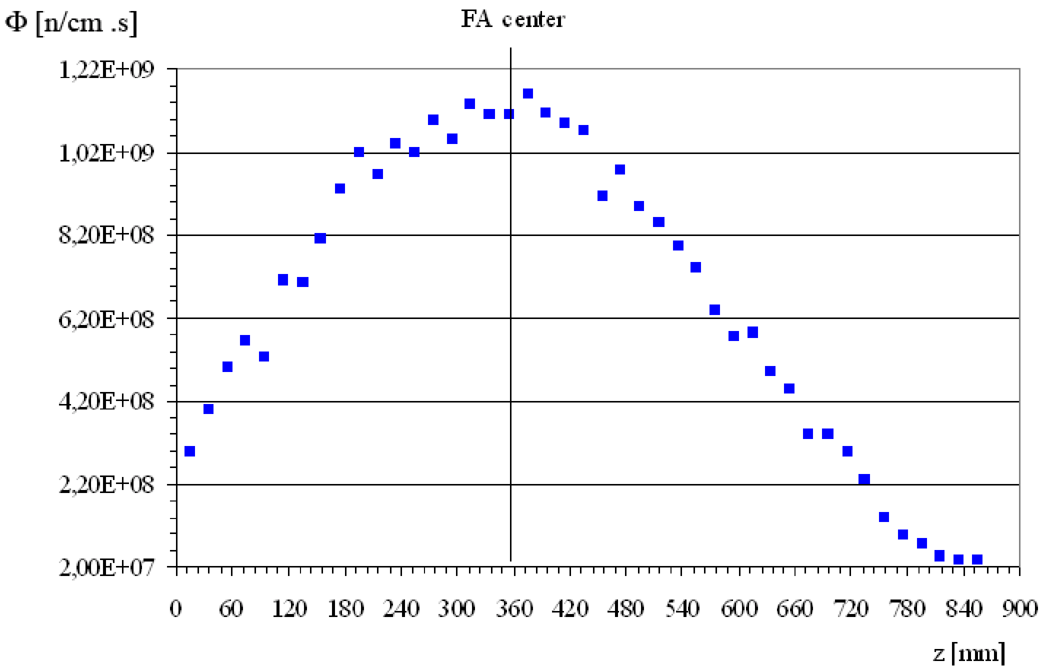

FIG. 6. Distribution of the thermal neutron flux density in axial direction of the core C1

4. Comparison of the MCNP calculations and experimental results for the LEU fuel

The first critical state with LEU fuel at the reactor (with the C1 core) was attained on October 18, 2005 [2], [3]. The measured first critical state was attained for the second control rod R2 in the position of 295 mm and other rods in the top position. The deviation of the critical state from the calculated values was 0.30 % [Δk/k] only (see Table 2.).

Table 2. Calculated and measured the first critical state with LEU fuel

<table>
<tr><td>control rod</td><td>B1</td><td>B2</td><td>B3</td><td>E1</td><td>E2</td><td>R1</td><td>R2</td></tr>
<tr><td>control rod position for the first critical state</td><td>680</td><td>680</td><td>680</td><td>680</td><td>680</td><td>680</td><td>295</td></tr>
<tr><td colspan="8"></td></tr>
<tr><td rowspan="2">calculation of
the experiment</td><td colspan="2">k_{eff}</td><td colspan="2">deviation</td><td colspan="2">ρ [%]</td><td>σ_ρ [%]</td></tr>
<tr><td colspan="2">1.00305</td><td colspan="2">0.00021</td><td colspan="2">+0.30</td><td>0.0208</td></tr>
</table>

The worth of all the rods and selected components in the core and its neighbourhood was also calculated and measured. The calculated results confirmed the assumption about the worth of the fuel elements and control rods. The measured control rods worth were slightly lower than the calculated ones (see Table 3. and FIG. 7.).

Table 3. Calculated and measured worth of the rods during the the first critical state with LEU fuel

control rod	position in the core	MCNP		Experiment	
		worth [%]	deviation	worth [%]	deviation
B1	D3	1.50	0.0848	1.37	0.0967
B2	E4	2.11	0.0861	1.89	0.0606
B3	D5	1.64	0.0878	1.46	0.0789
E1	F5	1.22	0.0811	1.00	0.0482
E2	C4	0.96	0.0901	0.93	0.0642
R1	C2	0.46	0.0888	0.42	0.0601
R2	E6	0.84	0.0849	0.90	0.0838

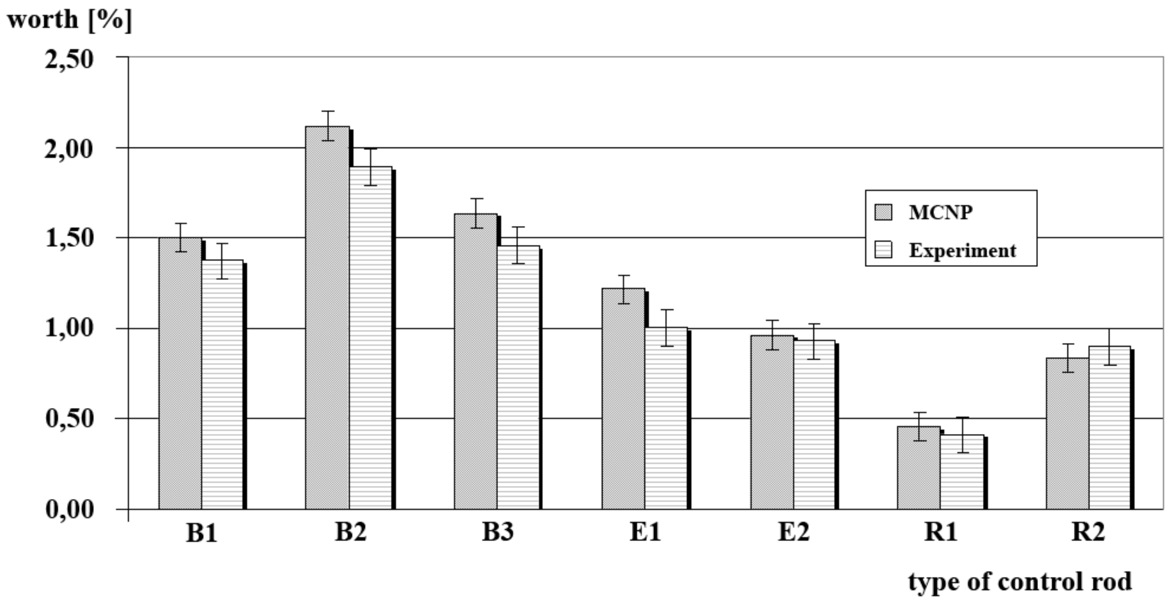

FIG. 7. Calculated and measured worth of the control rods during the first critical state with LEU fuel

Calibration curve of the R1 and R2 rods were calculated and measured for the core configuration C1 as well. The results for the control rod R1 are shown FIG. 8.

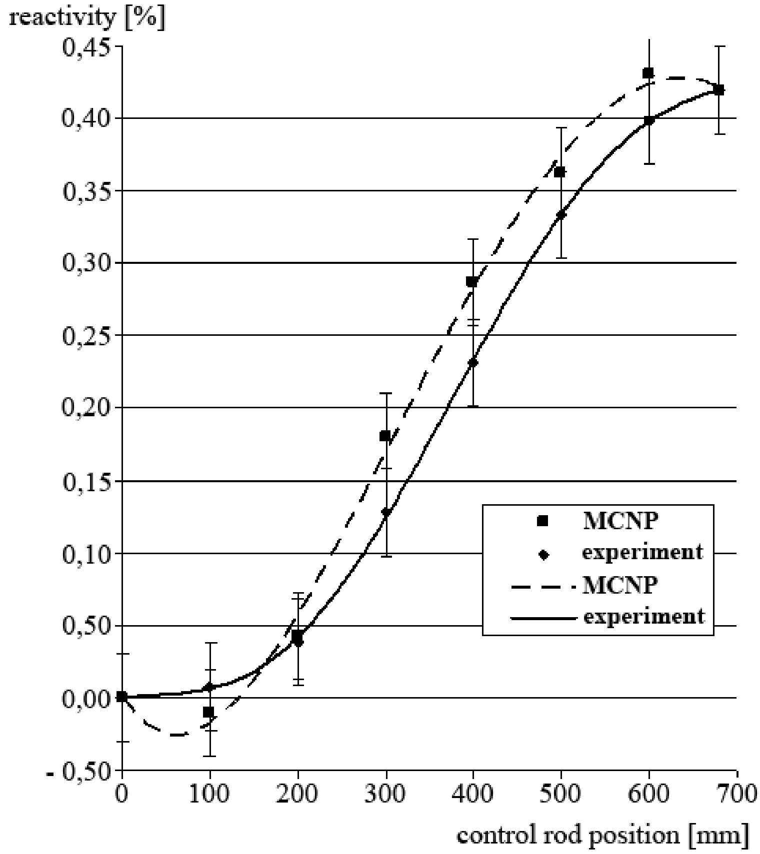

FIG. 8. Calibration curve of the R1 control rod

Core configuration C2 was the second core with the new fuel IRT-4M at the reactor VR-1 [4]. The basic critical experiment with the core configuration C2 was carried out in the start of June 2006. The reason of assembling the C2 core configuration was to validate larger scale core geometry with the LEU fuel as well as setting up a framework for irradiation experiments. It is assumed that in the future the graphite block would be replaced by an irradiation module. The first critical state with the C2 configuration was attained on June 15, 2006. The deviation of the critical state from the calculated values was 0.19 % [Δk/k] only (see Table 4.).

Table 4. Calculated and measured critical state of the reactor (C2 core)

<table>
<tr><td>control rod</td><td>B1</td><td>B2</td><td>B3</td><td>E1</td><td>E2</td><td>R1</td><td>R2</td></tr>
<tr><td>control rod position for the first critical state</td><td>680</td><td>680</td><td>680</td><td>680</td><td>680</td><td>450</td><td>452</td></tr>
<tr><td colspan="8"></td></tr>
<tr><td rowspan="2">calculation of
the experiment</td><td>k_{eff}</td><td colspan="2">deviation</td><td colspan="2">ρ [%]</td><td colspan="2">σ_ρ [%]</td></tr>
<tr><td>1.00186</td><td colspan="2">0.00034</td><td colspan="2">+0.19</td><td colspan="2">0.034</td></tr>
</table>

5. Conclusions

Reactor physicists of the training reactor VR-1 have been worked with MCNP code for many years and already performed calculating verifications of 15 core configurations at the VR-1 reactor. DNR performed detailed criticality calculations for core configurations with LEU fuel by the MCNP code as well. These calculations were the necessary condition to gain the approval to operating the reactor with the LEU fuel IRT-4M. The results of the calculations confirmed assumption that the new IRT-4M fuel is fully suitable for operation in the reactor and no consequences affected nuclear safety of the VR-1 reactor were found. The calculated results prove good agreement with experimental results.

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