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VALIDATION OF DYN3D PIN-POWER CALCULATION AGAINST EXPERIMENTAL VVER-FULL-CORE BENCHMARK

Jan Hádek
Nuclear Research Institute Rez plc
25068 Rez, Czech Republic
hdj@ujv.cz

Siegfried Mittag
Forschungszentrum Dresden-Rossendorf - Institute of Safety Research
P.O.B. 510119 D-01314 Dresden, Germany
s.mittag@fzd.de

ABSTRACT

The EU NURESIM V1000-VALCO-STAT benchmark is focused on three-dimensional VVER-1000 steady-states with assembly-averaged and fine-mesh power distributions. Calculation results are compared with measurements from the Moscow zero-power critical facility V-1000, which was used as a full-scale mock-up of the Russian VVER-1000 reactor core. A very low moderator temperature and radial-reflector asymmetries were significant for this core. The calculations are performed with the reactor dynamic nodal code DYN3D. The usual node-averaged approach is applied in the first step. Then, an intra-nodal pin-wise power reconstruction method and its combination with the pin-powers from the lattice code HELIOS zero-net-current fuel-assembly calculations are applied. The power distributions calculated by pin-wise reconstruction show better agreement with the measurement than the node-averaged values, which is particularly obvious for fuel assemblies with inserted control clusters.

Key Words: benchmark, NURESIM, VVER, DYN3D, pin-power reconstruction

1. INTRODUCTION

The creation of a generic methodology for LWR core physics benchmarking is one of the goals of the European NURESIM (Nuclear Reactor Simulation) code platform development [1]. This methodology is applied to VVER reactor cores [2]. It covers numerical, experimental, and operational benchmark problem definition and data collection. The experimental benchmarks are used for code validation. They must be well documented and accepted in the international community. Thus, steady-state power distributions measured in the experimental facility V-1000 (Moscow), documented within the EU-FP5 project VALCO were selected for the NURESIM V1000-VALCO-STAT benchmark. It is focused on three-dimensional steady-state calculations with a node-wise and fine-mesh approximation applying a pin-power reconstruction method. The calculation results are compared with measurements from the zero-power critical facility V-1000, which was used as a full-scale mock-up of the Russian VVER-1000 core. This type of core measurement is unique and was not realized so far for western PWR reactor types.
The reactor dynamic code DYN3D being a part of the NURESIM code platform was applied for the benchmark calculation.

2. THE V1000-VALCO-STAT BENCHMARK SPECIFICATION

The purpose of the V1000-VALCO-STAT static benchmark is to compare 3D steady-state calculations with measurements from the zero-power critical facility V-1000, which contains fuel assemblies (FA) of a standard Russian VVER-1000 nuclear power plant core [3,4]. The V-1000 core had been equipped with 163 original VVER-1000 hexagonal fuel assemblies (Fig. 1) and 61 standard control rod clusters, each comprising 18 absorber rods. The clusters are assigned to 10 groups (Roman numerals I – X in Fig. 1). The hexagonal assembly pitch is 23.6 cm, the 312 fuel rods being 353 cm long (active length). The core was surrounded by a radial reflector made of stainless steel with vertical cylindrical holes only at certain positions, causing radial-reflector asymmetries, while the fuel loading was symmetric.

The measurements were carried out in a fresh core that represents the first loading of a three-year fuel cycle of VVER-1000. The moderator was at room temperature, which is extremely low in comparison with NPP operation conditions. Criticality can be achieved in the V-1000 facility by slowly increasing the moderator level in the core. Power distributions were measured by irradiating special short fuel rods that had been placed in the central tubes of the fuel assemblies. Measured data of two steady states are available:

1. V-1000 with control rod group No. 10 fully inserted.
2. V-1000 without any control rods inserted.

Two-group node-homogenized diffusion parameters, assembly discontinuity factors, and pin powers for the V-1000 fuel assemblies were prepared by the lattice code HELIOS-1.5 [5]. The power distribution in such „cold“ V-1000 core turned out to be very sensitive to radial-reflector properties, thus extra attention was devoted to the radial-albedo-coefficients calculation by the neutron transport code MARIKO [6,7]. The basic V-1000 core operation parameters for both steady states are provided in Table I.

Table I: V-1000 basic core operation parameters

	date of measurement	**T_m=T_f** [^oC]	**C_b** [gH_3BO_3/kgH_2O]	**water level** [cm]	**CR position**	**short fuel rods**
State 1	04.12.1990	15.2	8.49	253.5	CR10 fully in	present
State 2	12.12.1990	15.2	8.68	266.8	all CR fully out	present

The water level, given in the table, is defined as the distance from the fuel bottom. The moderator (T_m) and fuel (T_f) temperatures as well as the boric acid concentration (C_b) were constant during both experiments.

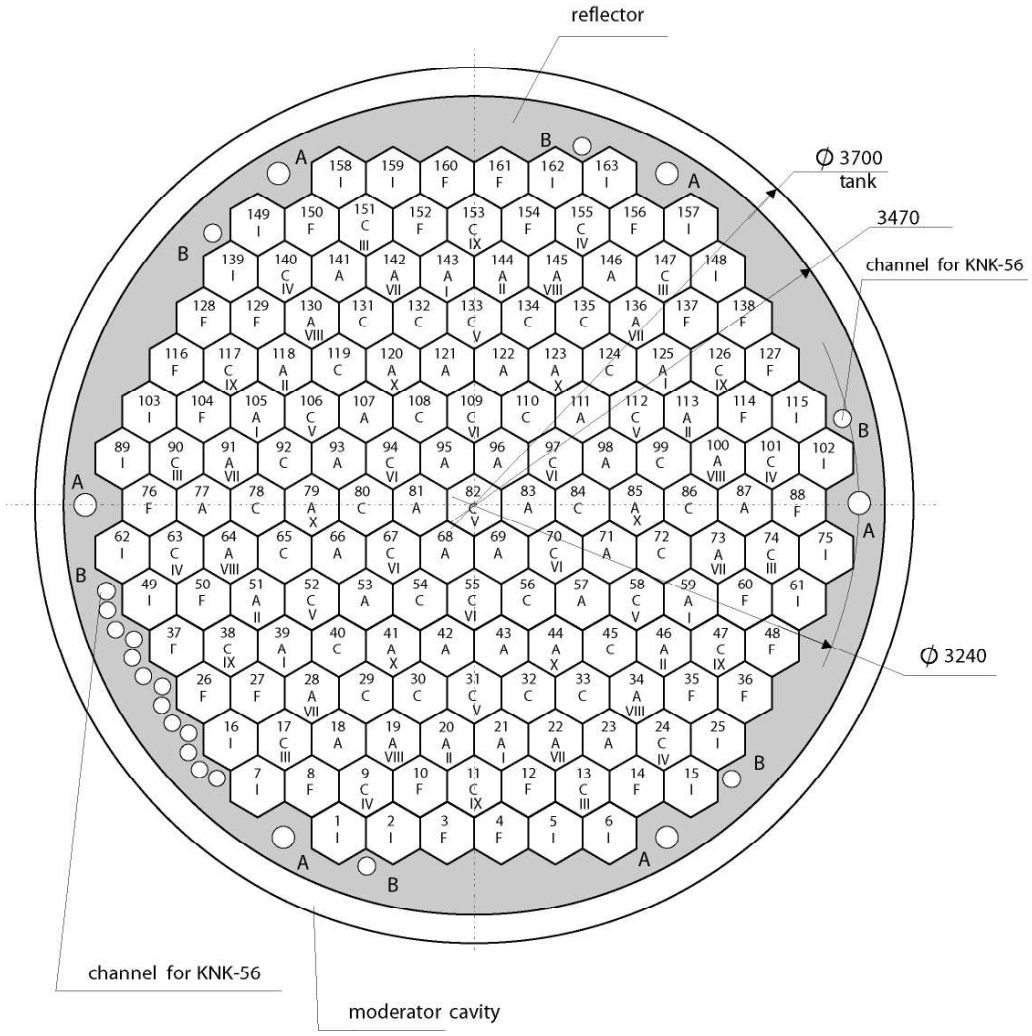

Figure 1. Radial geometry of V-1000 core (VVER-1000 mock-up). VVER-1000 first cycle loading with U-235 enrichments: A - 1.6 %, C - 3.0 %, F - 4.4%+3.6% (profiled), I - 4.4 %. Control rod group numbers denoted by Roman numerals. KNK: out-core ionization chambers.

All fuel assemblies consisted of fresh fuel with zero burnup. Particular short fuel rods were inserted into the central tubes of the fuel assemblies in order to measure the relative power in these positions. They were only 50 cm long and their middles were located at distance of 120 cm from the fuel bottom. These irradiated rods were analysed by γ-activation detectors to measure the powers in the fuel-assembly centers (center-of-node powers) at this height. Moreover, the powers of some standard fuel pins in assembly No. 85 (Fig.1) were measured the same way, after assembly dismantling. These measurements were made also at the level of 120 cm.

The measurement errors of relative power values, provided by the experimenters are for the values >0.1 up to 3% and for the values <0.1 up to 10%. Calculated core power distributions and multiplication factors (k_{eff}) should be compared with measured values for the both critical states ($k_{eff} = 1$) in this benchmark.

3. THE REACTOR DYNAMIC CODE DYN3D

The code DYN3D has been developed at Forschungszentrum Dresden-Rossendorf (FZD) [8]. It calculates the three-dimensional neutron flux distribution by solving the time-dependent diffusion equations for two energy groups and six groups of delayed-neutron precursors. The reactor core is divided into horizontal layers, thus defining hexagonal or quadratic prisms ("nodes"), depending on the fuel-assembly geometry. The thicknesses of the axial slices can be different. All neutron group constants are assumed to be spatially constant within each node. The three-dimensional diffusion equation in a hexagonal-z node is split into a one-dimensional equation of the axial direction and a two-dimensional equation of the hexagonal plane by transverse integrations. Two different methods, HEXNEM1 and HEXNEM2, were developed for the solution of the two-dimensional diffusion equation in the hexagonal plane [9,10]. Considering neighboring nodes, the side-averaged values of partial currents are coupled in case of HEXNEM1. Additionally, the corner values are used in the HEXNEM2 method, leading to higher accuracy for cores with larger assembly pitch, like the VVER-1000. For steady states, the homogeneous eigenvalue problem or the heterogeneous problem with given source is solved. An inner and outer iteration strategy is applied. The outer iteration (fission source iteration) is accelerated by Chebychev extrapolation. Concerning the time integration over neutronic time steps, an implicit difference scheme with exponential transformation is used. The exponents in each node are calculated from the previous time step or during the iteration process.

A thermal-hydraulic model of the reactor core and a fuel rod model are implemented in the module FLOCAL being a part of DYN3D. The reactor core is modeled by parallel cooling channels, which can describe one or more fuel elements. Additionally, so-called hot channels can be considered connected to core channels with given power peaking factors.

In order to identify the fuel pin with the maximum power within a selected assembly, a two-dimensional flux reconstruction of the nodal flux can be performed on the basis of the node-homogenized cross sections [11,12]. The method of successive smoothing is applied for the reconstruction of the neutron flux in chosen fuel assemblies [13,14]. The neutron flux is reconstructed by an analytical solution of the two-dimensional diffusion equation in each axial layer of the fuel assembly. The analytical solution is calculated under the following assumption: exponential behavior of neutron fluxes during the time step, the distribution of delayed neutrons is proportional to the prompt neutrons, and the axial leakage is described by the transversal buckling. A superposition of this solution with the pin powers obtained from the respective 2D zero-net-current lattice calculations can be made. The resulting pin powers can be further processed in the DYN3D thermal-hydraulic module FLOCAL for the improvement of hot-channel-factor assessment.

4. OVERVIEW OF BENCHMARK SOLUTIONS

4.1. State 2: V-1000 state without any control rods inserted

In axial (vertical) direction, the "active" core (the part covered by water) was divided into 17 layers with the total length of 266.8 cm (20.0 cm, 6×15.0 cm, 20.0 cm, 8×15.cm and 16.8 cm from the bottom to the top). The effective multiplication factor, calculated by DYN3D, was k_{eff} = 1.008794.

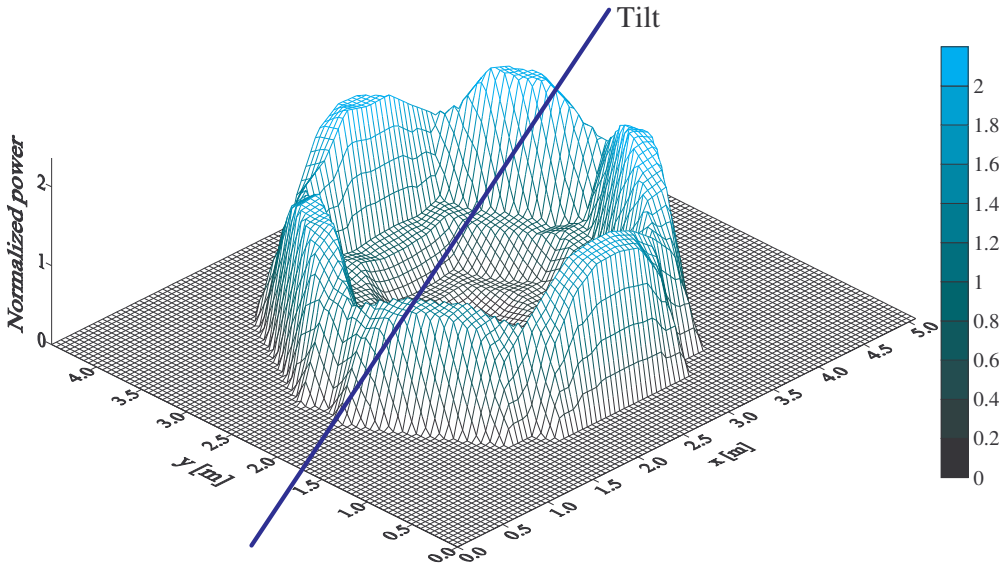

Figure 2. State 2 – measured power distribution.

The benchmark calculation has been performed by using the code DYN3D Version 3.2 [15] with HEXNEM2 method [16]. Different powers, all of them calculated for the height position of the short-fuel-rod middles, were compared to the measurements:

(1) DYN3D node-averaged powers,
(2) centre-of-node powers, obtained by the intra-nodal neutron flux reconstruction method implemented in DYN3D [15,11],
(3) central-pin powers produced by weighting (multiplying) the centre-of-node powers (reconstruction results) with the (central) pin powers from the lattice-code (HELIOS) zero-net-current fuel-assembly calculations [4].

Both the calculated and experimental values are normalized to their average. The experimental results are in Figure 2, showing a heavy power variation and a radial power tilt that was caused by asymmetries in the radial reflector. In the following, the deviation of calculation versus measurement is expressed as:

Deviation = ((calculation-measurement)/calculation) × 100 [%].

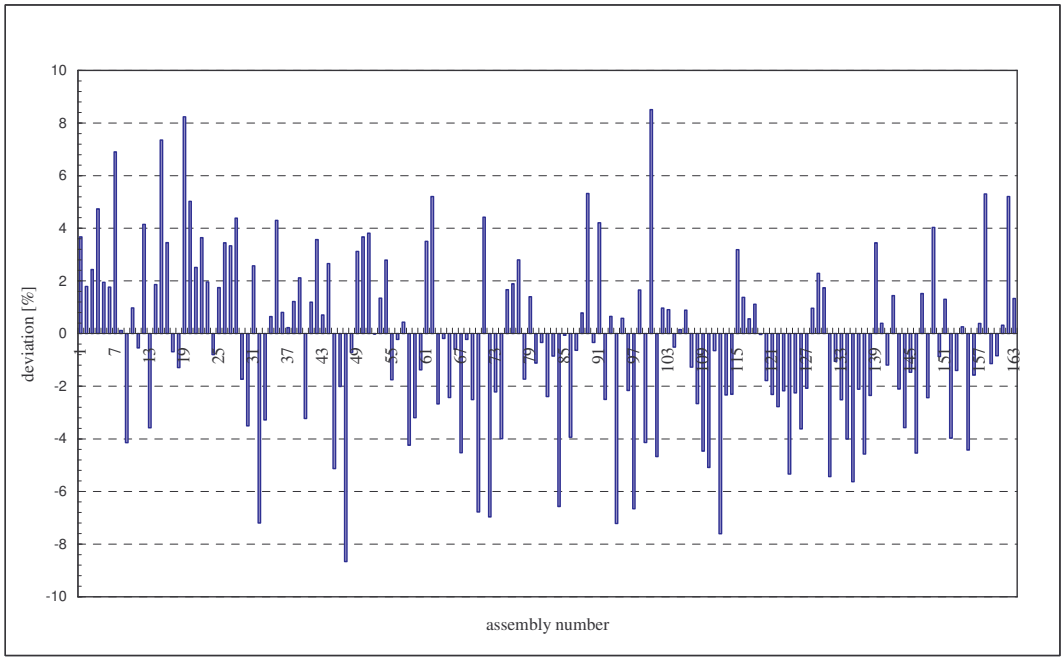

Figure 3. State 2 – deviation of calculated central-pin power (method (3)) from measurement.

The maximum deviations are 14.1 % (FA-100 - see Figure 1) for the node-averaged powers (1), -10.4 % (FA-47) for the centre-of-node powers (2), and -8.7 % (FA-47) for the central-pin powers (3), which represent - as to be expected - the best approximation. Figure 3 depicts this latter case.

Figure 4 shows the positions of the FA-85 fuel pins used for power measurement after dismantling. Measurements were performed for only 31 of the 312 fuel pins, determining the relative pin power distribution within this special fuel assembly (No. 85, see Figure 1) from the γ-activities of 31 dismantled fuel rods. The calculated pin powers, produced by weighting the centre-of-pin powers distribution (from DYN3D flux reconstruction) with the pin powers from the lattice code (method (3)), are compared to these 31 measured values. The differences are shown in Figure 5, the maximum deviation is 3.7 % (fuel pin No. 258). As the relative powers here are normalized to the average of only this one fuel assembly, the deviations are evidently smaller than the deviations of assembly-centre powers from the whole-core average (Fig. 3), where different enrichments of the FA and the effect of the core edge influence results.

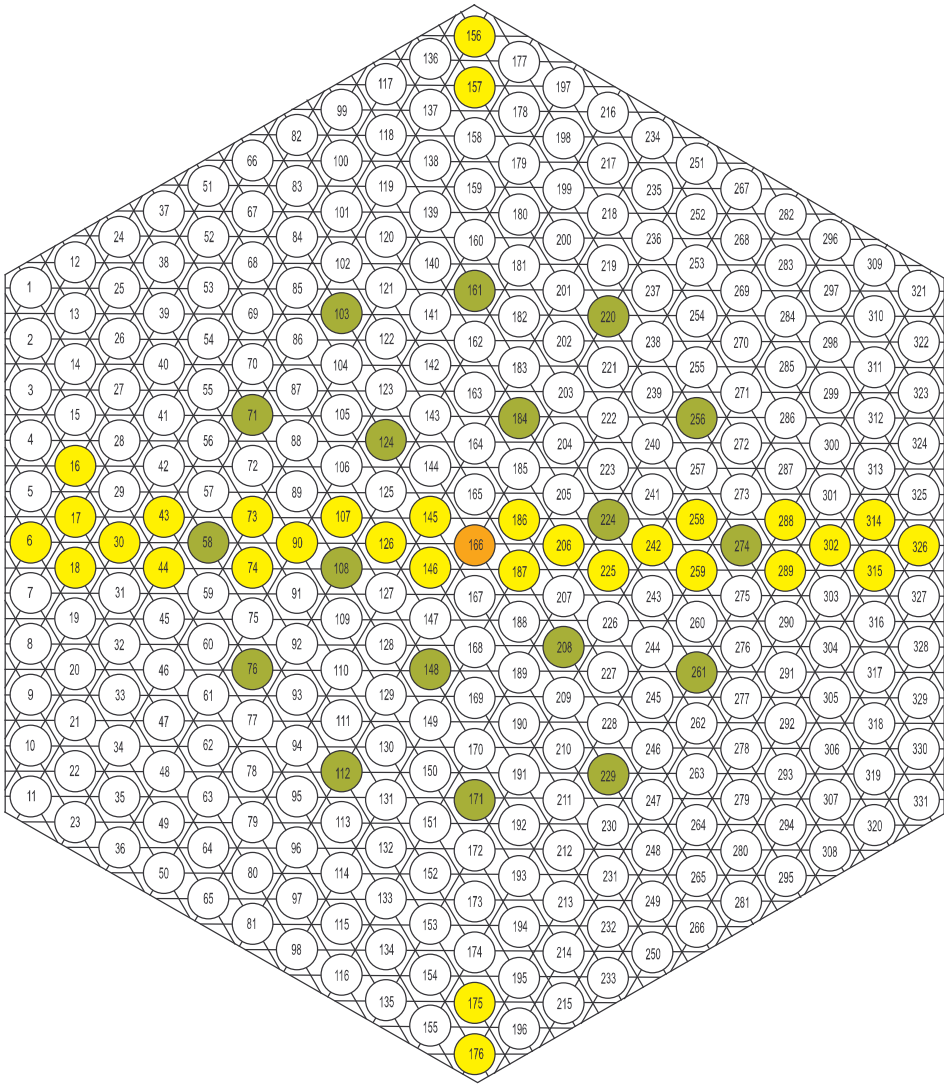

Figure 4. Positions of measured pin powers (yellow) in fuel assembly No. 85. Green: positions of control rods (inserted in state 1, driven out in state 2). Orange (166): central tube. Pin No. 16 measured only in state 2.

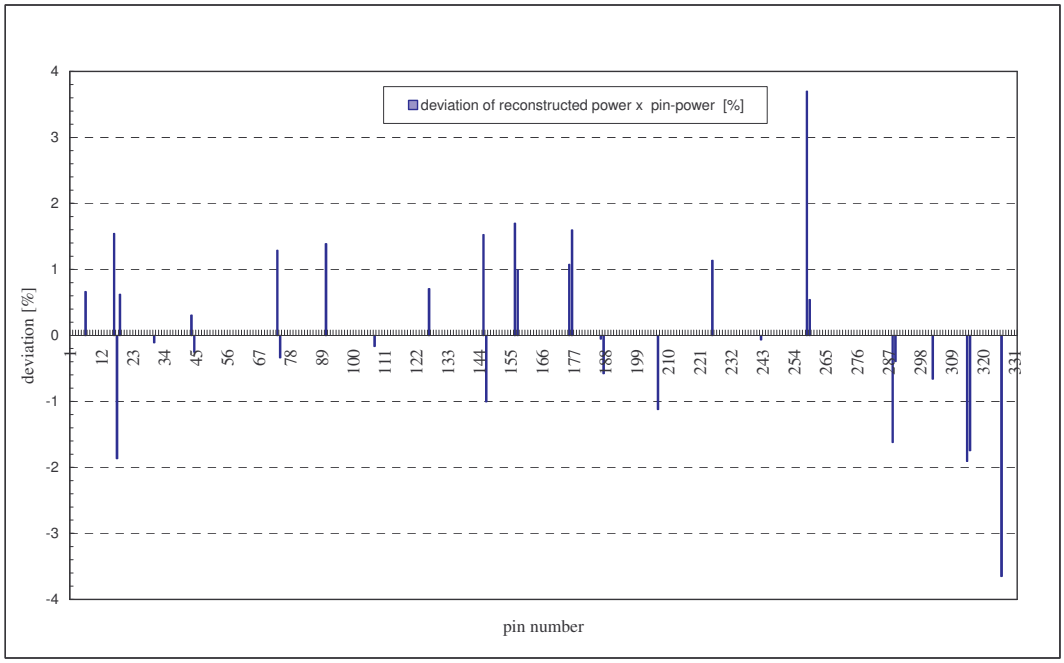

Figure 5. State2 - deviation of calculated pin-power (method (3)) from measurement in fuel assembly No. 85.

4.2. State 1: V-1000 state with all control rod group No. 10 fully inserted

In axial direction, the core was divided into 16 layers with the total length of 253.5 cm (20.0 cm, 6×15.0 cm, 20.0 cm, 7×15.cm and 18.5 cm from the bottom to the top). The control rods of group No. 10 ("X") are fully inserted in fuel assemblies No. 41, 44, 79, 85, 120 and 123 (Fig. 1). The calculated effective multiplication factor was k_{eff} = 1.011719.

Measurements were performed only in 81 of the 163 fuel assemblies. As in the previous state, three kinds of calculation results are compared to the measured relative powers. For the cases (1), (2), and (3), the maximum deviations are 33.7 % (FA-120), 21.8 % (FA-120), and 9.3 % (FA-62), respectively. Figure 6 depicts the most accurate results (3). The maximum deviations are in the control-rodded assemblies, where the measuring short fuel rod, placed in the assembly centre, had been "shielded" by surrounding control rods (cf. Fig. 4).

For these rodded assemblies, it is evident that the simple node-averaged DYN3D power (1) must be higher than the power measured in the node centre. Using all the available information from both core diffusion calculation (DYN3D flux reconstruction) and assembly lattice calculations (HELIOS), i.e. applying the method (3), is particularly effective for these rodded nodes, reducing their error to the error level of the un-rodded assemblies (< 10 %). Figure 7 has the results of method (3) for the control-rodded assembly No. 85. The maximum deviation is -8.8 % (fuel pin No. 288).

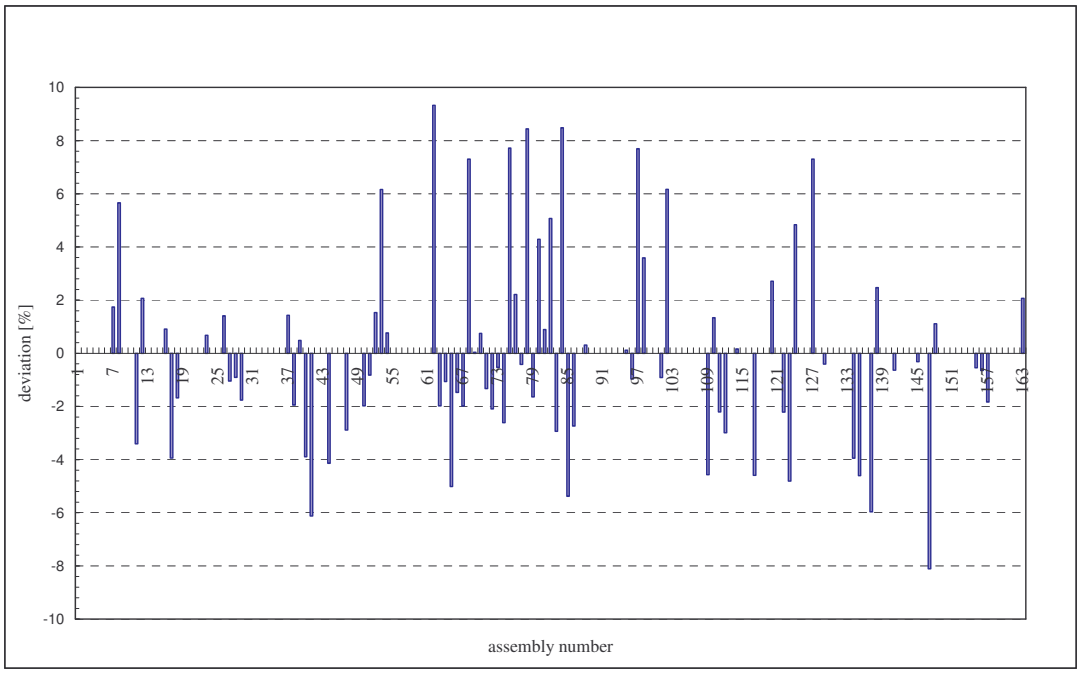

Figure 6. State 1 - deviation of calculated central-pin power (method (3)) from measurement.

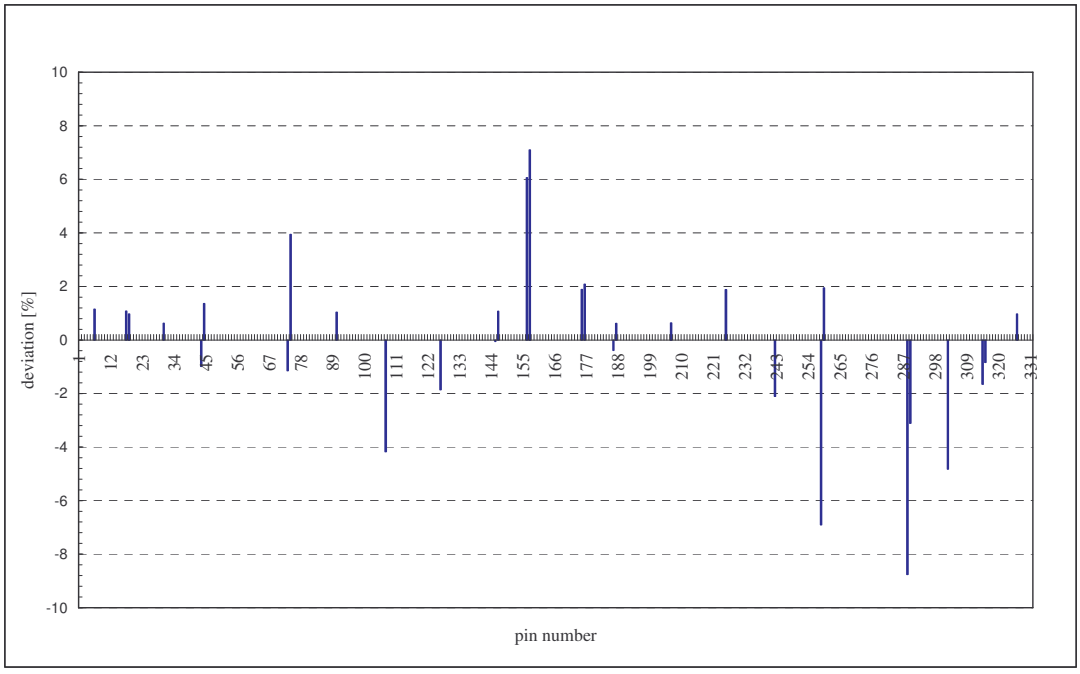

Figure 7. State1 - deviation of calculated pin-power (method (3)) from measurement in fuel assembly No. 85.

4.3. Multiplication factor discussion

Both calculations clearly overestimate the criticality. The deviation of k_{eff} from unity can be partly caused due to measurements errors of the boric acid concentration, estimated by the experimenters [3,4] to reach ±0.3 g boric acid per kg water, which corresponds to an uncertainty of about ±600 pcm in the k_{eff}. The overestimation is higher by 290 pcm in the case with control rod group No. 10 inserted, compared to the un-rodded state. Unfortunately, the two steady states had different boric-acid concentrations (cf. Table 1), both values being independently affected by the high measurement error. Other benchmark results [3] have shown that the two-group nodal approximations, applied in the reactor dynamic codes cause an overestimation of about 200 pcm in the k_{eff}. This effect is confirmed by the comparison of two-group nodal calculation (BIPR8 code) and four-group heterogeneous fine-mesh results (PERMAK code), both codes using data based on the same cell code (TVS-M).

5. CONCLUSIONS

A challengingly heavy power variation (including a radial power tilt), measured in the cold V-1000 core, which is quite unusual for PWR cores at nominal operation conditions, was successfully modeled by the code DYN3D. The powers calculated for the central pins give better agreement with measurements than the node-averaged values, particularly for assemblies with control rods inserted. The pin power calculation for assembly 85 is in good agreement with measured pin power distributions. The effective multiplication factor was overestimated in both states by 0.9 % and 1.2 %. The configuration with inserted absorber rods represents a greater challenge for the pin power recovery, compared to the un-rodded case, because of increased heterogeneity and therefore higher inner-assembly flux gradients.

The V-1000 critical facility is a unique device. More measurements under modified core conditions would be very useful for an extended reactor dynamic codes validation. Unfortunately, the facility is not in operation at the present time.

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