V1000CT-1 BENCHMARK ANALYSES WITH THE DYN3D/RELAP5 AND DYN3D/ATHLET COUPLED CODE SYSTEMS

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ABSTRACT

Plant-measured data provided within the specification of the OECD/NEA VVER-1000 coolant transient benchmark (V1000CT) were used to validate the DYN3D/RELAP5 and DYN3D/ATHLET coupled code systems. Phase 1 of the benchmark (V1000CT-1) refers to the MCP (main coolant pump) switching on experiment conducted in the frame of the plant-commissioning activities at the Kozloduy NPP Unit 6 in Bulgaria. The experiment was started at the beginning of cycle (BOC) with average core expose of 30.7 effective full power days (EFPD), when the reactor power was at 27.5% of the nominal level and 3 out of 4 MCPs were operating. The transient is characterized by a rapid increase in the primary coolant flow through the core and, as a consequence, a decrease of the space-dependent core inlet temperature. Control rods were not changing their positions during the transient. Both DYN3D/RELAP5 and DYN3D/ATHLET analyses were based on the same reactor model, including identical MCP characteristics, boundary conditions, benchmark-specified nuclear data library and nearly identical nodalization schemes. In addition to validation of the coupled code systems against measured data, a code-to-code comparison between simulation results has been performed to evaluate relevant thermohydraulic models of the system codes RELAP5 and ATHLET.

KEYWORDS

Coupled code systems, 3D neutron kinetics, code validation, code-to-code comparison, VVER-1000 model, coolant transient benchmark, main coolant pump.

1. INTRODUCTION

Due to the need of performing consistent analyses of the whole reactor systems and the rapid progress in computer technology, the advanced thermohydraulic codes are coupled with the codes of 3D neutron kinetics. The resulting code systems acquire the capability of modeling both operational transients and accident scenarios, taking into account the evolution of power distribution in the core depending on the interaction between the core and the rest of the plant systems.

In the last years, a series of integration techniques has been developed to couple the best-estimate thermohydraulic codes ATHLET (Teschendorff *et al.*, 1996) and RELAP5 (Ramsom, 1994) with the 3D core transient code DYN3D (Grundmann *et al.*, 1998). Three different ways of coupling based on so-called “external”, “internal” and “parallel” coupling options have been realized in FZR for the integration of the ATHLET and DYN3D codes into the DYN3D/ATHLET code system (Grundmann *et al.*, 1995). The coupling of RELAP5 and DYN3D has been performed in cooperation between FZR and the Russian Institute of Physics and Power Engineering (IPPE) using the internal integration technique (Kozmenkov *et al*, 2001).

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Using the internal coupling option, the core thermohydraulics is calculated by the system code (ATHLET or RELAP5), and only the neutron kinetics part of DYN3D is employed in this case. The cross-sections are updated using the feedback from the system code thermohydraulics.

The external coupling option means that both neutron kinetics and thermal hydraulics of the core are simulated with the code of 3-D neutron kinetics, and the system code calculates thermohydraulic conditions outside the core.

With the parallel coupling option, the core thermohydraulics is calculated by the coupled codes within the same run of the code system. The core inlet and outlet boundary conditions are calculated by the system code and passed to DYN3D. Based on these data, DYN3D recalculates the core thermohydraulics and uses these results to update the core power distribution.

DYN3D is a three-dimensional two-group nodal neutron kinetic code developed in FZR. The code is applicable to both hexagonal and rectangular fuel assembly geometries and incorporates a thermohydraulic model of the core, including a thermo-mechanical fuel rod model. Both ATHLET and RELAP5 codes include basic modules for hydrodynamics, heat transfer, heat conduction and balance of plant simulation.

Unlike the validation of stand-alone neutron kinetics and thermohydraulic codes, which can be carried out against measured data obtained from critical (zero-power) and thermohydraulic facilities, the validation of the coupled code systems is entirely based on the direct measurements conducted in nuclear power plants. Previous FZR activities on the VVER-related validation of the DYN3D/ATHLET and DYN3D/RELAP5 code systems include participation in the EU Phare project SRR1/95 (Weiß and Mittag, 2000) and EU FP5 project VALCO (Hämäläinen *et al.*, 2003). Within the framework of these two projects the coupled neutron kinetic / thermohydraulic codes, including DYN3D/ATHLET code system, have been validated against transients measured in Loviisa-1 VVER-440, Balakovo-4 VVER-1000 and Kozloduy-6 VVER-1000 units. The real plant transients initiated by the trip of the steam generator (SG) feed water pump, the trip of the main coolant pump and by the load drop of one turbo-generator have been modelled. As a result, the employed computational models of reactor plants have been improved and the ability of analyzers to interpret plant data has been markedly increased.

In 2002 a new benchmark labelled as V1000CT (the VVER-1000 coolant transient benchmark) was proposed to continue and extend the activities on validation of the coupled neutron kinetic / thermohydraulic codes. This paper provides the results of the V1000CT 'basic scenario' simulations with the coupled code systems DYN3D/ATHLET and DYN3D/RELAP5.

2. V1000CT BENCHMARK OVERVIEW

The coupled 3D neutron kinetic / thermohydraulic benchmark V1000CT (Ivanov *et al.,* 2003) has been specified as the result of co-operative efforts between the Nuclear Energy Agency (NEA) of OECD, the United States Department of Energy (US DOE), and the Commissariat a l'Energie Atomique (CEA, France). The benchmark consists of two major phases. Phase 1 (V1000CT-1) is related to the modeling of a main coolant pump (MCP) switching on transient, and phase 2 (V1000CT-2) considers modeling of coolant mixing experiments and a main steam line break (MSLB) analysis. Three exercises are specified within the Phase 1 of the V1000CT benchmark: Exercise 1 – point kinetics plant simulations, Exercise 2 – coupled 3-D neutronics/core T-H response evaluation, and Exercise 3 – best-estimate coupled code plant transient modeling. Combining elements of the first two exercises, Exercise 3 includes (1) the 'basic' transient scenario defined to assess the coupled code systems against the original experimental data from the 6-th unit of Kozloduy NPP (Bulgaria) and (2) the "extreme" transient scenario aimed at the code-to-code comparison. Only the results of the Exercise 3 basic scenario simulation are analyzed in this paper.

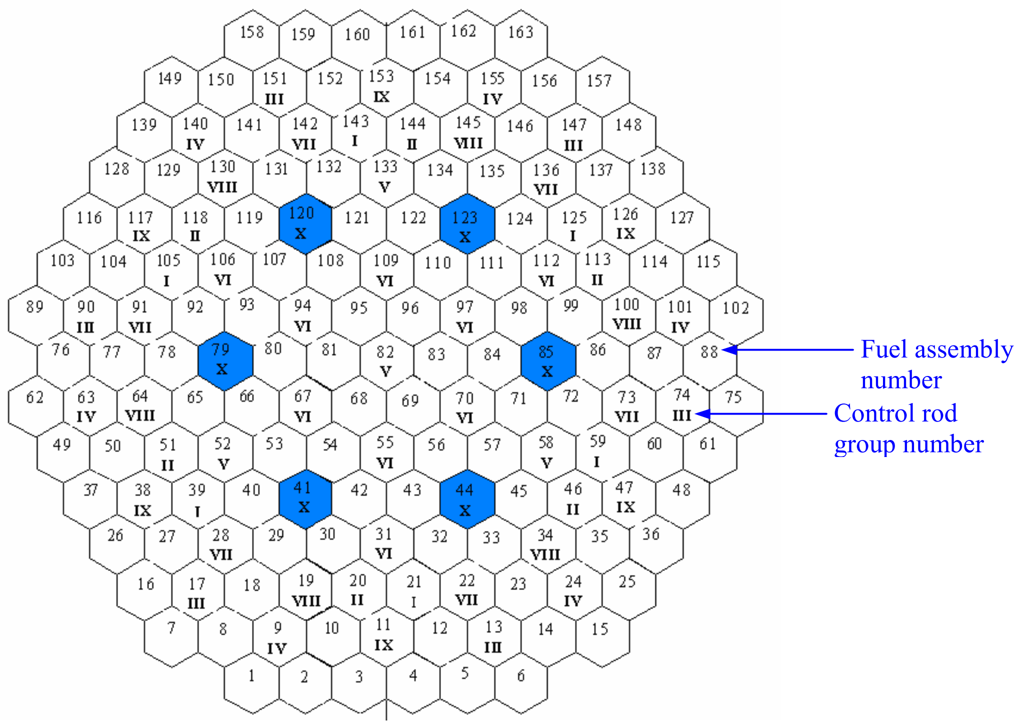
The reference basic scenario describes one of the start-up experiments conducted at Kozloduy-6. The experiment was started at the beginning of cycle (BOC) with average core expose of 30.7

effective full power days (EFPD). The transient was initiated by the MCP switching on in the 3rd reactor loop, when the reactor power was at 27.5% of the nominal level (824 MW) with 3 of 4 MCPs in operation. A reverse mass flow through the 3rd reactor loop was observed at the beginning of the transient. All control rod groups were out of the core except the group no. 10 (see Figure 1), which was inserted into the core at about 64% of the core height. All control rod banks remained at their initial positions throughout the transient. The secondary side pressure in the main steam header (MSH) and the feedwater temperature at the inlets of steam generators are constant during the transient, and their measured values are 6.0±0.05 MPa and 437.0 K, respectively.

The following measured plant data are available for validation of the code systems:

1. Steady-state conditions - core power, primary side pressure (above the core), cold and hot leg temperatures, core flow rate, loop flow rates, pressurizer water level, water levels in steam generators, and secondary side pressure,
2. Time histories measured for the first 130 seconds of the transient – primary side pressure, cold and hot leg temperatures, MCP pressure drops, pressurizer water level, and water levels in steam generators.

A library of macroscopic cross-sections generated with the HELIOS code and the relative fractions of delay neutrons are given within the V1000CT-1 benchmark specification. To minimize the size of the cross-section tables, a complete set of diffusion coefficients and macroscopic cross-sections is defined as a function of the moderator density and fuel temperature, only. This set of neutronic data is calculated for the boron acid concentration of 5.95 g/kgH_2O and the initial state values of xenon / samarium concentrations and fuel burnup. The assembly discontinuity factors (ADFs) are taken into consideration implicitly.



Fuel assembly number

Control rod group number

Figure 1: Arrangement of the 10th control rod bank

3. REACTOR MODEL DESCRIPTION

The computer models of VVER-1000 used in the simulations of the V1000CT-1 basic scenario represent the reactor plant models developed within the EU Phare SRR1/95 and VALCO projects and modified to meet the benchmark specifications. The implemented modifications mainly concern the core model and the secondary side boundary conditions. The *externally* coupled code system

DYN3D/ATHLET(E) and the *internally* coupled code system **DYN3D/RELAP5(I)** were used in the benchmark calculations.

A non-symmetric (360-degree) reactor core containing 163 fuel assemblies (FA) is modelled (see Figure 1). The axial core nodalization is identical for the both code systems, comprising 10 layers of equal height in the heated part of the core and 2 (lower and upper) axial reflector regions.

In simulations with the code system DYN3D/ATHLET(E) the core thermohydraulics is modelled by the DYN3D code, and 163 FAs correspond to 163 fluid channels (FA by FA model of the core with the equal number of neutronic and thermohydraulic nodes).

In the DYN3D/RELAP5(I) core model 163 fuel assemblies are radially distributed between 18 coarse fluid channels modelled by the RELAP5 code as shown in Figure 2 (6, 7, 8, 9 or 12 FAs per a fluid channel).

The results of the SRR1/95 and VALCO projects revealed a strong sensitivity of the calculated fuel temperature to the modeling of the gas gap between fuel pellets and rod cladding. A dynamic treatment of the gap width was recommended. According to this conclusion, the dynamic gap conductance options were activated in the fuel rod models of DYN3D and RELAP5. The rod models of both codes define the Doppler temperatures as volume-averaged nodal fuel temperatures. This definition of the Doppler temperatures does not comply with the benchmark specifications, where it is defined as a linear superposition of the fuel centerline and the fuel surface temperatures.

The computer model of the Kozloduy-6 plant incorporates 4 separate primary system loops and employs a dynamic model of the main coolant pump. The MCP model is based on the empirical set of homologous curves given in the V1000CT benchmark specification. A steam pressurizer is connected to the loop #4. The 1st group of the pressurizer heaters has the power of 270 kW, and this heater group is the only one operating during the transient. Primary system heat losses are taken into consideration by the plant model.

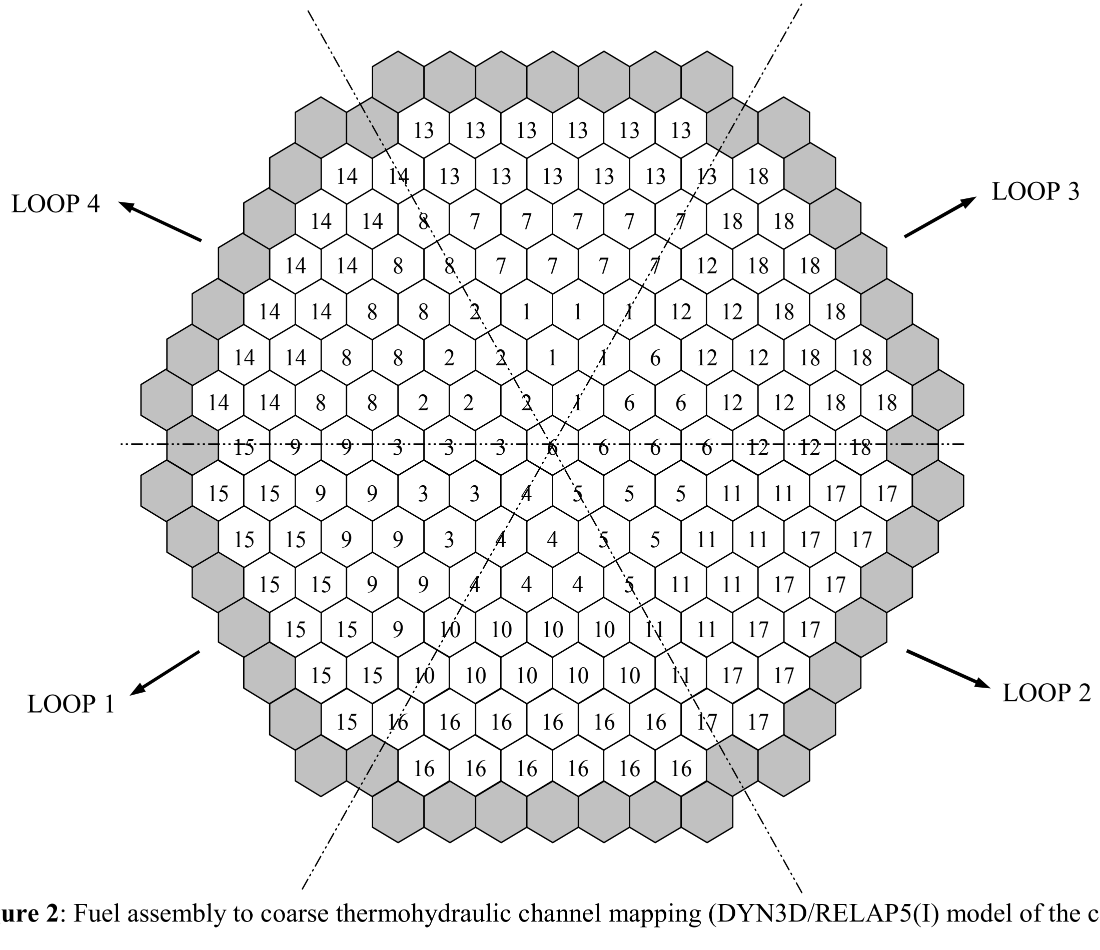


Figure 2: Fuel assembly to coarse thermohydraulic channel mapping (DYN3D/RELAP5(I) model of the core)

To obtain a more realistic prediction of the loop temperatures, the upper plenum region at the elevation of the hot leg nozzles has been symmetrically divided into two volumes of equal size without connection between them (nodes A and B on Figure 3). The hot leg-nozzle volumes A and B do not exchange coolant directly, but through the adjacent node C only. The intensity of the coolant exchange is controlled through the values of the flow loss coefficients in junctions 1 and 2 shown on Figure 3. This simplified approach to the modeling of coolant mixing in the upper plenum is based on the fact, that the azimuthal angle between hot leg nozzles of the loops #1 and #4, as well as between the loops #2 and #3, is 55 degrees. Hence, there are two symmetric pairs of the neighboring outlet nozzles in the V-320 design of VVER-1000 (see Figure 2). The described nodalization of the upper plenum is used in both DYN3D/RELAP5(I) and DYN3D/ATHLET(E) plant models.

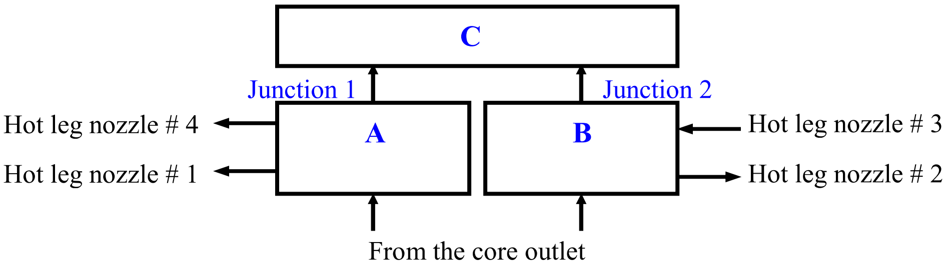


Figure 3: Upper plenum nodalization at the elevation of hot leg nozzles (DYN3D/RELAP5(I) and DYN3D/ATHLET(E) models)

Figure 4 represents the radial nodalization scheme for the modeling of coolant mixing in the downcomer and the lower plenum regions using the RELAP5 code. The scheme includes one 240-degree and two 60-degree radial sections connected by the crossflow junctions (double arrows crossing the boundaries between sections A, B and C on Figure 4).

The assumption of ideal coolant mixing is made for the ATHLET nodalization of the downcomer and lower plenum. It means that these regions are modelled using 360-degree radial sectors (single fluid channel) in the ATHLET simulations.

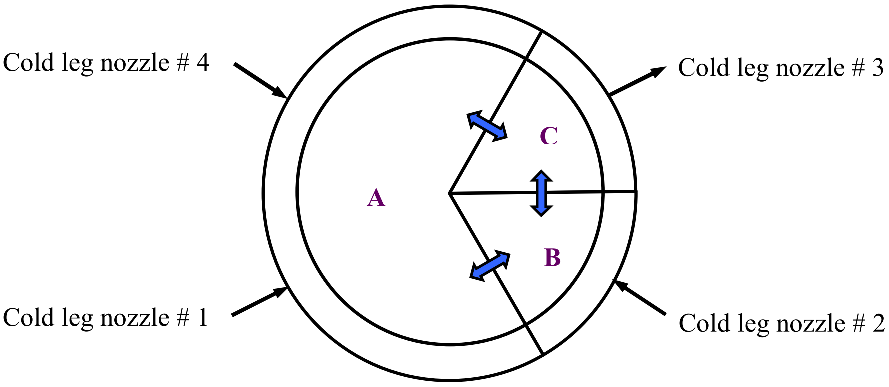


Figure 4: Radial nodalization of downcomer and lower plenum (DYN3D/RELAP5(I) model)

The secondary system model incorporates 4 steam generators with steam separators, 4 main steam lines (MSL) up to the turbine inlets and the main steam header (MSH). The measured values of the feedwater temperature, feedwater mass flow and the MSH pressure are used as the boundary conditions in the benchmark simulations.

Finally, there are two differences between the V-320 plant models of the DYN3D/ATHLET(E) and DYN3D/RELAP5(I) code systems related to the radial nodalizations of (1) the core coolant channels and (2) the downcomer and lower plenum regions. The DYN3D/RELAP5(I) model of the plant utilizes a coarser radial nodalization of the core fluid channels and a more detailed nodalization of the downcomer and lower plenum compared with the plant model of DYN3D/ATHLET(E).

4. INITIAL STEADY-STATE SIMULATIONS

Prior to the transient calculations, the initial steady-state was simulated with the DYN3D/ATHLET(E) and DYN3D/RELAP5(I) code systems. First results of the initial state simulations indicated a deviation between the values of effective multiplication factor (Keff) calculated by two codes. A lower value of Keff was predicted by the DYN3D/ATHLET(E) code compared with the DYN3D/RELAP5(I)-calculated value. A comprehensive analysis of the obtained results proved that the dominant reason for the discrepancy in Keff is a deviation in the gas gap width predicted by the fuel rod models of the DYN3D and RELAP5 codes. The RELAP5 estimation of the gas gap width is appeared to be about 10% less than that predicted by the DYN3D code, and as a result, the average temperature of fuel in the core is also lower in this case. Different radial nodalizations of the core fluid channels described in the previous section as well as discrepancies in the calculated mass flow rates through the core and in the core inlet coolant temperatures may also contribute to the Keff deviation.

In order to decrease the difference between the initial state Keff (see the first row of Table 1), the effective heat conductivity of the gas gap in the fuel rod model of RELAP5 has been adjusted (reduced) via partial replacement of helium in the gap with having a less heat conductivity xenon, by decreasing the helium mole fraction in the gap. As the result, the benchmark-specified thermal-physical properties of the fuel rod gap are not met.

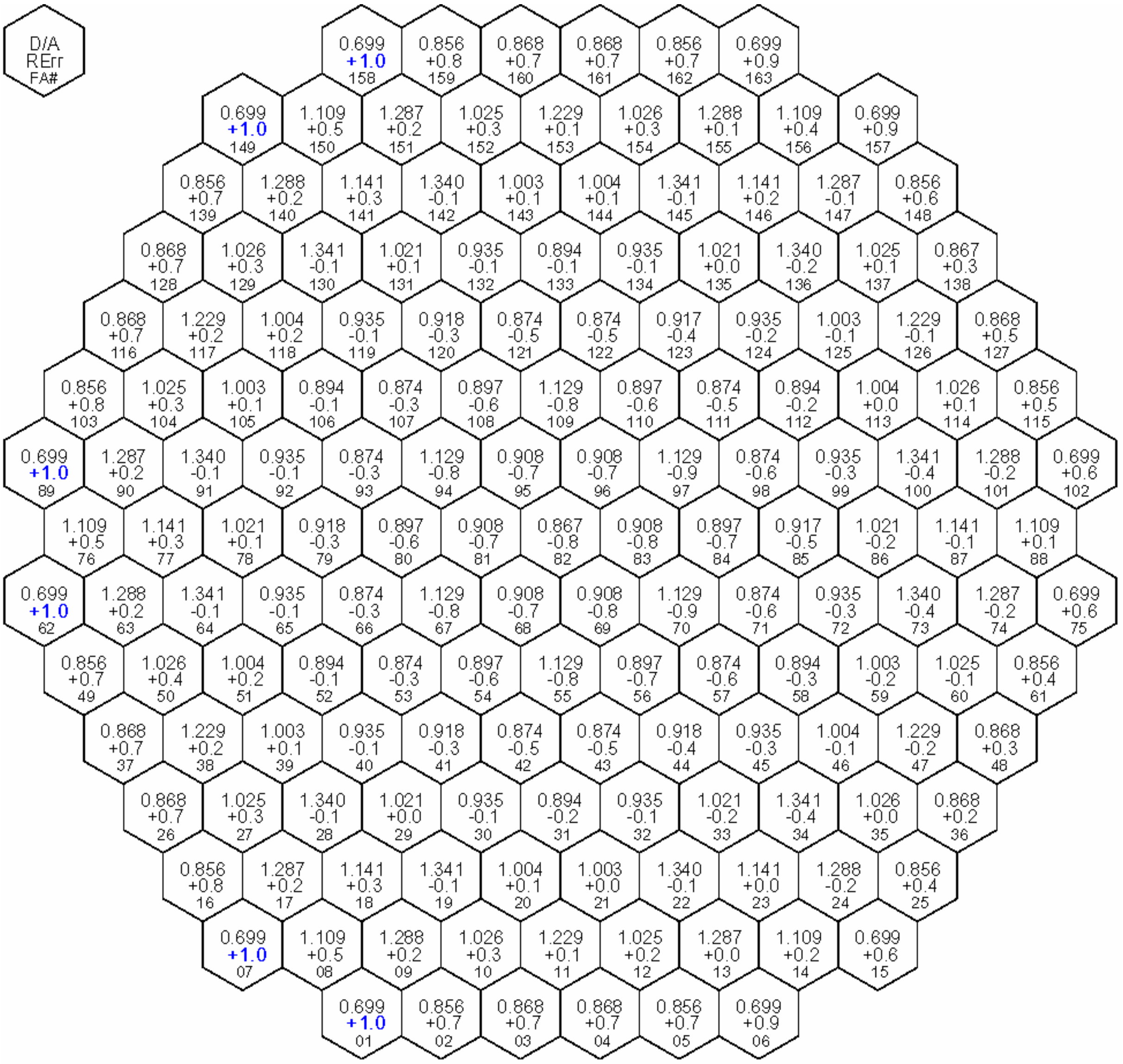
The results of the performed steady-state calculations are compared with the measured initial state parameters in Table 1. The leg temperatures predicted with the ATLET code are below the RELAP5-calculated values, with the highest difference of 1.7 K occurring in the hot leg #2. The following two factors were found to cause the observed deviation. Firstly, a higher heat transfer efficiency of the ATHLET steam generator model leads to a lower average level of the ATHLET-predicted primary coolant temperature, which is about 0.7 K less then in the RELAP5 calculation. Secondly, the codes predict different distributions of the primary coolant flow in the upper plenum region. In the node B of the upper plenum model (Figure 3) the reactor coolant coming from the core outlet is mixed with a less heated coolant bypassed through the loop # 3. The codes give close values of the reverse mass flow rate and temperature in the loop #3 (Table 1), but diverge in the estimations of the core outlet flow distribution and coolant exchange between nodes A and B of the upper plenum model. The ATHLET-predicted part of the core outlet flow entering volume B is less then that of RELAP5. It leads to an underestimation of the ATHLET-calculated coolant temperature in node B and, as a result, in the connected hot leg #2. The second factor is significant for the initial phase of the simulated transient only, when the upper plenum flow is non-symmetric.

Parameter	Measured data	Accuracy	DYN3D/ATHLET(E)	DYN3D/RELAP5(I)
Keff (first estimation/adjusted)	-	-	0.999200/0.999200	1.000618/0.999108
Core power, MW	824.00	±60 MW	823.85	824.00
Primary system pressure, MPa	15.600	±0.3 MPa	15.606	15.600
Cold leg 1 temperature, K	555.55	±2.0 K	554.83	555.38
Cold leg 2 temperature, K	554.55	±2.0 K	553.50	554.25
Cold leg 3 temperature, K	554.35	±2.0 K	554.42	554.69
Cold leg 4 temperature, K	555.25	±2.0 K	554.93	555.46
Hot leg 1 temperature, K	567.05	±2.0 K	566.06	566.26
Hot leg 2 temperature, K	562.85	±2.0 K	560.96	562.70
Hot leg 3 temperature, K	550.75	±2.0 K	550.53	550.54
Hot leg 4 temperature, K	566.15	±2.0 K	566.06	566.26
Core flow rate, kg/s	13611	±800 kg/s	13631	13538
Loop 1 flow rate, kg/s	5031	±200 kg/s	5037	5033
Loop 2 flow rate, kg/s	5069	±200 kg/s	5030	4932
Loop 3 flow rate, kg/s	-1544	±200 kg/s	-1569	-1543
Loop 4 flow rate, kg/s	5075	±200 kg/s	5133	5114
Secondary side pressure, MPa	5.937	±0.2 MPa	6.099	6.100

Table 1: Comparison of the steady-state conditions

The observed discrepancies between calculated and experimental data do not exceed the uncertainty measurement ranges included into Table 1.

Figure 5 represents the comparison between calculated normalized radial power distributions in the core. The maximum relative deviation in the predicted FA powers is 1%. This deviation can be explained by the differences in the DYN3D/RELAP5(I) and DYN3D/ATHLET(E) radial nodalizations of the core fluid channels and in modeling of the lower plenum coolant mixing. Both coupled code systems identifies the fuel assembly # 100 as the most heated FA in the core. Code-to-code comparisons between axial distributions of the heat fluxes and fuel temperatures related to the assembly # 100 are shown in Figures 6 to 8. Calculated axial distributions of the total core power are compared in Figure 9. A close agreement between two calculations is obtained.



D/A – results of DYN3D/ATHLET(E) calculation

RErr – relative deviation of DYN3D/ATHLET(E) results from DYN3D/RELAP5(I) results (%)

FA# - FA reference number

Figure 5: Code-to-code comparison between radial distributions of normalized FA powers (initial state)

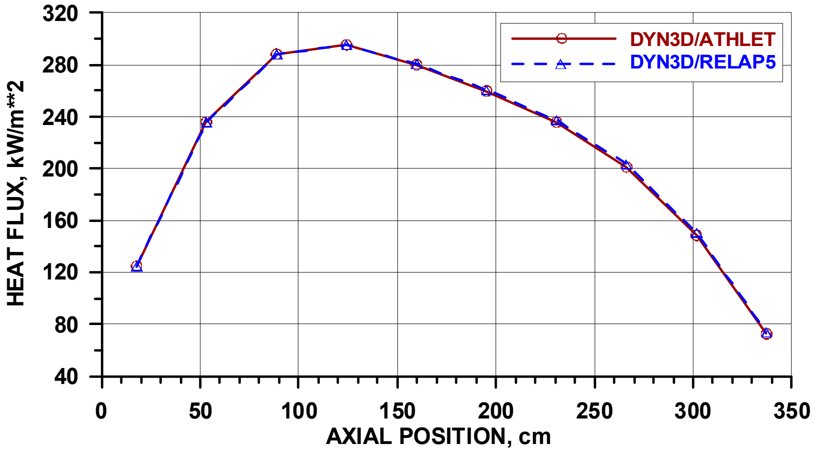


Figure 6: Code-to-code comparison between axial distributions of heat fluxes (FA # 100, initial state)

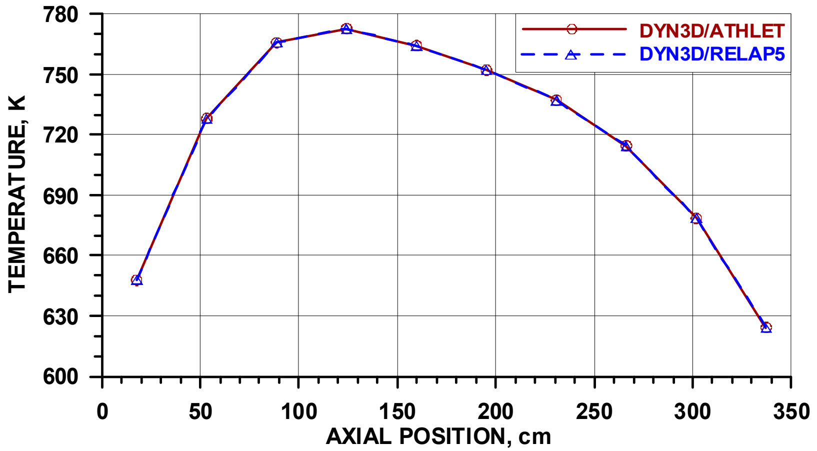


Figure 7: Code-to-code comparison between axial distributions of average fuel temperature (FA # 100, initial state)

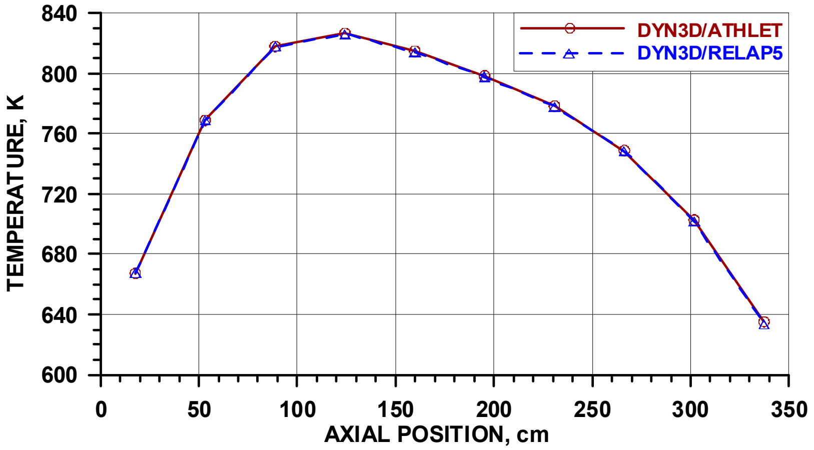


Figure 8: Code-to-code comparison between axial distributions of maximum fuel temperature (FA # 100, initial state)

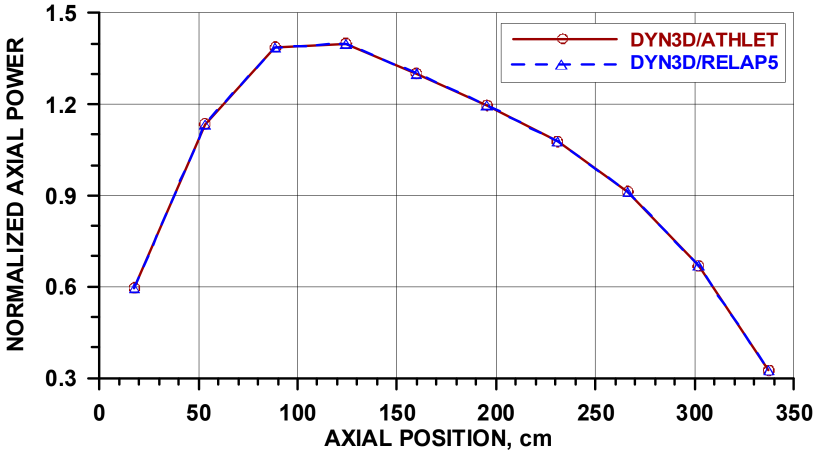


Figure 9: Code-to-code comparison between normalized total power distributions (initial state)

5. TRANSIENT SIMULATIONS

After switching on the MCP in the 3rd reactor loop, the mass flow rate through the core starts to increase from the initial steady-state value of 824 MW. The MCP #3 rotor speed as a function of time is given within the V1000CT-1 benchmark specification and reproduced in Table 2.

Time, s	Pump velocity, rad/s
0.0	0.0000
0.1	0.0000
0.5	9.4732
1.0	19.9464
1.5	31.4196
2.0	41.8928
4.0	61.3660
6.0	73.8392
8.0	83.3124
10.0	90.7856
11.0	94.3567
14.0	102.3032
15.0	104.1964

Table 2: MCP #3 rotor speed boundary conditions

A rapid increase in coolant flow through the core leads to decrease of the core inlet temperature and improvement in the core cooling. Figure 10 shows distribution of the core inlet temperature between sections A, B and C of the RELAP5 lower plenum model represented on Figure 4. The direction of coolant flow in the 3rd loop is changed from reverse to forward about 4 seconds after transient initiation, and as a result, the difference in coolant temperature between the lower plenum sections reaches 2 K at $t \approx 14$ s. The RELAP5 model of coolant mixing in the lower plenum predicts practically uniform distribution of the core inlet temperature after $t = 40$ s (nearly ideal mixing).

The core power behavior is determined by the positive effect of increasing moderator density and the negative fuel temperature (Doppler) feedback, which is sensitive to the effective heat conductivity of the gas gap between fuel rod pellets and cladding. Code-to-code comparisons between the predictions of the total core power and the total reactivity are shown on Figures 11 and 12 (the measured data are not available). The agreement between the two calculations is very good due to close values of the core thermohydraulic parameters in the compared plant models, including the effective heat conductivity in the gas gap, with which the close values of Keff were obtained in the initial steady-state calculations. During the transient, the changes in the fuel and cladding temperatures are relatively small; therefore, the related change in the gap width is negligible. Figures 11 and 12 indicate that the differences in the employed models of lower plenum mixing do not result in any noticeable discrepancy between the obtained time histories of the total core power and reactivity.

A reasonably good agreement of calculated and experimental data is obtained with respect to the primary pressure above the core and the hot leg coolant temperatures, compared on Figures 13 and 14. The primary pressure time histories calculated with the DYN3D/ATHLET(E) and DYN3D/RELAP5(I) code systems are, respectively, close to the lower and upper bounds of the measured data. The deviation between presented results is much less then the measurement accuracy of 0.3 MPa.

During the transient, the primary pressure depends on the balance of thermal power in the primary system. Close predictions are given by the both code systems with respect to the core-generated power and the thermal power transferred to the coolant within the core throughout the transient. However, the predictions of the primary system cooling through the SGs are different in the initial phase of the transient. The maximum discrepancy in the SG power, which exceeds 3%, occurs at about 12th second of the transient, with a higher value of the transferred power predicted by the DYN3D/ATHLET(E) code.

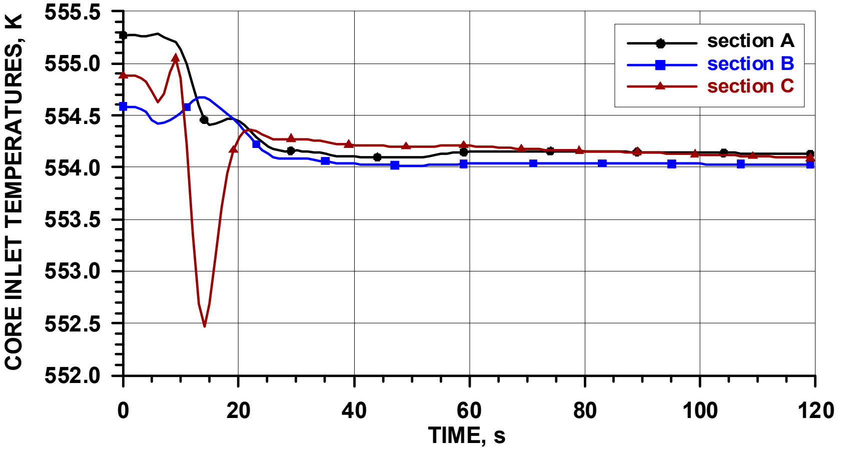


Figure 10: Core inlet temperature distribution in the RELAP5 model of lower plenum

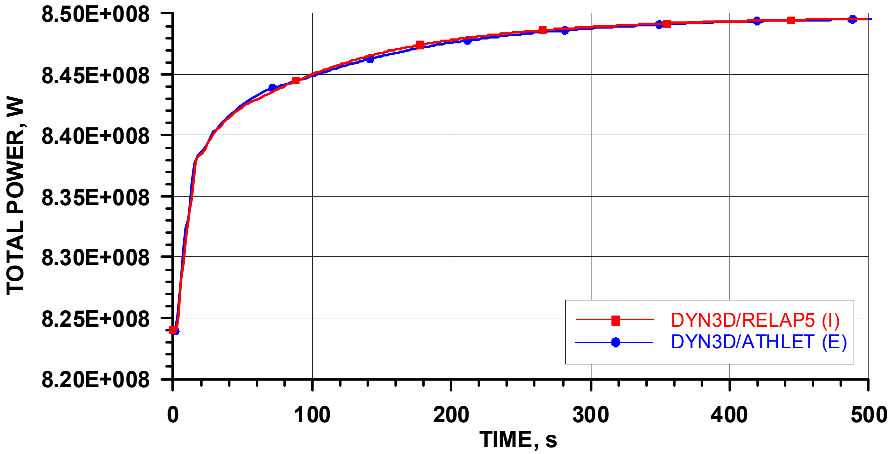


Figure 11: Code-to-code comparison of total core power

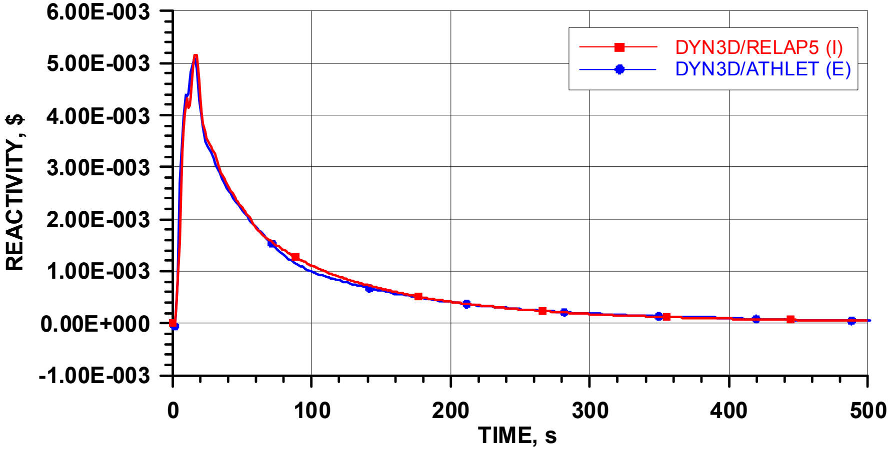


Figure 12: Code-to-code comparison of total reactivity

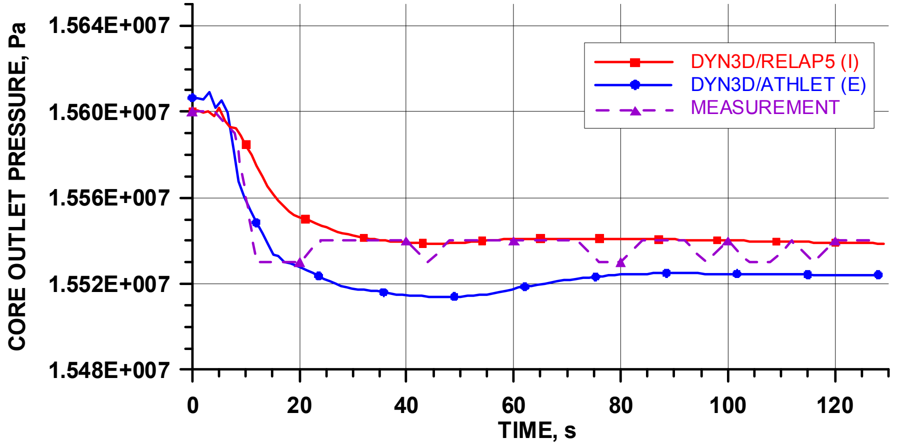


Figure 13: Measured and calculated pressure above the core

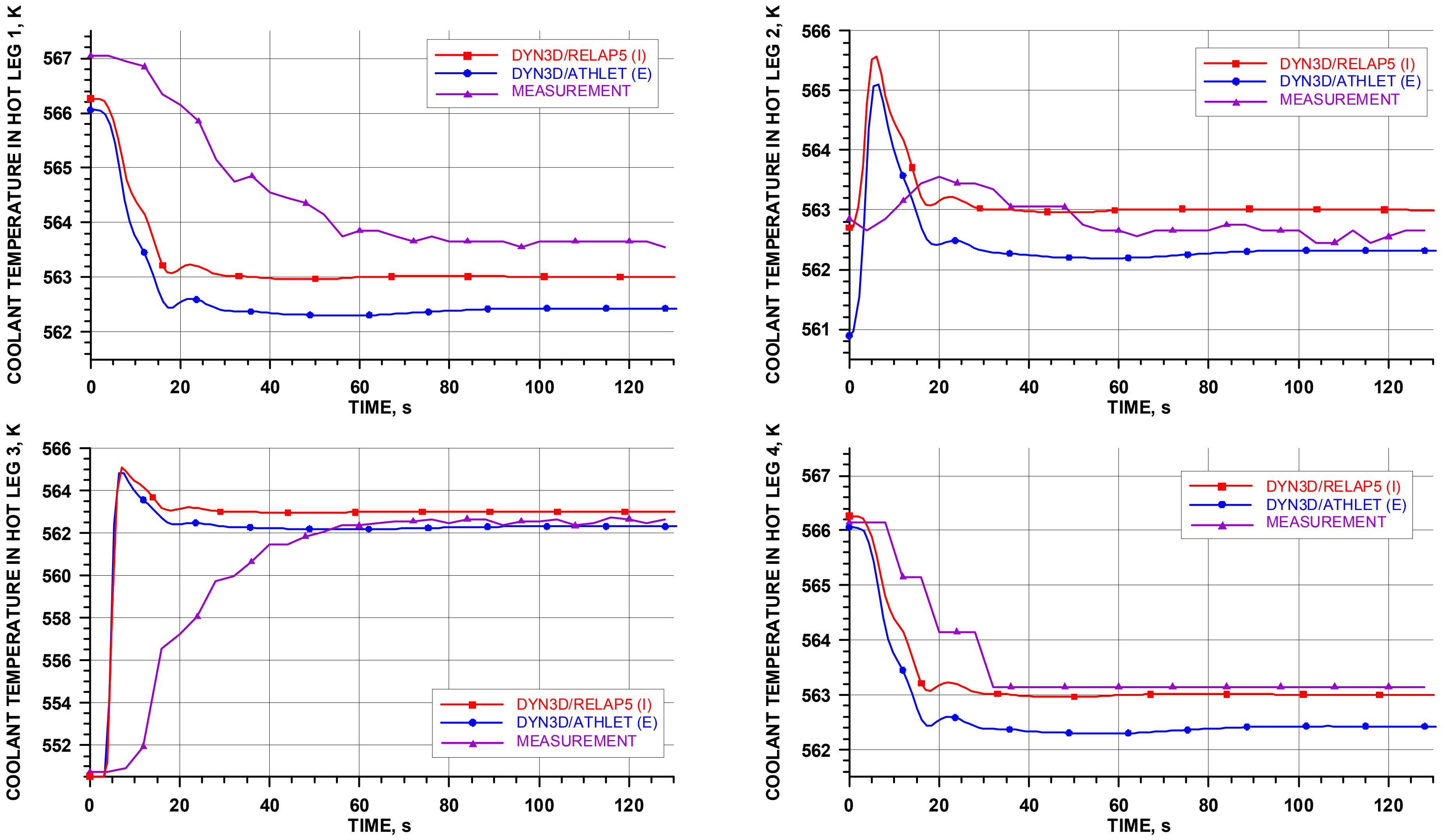


Figure 14: Measured and calculated coolant temperatures in hot legs

It leads to a larger primary pressure drop in the case of DYN3D/ATHLET(E) simulation. After approx. the 60th second of the transient, the primary pressure is stabilized and the deviation between predicted values of the SG powers is below 1%. The role of heat losses, especially from the pressurizer, is negligible during the initial phase of the transient and important for the final pressure stabilization only.

The operation of make-up and let-down systems was not modeled, thus the influence of this system on the primary pressure was not considered in the simulations.

According to the V1000CT-1 specification time delays of the temperature measurements do not have to be taken into account by the benchmark participants. Thus, a real thermocouple behavior was not modelled. As a result, the maximum discrepancy between the calculated and measured hot leg temperatures occurs during first 40 seconds of the transient (Figure 14), however, for the initial and final states the deviation is less then the measurement accuracy of 2 K. A realistic behavior of the hot leg temperatures proves an adequacy of the coolant mixing modelling in the upper plenum region.

The impact of the different RELAP5 and ATHLET nodalizations of the downcomer and lower plenum on the normalized radial distribution of the core power is analyzed in Figures 15 and 16. At the 15th second of the transient the maximum relative deviation (RErr) between FA powers increases from the initial 1% (Figure 5) to 1.2% (Figure 15) due to an increased non-uniformity of the core inlet temperature distribution predicted by the RELAP5 code (Figure 10). At the end of the transient, when all MCPs are operating and nearly uniform distribution of the core inlet temperature is reached, the maximum RErr decreases to about 0.7% (Figure 16). These results indicate a low sensitivity of the radial core power distribution to the differences between the employed models of coolant mixing in the downcomer and lower plenum.

6. CONCLUSIONS

The externally coupled neutronic / thermohydraulic code system DYN3D/ATHLET(E) and internally coupled code system DYN3D/RELAP5(I) have been evaluated against the available plant-measured data specified within the V1000CT-1 benchmark as the basic scenario of Exercise 3. The MCP switching on test conducted at the Kozloduy NPP Unit 6 was simulated. The employed VVER-1000 (V-320) models allow to reproduce the experimental data with a reasonable accuracy. A code-to-code comparison shows an acceptable agreement between the results of two simulations.

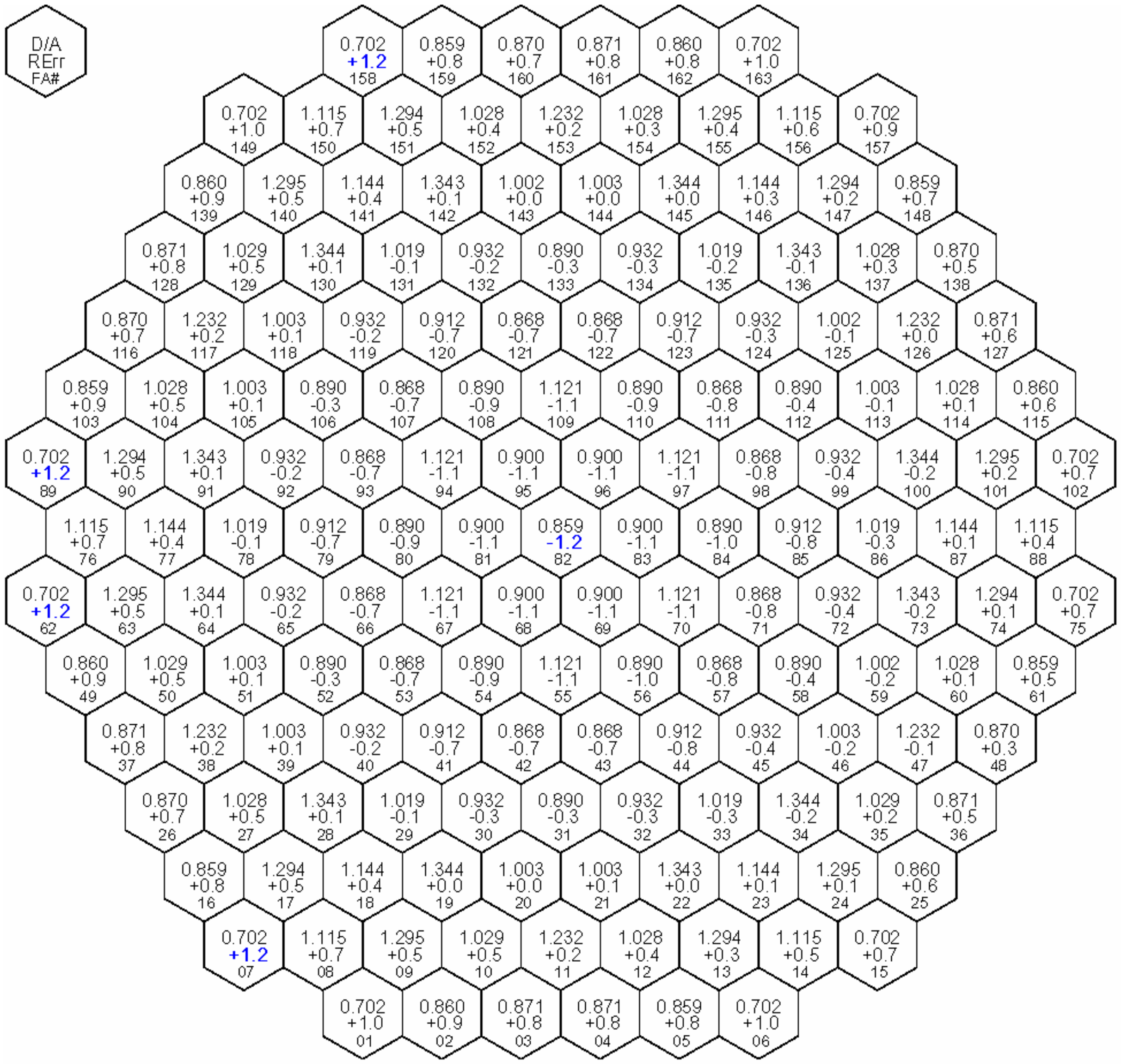
The following conclusions can be drawn from the results of performed calculations:

(1) The discrepancies in modeling the core initial state were notably reduced through the adjustment of the DYN3D and RELAP5 fuel rod models. As a consequence, a close agreement was achieved between the total power time histories predicted by the evaluated coupled code systems.

(2) A higher heat transfer efficiency of the steam generator model in the DYN3D/ATHLET(E) simulations leads to a deeper primary pressure drop and a lower average primary coolant temperature compared with the corresponding DYN3D/RELAP5(I) predictions.

(3) Adequate modeling of the primary coolant mixing in the reactor upper plenum is important for a realistic prediction of the loop temperatures during the initial phase of the transient. For the initial and final states the observed deviations between the calculated and measured hot leg temperatures do not exceed the accuracy of the measurements. However, ignoring the measurement inertia in the performed simulations results in a higher deviation between the calculated and measured leg temperatures.

(4) For the considered transient, a low sensitivity of the radial core power distribution to the differences between the employed models of coolant mixing in the downcomer and lower plenum regions is demonstrated.



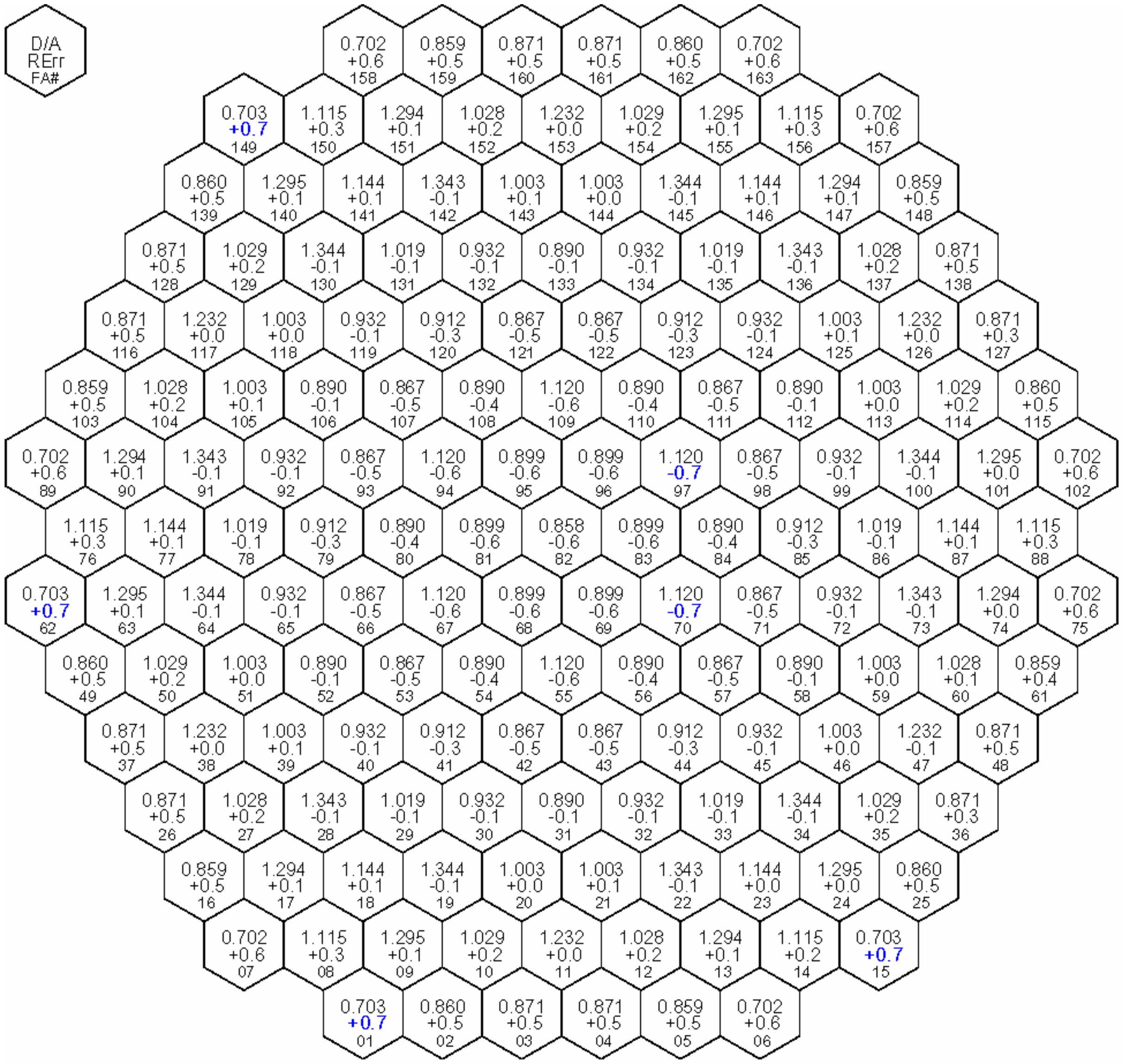
FA#	D/A	RErr
158	0.702	+1.2
159	0.859	+0.8
160	0.870	+0.7
161	0.871	+0.8
162	0.860	+0.8
163	0.702	+1.0
149	0.702	+1.0
150	1.115	+0.7
151	1.294	+0.5
152	1.028	+0.4
153	1.232	+0.2
154	1.028	+0.3
155	1.295	+0.4
156	1.115	+0.6
157	0.702	+0.9
139	0.860	+0.9
140	1.295	+0.5
141	1.144	+0.4
142	1.343	+0.1
143	1.002	+0.0
144	1.003	+0.0
145	1.344	+0.0
146	1.144	+0.3
147	1.294	+0.2
148	0.859	+0.7
128	0.871	+0.8
129	1.029	+0.5
130	1.344	+0.1
131	1.019	-0.1
132	0.932	-0.2
133	0.890	-0.3
134	0.932	-0.3
135	1.019	-0.2
136	1.343	-0.1
137	1.028	+0.3
138	0.870	+0.5
116	0.870	+0.7
117	1.232	+0.2
118	1.003	+0.1
119	0.932	-0.2
120	0.912	-0.7
121	0.868	-0.7
122	0.868	-0.7
123	0.912	-0.7
124	0.932	-0.3
125	1.002	-0.1
126	1.232	+0.0
127	0.871	+0.6
103	0.859	+0.9
104	1.028	+0.5
105	1.003	+0.1
106	0.890	-0.3
107	0.868	-0.7
108	0.890	-0.9
109	1.121	-1.1
110	0.890	-0.9
111	0.868	-0.8
112	0.890	-0.4
113	1.003	-0.1
114	1.028	+0.1
115	0.860	+0.6
89	0.702	+1.2
90	1.294	+0.5
91	1.343	+0.1
92	0.932	-0.2
93	0.868	-0.7
94	1.121	-1.1
95	0.900	-1.1
96	0.900	-1.1
97	1.121	-1.1
98	0.868	-0.8
99	0.932	-0.4
100	1.344	-0.2
101	1.295	+0.2
102	0.702	+0.7
76	1.115	+0.7
77	1.144	+0.4
78	1.019	-0.1
79	0.912	-0.7
80	0.890	-0.9
81	0.900	-1.1
82	0.859	-1.2
83	0.900	-1.1
84	0.890	-1.0
85	0.912	-0.8
86	1.019	-0.3
87	1.144	+0.1
88	1.115	+0.4
62	0.702	+1.2
63	1.295	+0.5
64	1.344	+0.1
65	0.932	-0.2
66	0.868	-0.7
67	1.121	-1.1
68	0.900	-1.1
69	0.900	-1.1
70	1.121	-1.1
71	0.868	-0.8
72	0.932	-0.4
73	1.343	-0.2
74	1.294	+0.1
75	0.702	+0.7
49	0.860	+0.9
50	1.029	+0.5
51	1.003	+0.1
52	0.890	-0.3
53	0.868	-0.7
54	0.890	-0.9
55	1.121	-1.1
56	0.890	-1.0
57	0.868	-0.8
58	0.890	-0.4
59	1.002	-0.2
60	1.028	+0.1
61	0.859	+0.5
37	0.871	+0.8
38	1.232	+0.2
39	1.003	+0.1
40	0.932	-0.2
41	0.912	-0.7
42	0.868	-0.7
43	0.868	-0.7
44	0.912	-0.8
45	0.932	-0.4
46	1.003	-0.2
47	1.232	-0.1
48	0.870	+0.3
26	0.870	+0.7
27	1.028	+0.5
28	1.343	+0.1
29	1.019	-0.1
30	0.932	-0.3
31	0.890	-0.3
32	0.932	-0.3
33	1.019	-0.3
34	1.344	-0.2
35	1.029	+0.2
36	0.871	+0.5
16	0.859	+0.8
17	1.294	+0.5
18	1.144	+0.4
19	1.344	+0.0
20	1.003	+0.0
21	1.003	+0.1
22	1.343	+0.0
23	1.144	+0.1
24	1.295	+0.1
25	0.860	+0.6
07	0.702	+1.2
08	1.115	+0.7
09	1.295	+0.5
10	1.029	+0.5
11	1.232	+0.2
12	1.028	+0.4
13	1.294	+0.3
14	1.115	+0.5
15	0.702	+0.7
01	0.702	+1.0
02	0.860	+0.9
03	0.871	+0.8
04	0.871	+0.8
05	0.859	+0.8
06	0.702	+1.0

D/A – results of DYN3D/ATHLET(E) calculation

RErr – relative deviation of DYN3D/ATHLET(E) results from DYN3D/RELAP5(I) results (%)

FA# - FA reference number

Figure 15: Code-to-code comparison between radial distributions of normalized FA powers (15-th second of the transient)



FA#	D/A	RErr
158	0.702	+0.6
159	0.859	+0.5
160	0.871	+0.5
161	0.871	+0.5
162	0.860	+0.5
163	0.702	+0.6
149	0.703	+0.7
150	1.115	+0.3
151	1.294	+0.1
152	1.028	+0.2
153	1.232	+0.0
154	1.029	+0.2
155	1.295	+0.1
156	1.115	+0.3
157	0.702	+0.6
139	0.860	+0.5
140	1.295	+0.1
141	1.144	+0.1
142	1.343	-0.1
143	1.003	+0.1
144	1.003	+0.0
145	1.344	-0.1
146	1.144	+0.1
147	1.294	+0.1
148	0.859	+0.5
128	0.871	+0.5
129	1.029	+0.2
130	1.344	-0.1
131	1.019	-0.1
132	0.932	-0.1
133	0.890	-0.1
134	0.932	-0.1
135	1.019	-0.1
136	1.343	-0.1
137	1.028	+0.2
138	0.871	+0.5
116	0.871	+0.5
117	1.232	+0.0
118	1.003	+0.0
119	0.932	-0.1
120	0.912	-0.3
121	0.867	-0.5
122	0.867	-0.5
123	0.912	-0.3
124	0.932	-0.1
125	1.003	+0.1
126	1.232	+0.0
127	0.871	+0.3
103	0.859	+0.5
104	1.028	+0.2
105	1.003	+0.1
106	0.890	-0.1
107	0.867	-0.5
108	0.890	-0.4
109	1.120	-0.6
110	0.890	-0.4
111	0.867	-0.5
112	0.890	-0.1
113	1.003	+0.0
114	1.029	+0.2
115	0.860	+0.5
89	0.702	+0.6
90	1.294	+0.1
91	1.343	-0.1
92	0.932	-0.1
93	0.867	-0.5
94	1.120	-0.6
95	0.899	-0.6
96	0.899	-0.6
97	1.120	-0.7
98	0.867	-0.5
99	0.932	-0.1
100	1.344	-0.1
101	1.295	+0.0
102	0.702	+0.6
76	1.115	+0.3
77	1.144	+0.1
78	1.019	-0.1
79	0.912	-0.3
80	0.890	-0.4
81	0.899	-0.6
82	0.858	-0.6
83	0.899	-0.6
84	0.890	-0.4
85	0.912	-0.3
86	1.019	-0.1
87	1.144	+0.1
88	1.115	+0.3
62	0.703	+0.7
63	1.295	+0.1
64	1.344	-0.1
65	0.932	-0.1
66	0.867	-0.5
67	1.120	-0.6
68	0.899	-0.6
69	0.899	-0.6
70	1.120	-0.7
71	0.867	-0.5
72	0.932	-0.1
73	1.343	-0.1
74	1.294	+0.0
75	0.702	+0.6
49	0.860	+0.5
50	1.029	+0.2
51	1.003	+0.0
52	0.890	-0.1
53	0.867	-0.5
54	0.890	-0.4
55	1.120	-0.6
56	0.890	-0.4
57	0.867	-0.5
58	0.890	-0.1
59	1.003	+0.0
60	1.028	+0.1
61	0.859	+0.4
37	0.871	+0.5
38	1.232	+0.0
39	1.003	+0.1
40	0.932	-0.1
41	0.912	-0.3
42	0.867	-0.5
43	0.867	-0.5
44	0.912	-0.3
45	0.932	-0.1
46	1.003	+0.0
47	1.232	-0.1
48	0.871	+0.5
26	0.871	+0.5
27	1.028	+0.2
28	1.343	-0.1
29	1.019	-0.1
30	0.932	-0.1
31	0.890	-0.1
32	0.932	-0.1
33	1.019	-0.1
34	1.344	-0.1
35	1.029	+0.2
36	0.871	+0.3
16	0.859	+0.5
17	1.294	+0.1
18	1.144	+0.1
19	1.344	-0.1
20	1.003	+0.0
21	1.003	+0.1
22	1.343	-0.1
23	1.144	+0.0
24	1.295	+0.0
25	0.860	+0.5
07	0.702	+0.6
08	1.115	+0.3
09	1.295	+0.1
10	1.029	+0.2
11	1.232	+0.0
12	1.028	+0.2
13	1.294	+0.1
14	1.115	+0.2
15	0.703	+0.7
01	0.703	+0.7
02	0.860	+0.5
03	0.871	+0.5
04	0.871	+0.5
05	0.859	+0.5
06	0.702	+0.6

D/A – results of DYN3D/ATHLET(E) calculation

RErr – relative deviation of DYN3D/ATHLET(E) results from DYN3D/RELAP5(E) results (%)

FA# - FA reference number

Figure 16: Code-to-code comparison between radial distributions of normalized FA powers (end of the transient)

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