TRACE/PARCS Calculations of Exercises 1 and 2 of the V1000CT-2 Benchmark

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Abstract

Exercises 1 and 2 of the VVER-1000 Coolant Transient Benchmark Phase 2 (V1000CT-2) are investigated using coupled three-dimensional (3-D) neutron kinetics/thermal-hydraulics code TRACE/PARCS. Two coarse mesh 3-D thermal-hydraulic models (with six angular sectors and with eighteen angular sectors) were developed for the system code TRACE for Exercise 1 and their applicability is evaluated using the test data provided in the benchmark specification. The six sector model is then coupled with the PARCS 3-D neutron kinetics model in order to analyze Exercise 2 of the benchmark.

The results show that TRACE code is accurate enough to simulate the flow mixing occurring in the downcomer of the VVER-1000 reactor.

KEYWORDS: V1000CT, TRACE, PARCS, Coupled Codes, TRACE/PARCS

1. Introduction

The V1000CT-2 benchmark [1] is based on data from Kozloduy Nuclear Power Plant (KNPP). The task of Exercise 1 of the benchmark is to simulate coolant mixing experiments that have been conducted during the KNPP Unit 6 commissioning phase. The test is very informative to examine the real loop mixing taking place in a VVER-1000 reactor vessel. The Exercise 2 is based on a Main Steam Line Break (MSLB) transient scenario modeling. The transient to be analyzed is initiated by a main steam line break in a VVER-1000 between the steam generator (SG) and the steam isolation valve (SIV), outside the containment. A mechanical failure of the main feed water regulation valve is assumed. This event is characterized by a large asymmetric cooling of the core, stuck control rods, and a large primary coolant flow variation. Exercise 1 is a real plant transient and plant measured data is provided in the specification, while Exercise 2 will be used only for code-to-code comparisons.

Two coarse mesh three-dimensional (3-D) thermal-hydraulic (T-H) models in cylindrical geometry (with six angular sectors and with eighteen angular sectors) were developed for the TRACE system code. Both models were used to analyze Exercise 1. Code predictions are then compared to the available plant measured data.

The TRACE six sector model is coupled with the PARCS 3-D neutron kinetics model, consisting of 211 nodes in radial plane (one node per assembly), in order to analyze Exercise 2 of the benchmark. As it was mentioned earlier, Exercise 2 is a MSLB transient. For this exercise only the vessel needs to be modeled and boundary conditions (provided in the specification) are applied to

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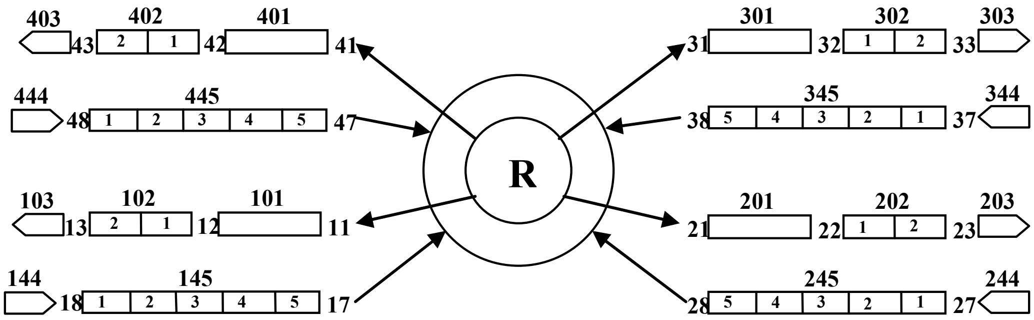
the reactor vessel inlets and outlets.

2. Model Description

2.1 Exercise 1

This section presents description of the VVER-1000 TRACE 3-D vessel boundary condition model. This model is based on a previously developed TRAC-PF1 model for the first phase of the benchmark (V1000CT-1) [2]. The scheme of the model is shown in Figure 1. The model consists of 3-D reactor vessel, part of the loops and boundary conditions.

Figure 1: Nodalization scheme



The inlet boundary conditions were imposed by using TRACE "FILL" component and the outlet boundary conditions were imposed by using TRACE "BREAK" component. The boundary conditions are given in Table 1. In Table 1 CL stands for Cold Leg and HL stands for Hot Leg. These boundary conditions correspond to the final state of Exercise 1 of the V1000CT-2 benchmark.

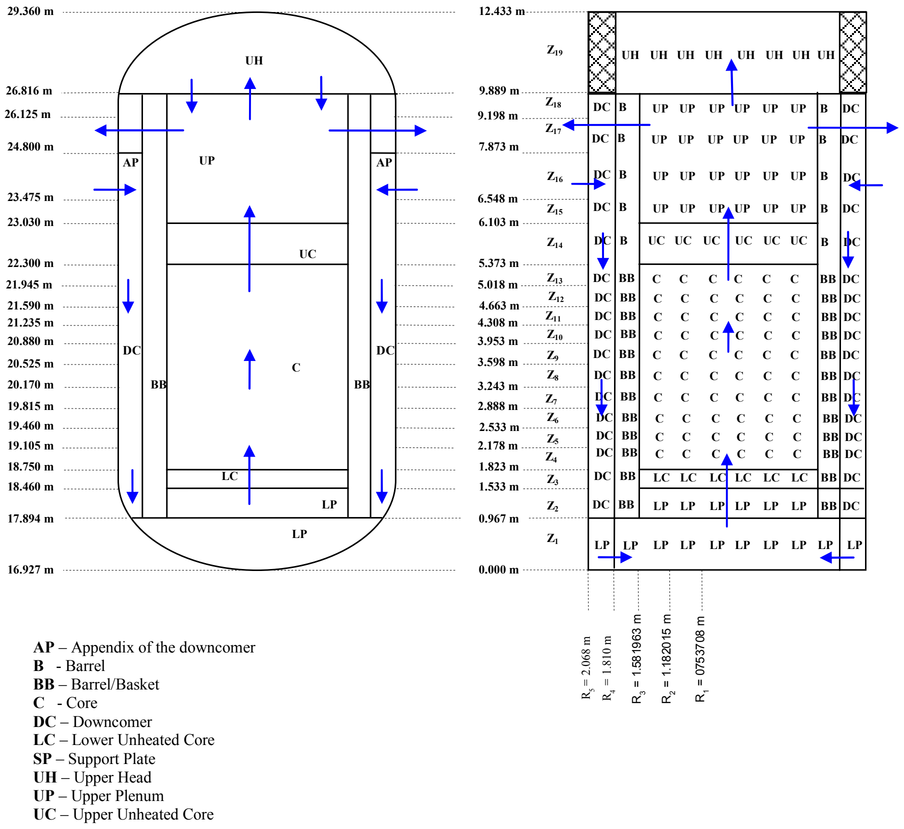
Table 1: Boundary conditions

Component		**T, K**	**P, MPa**	**G, kg/s**
Fill	CL1	555.35	-	4566
	CL2	543.05	-	4676
	CL3	542.15	-	4669
	CL4	542.35	-	4819
Break	HL1	-	15.55	-
	HL2	-	15.55	-
	HL3	-	15.55	-
	HL4	-	15.55	-

The reactor vessel is modeled with the TRACE 3-D "VESSEL" component in cylindrical geometry. The vessel comprised nineteen axial levels, five radial rings, and six angular sectors. The reactor vessel axial nodalization can be seen on Figure 2. The reactor vessel radial nodalization can be seen in Figure 3. The first three radial rings with radiuses R_1-R_3 represent the core, the fourth radial ring with radius R_4 represents the Barrel/Basket/Water region (reflector), and the last radial ring with radius R_5 represents the downcomer. Dividing these rings into six angular sectors constitute

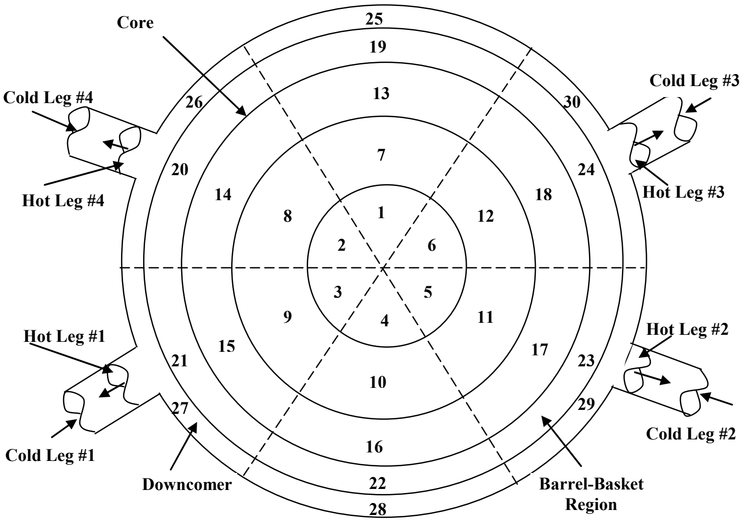
30 T-H cells in radial plan. In the case of eighteen sectors instead of six there are 90 T-H cells in radial plan, everything else stays the same.

Figure 2: Axial nodalization of the reactor vessel



AP – Appendix of the downcomer
B - Barrel
BB – Barrel/Basket
C - Core
DC – Downcomer
LC – Lower Unheated Core
SP – Support Plate
UH – Upper Head
UP – Upper Plenum
UC – Upper Unheated Core

Figure 3: Radial nodalization of the reactor vessel



2.2 Exercise 2

For simulation of the MSLB transient in Exercise 2, the TRACE T-H core model (six sectors) is coupled with the 211 neutronics nodes core model developed for the PARCS code. The axial coupling scheme is shown in Figure 4. Axially, there is a one-to-one correspondence between the T-H model and the neutron kinetics model.

Figure 4: Axial coupling scheme

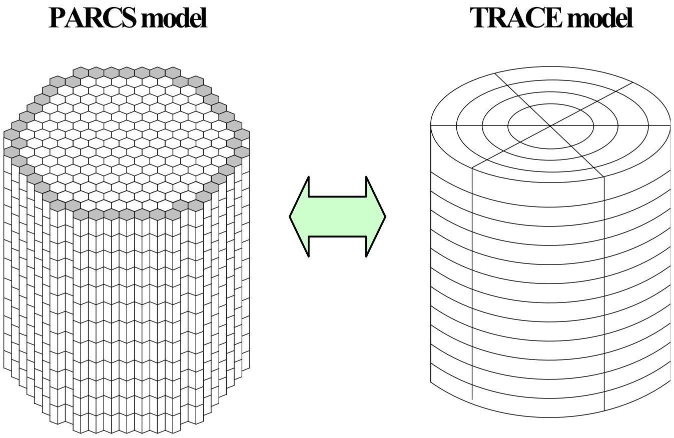
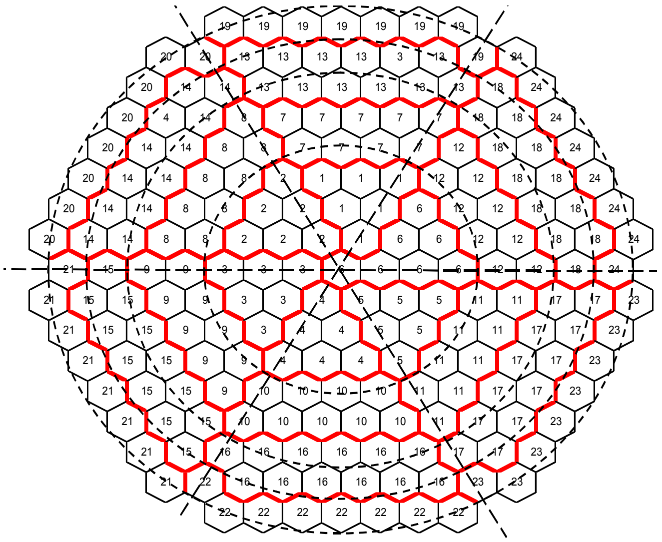


Figure 5 shows the radial mapping (coupling scheme) of the T-H cells and neutronics nodes. It is done by combining several neutronics nodes into a single T-H cell. Dashed lines represent T-H cells while the thick line represents the neutronics nodes that are lumped together into one T-H cell. The number of the neutronics nodes lumped in one T-H cell is not the same, because the area of the T-H cells is different in different rings. Each number shows to which T-H channel the neutronics node is mapped.

Figure 5: Radial coupling scheme



In order to be able to use PARCS code for calculation of Exercise 2 of the second phase of the V1000CT benchmark modifications in PARCS were performed. In the first phase of the benchmark only two independent variables for cross-section modelling have been used (T_f and ρ_m) while in the second phase three independent variables are used – T_f, T_m, and ρ_m. Therefore, for the second phase of the benchmark three dimensional interpolation into tables is required. The PARCS subroutine used for the first phase of the benchmark does only two dimensional interpolation. Therefore this subroutine had to be modified to do interpolation in 3-D or had to be replaced with the interpolation subroutine distributed among the benchmark participants, which does 4-D interpolation (lint4d.f). The second option has been chosen in order to be consistent with the benchmark requirements. In addition T_m was introduced as a feedback parameter in PARCS.

Another difference between the cross-section libraries in the first and second phase of the V1000CT benchmark is that the library for the second phase of the benchmark has additional information. At the end of each composition local decay constants (lambdas), delayed neutron fractions (betas), and the energy per fission values (kappas) are listed in addition to the inverse neutron velocities. This required changes into the cross-section reading subroutines as well as the incorporation of these new parameters into the PARCS calculation scheme.

3. Results

During the coolant mixing experiments the coolant temperature is measured at two locations, core exit temperature (individually in selected assemblies) and loop temperatures (hot and cold legs). These measurements are used to compare the code predictions for Exercise 1. In order to properly compare the test data (fuel assembly exit temperatures) with the code predictions, the data needs to be averaged over the code mesh and the loops (in reality and in the model) need to be connected in the same way. While the first requirement is easy to accomplish, the second one is more complicated and is related to at least two effects that need to be taken into account:

- In reality, the loops are asymmetrically connected to the otherwise symmetric core [3].
- Experimentally it was observed that the flow experiences excessive rotation regarding the loop position [4].

The first effect is simply a bias between the real loop connection and the centering of the loops in the code model. The second has an unknown origin and the system codes' physical models do not take credit for it. This phenomenon has been investigated in [3] and two different temperature zone mapping schemes have been proposed – the first one takes into account both effects, while the second one accounts only for the effect of different loop positions in the models and in reality. For the purpose of this work the second temperature zone mapping scheme has been adopted.

Table 2 shows the plant measured core exit temperatures averaged over the code mesh. Table 3 shows the absolute difference of TRACE results for core averaged temperatures from plant measured data.

Table 2: Core exit temperature, K

Sector # \ Ring #	1	2	3
1	544.43	545.06	545.03
2	545.57	546.02	546.17
3	553.46	554.77	554.84
4	551.99	555.24	554.57
5	545.15	545.92	546.04
6	544.40	545.00	545.08

Table 3: TRACE absolute difference from core exit measured temperature, K

Sector # \ Ring #	1	2	3
1	0.45	0.22	0.42
2	-0.63	-0.64	-0.62
3	1.69	1.99	2.13
4	0.99	-2.70	-2.06
5	1.12	1.03	1.15
6	0.60	0.28	0.35

Reasonable agreement can be observed from the comparison presented in Table 3 keeping in mind that the excessive rotation regarding the loop positions is not taken into account and the plant temperature measurement system uncertainty is ±2.0 K. It can be seen that the highest deviation of the code predictions from plant measured data is located in sectors 3, 4, and 5. This is expected since the flow with high temperature, introduced in the reactor vessel from loop 1 (sector 3) propagates in the neighboring loops counter-clockwise (sectors 4, and 5) and very little to the rest of the sectors (1, 2 and 6) due to the asymmetrical loops positions and the excessive flow rotation. The high temperature coolant reaches sector 5 while in ideal conditions (no excessive flow) it should have reached only sector 4. TRACE code predicted the ideal situation since the excessive flow rotation has not been taken into account.

Table 4 shows the comparison of hot leg coolant temperatures. This result once more confirms the accuracy of the TRACE prediction with differences of less than 0.5 K.

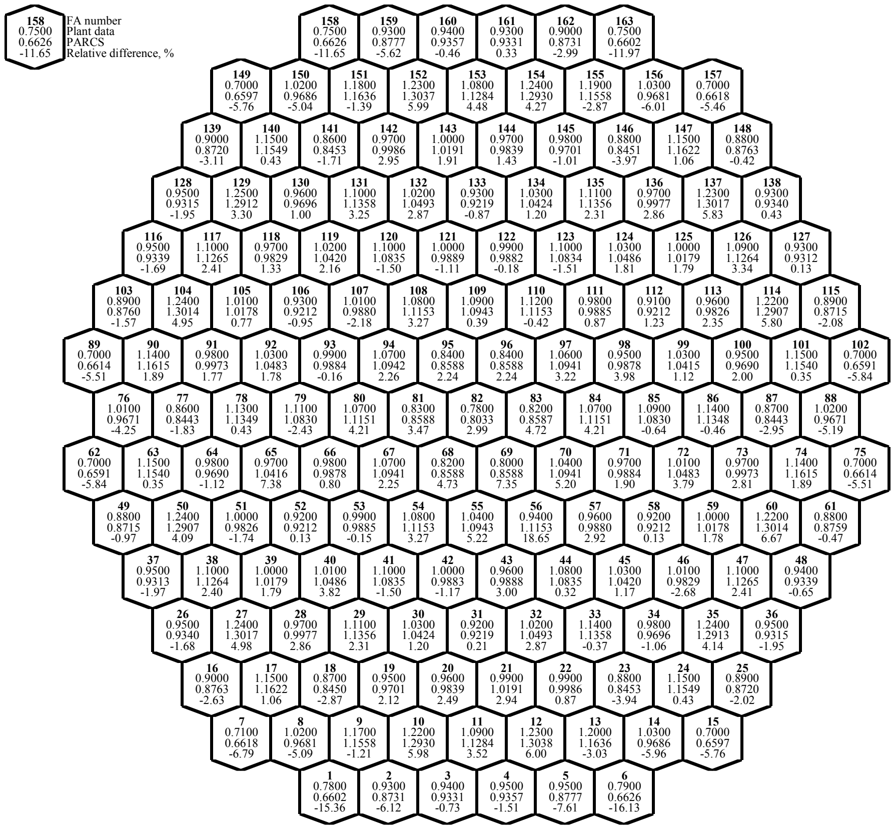
Table 4: Comparison of hot leg coolant temperatures, K

Hot leg #	Plant data	TRACE	Absolute Difference, K
1	554.85	554.4	-0.45
2	548.55	548.2	-0.35
3	545.75	545.8	0.05
4	546.45	546.1	-0.35

The eighteen sector TRACE model predicted correctly the coolant mixing although the results were less accurate when compared to the six sector model. In the original TRACE model (6 sectors) the discretization errors most probably balanced with some modeling error (input or code), while in the refined mesh model the error compensation decreased, making the obtained results worse. Therefore, the eighteen sector TRACE results are not included in this paper.

In Exercise 2 (MSLB) only the plant measured 2-D normalized power distribution at the initial steady-state is available for comparisons. Code-to-code comparisons will be done for the rest of the results. TRACE/PARCS results for the initial steady-state are compared to the plant measured normalized power distribution in Figure 6. Generally the relative error is approximately within ±6 % except for fuel assemblies 1, 6, 56, 158, and 163 were the error is above 10%. Since one-sixth symmetry was used for modeling the core with PARCS while the core loading at the real plant is slightly asymmetrical these errors are most probably due to this difference.

Figure 6: Plant measured data vs PSU-PARCS results for V1000CT-2 HP-SS



Doppler and Moderator Temperature Coefficients (DTC and MTC) were also calculated by perturbing the fuel temperature and moderator temperature with +5.0 K at HP-SS. In the case of the MTC the moderator density has also been perturbed with -10.862 kg/m^3 in order to correspond to the new moderator temperature at the same pressure. The pressure used is 15.7 MPa. Comparisons of calculated by PARCS DTC and MTC with the ones calculated by the BIPR code (the licensed core simulator at KNPP) can be seen in Table 5. This comparison show reasonable agreement between PARCS and BIPR.

Table 5: Comparison of MTC and DTC

	DTC, pcm	MTC, pcm
PARCS	-2.75	-55.17
BIPR	-2.86	-58.50

The transient calculations for Exercise 2 where performed by using vessel inlet and outlet boundary conditions as specified in the benchmark specification. Coolant temperature and mass-flow rate boundary conditions at the vessel inlet were used while pressure boundary condition is used at the vessel outlet. In addition to these boundary conditions, coolant temperature and mass-flow rate boundary conditions were also used at hot leg 4 in order to simulate the reverse flow in this loop.

The obtained transient results for Exercise 2 (MSLB) are presented in Figures 7 and 8.

The first figure shows reactor power during the MSLB transient. As it can be seen the reactor scram is activated at the beginning of the transient taking place at 0.36 second into transient. There are two scenarios. In the first one the Main Coolant Pump (MCP) in the faulted loop (loop # 4) trips while in the second scenario the MCP fails to trip. The results presented here are for the first scenario. As it can be seen from Figure 7 there is no return to power in the first scenario.

Figure 7: Reactor power during MSLB

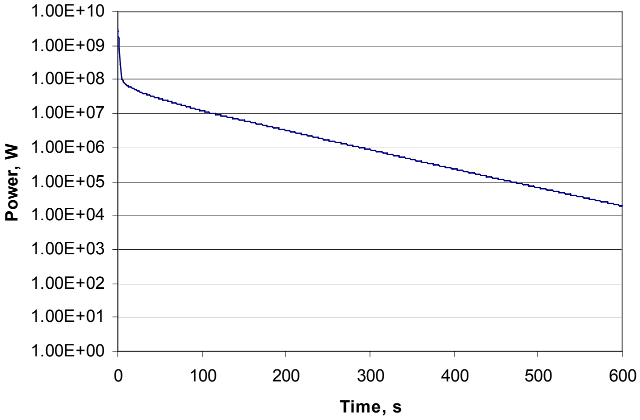
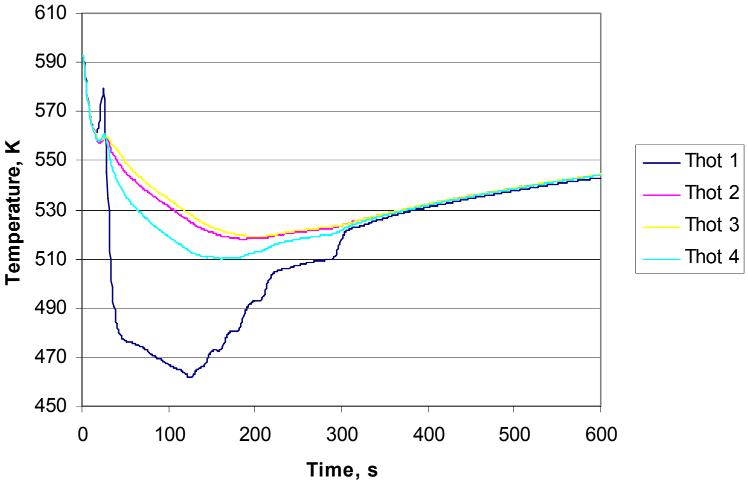


Figure 8 presents the hot leg coolant temperatures. The overall decrease of the hot legs coolant temperature is observed. The coolant temperature in hot leg 4 is significantly lower compared to the rest of the hot legs coolant temperatures due to the tripped MCP in this loop. After the trip of MCP 4 the flow in this loop is reversed and the coolant at the hot leg is overcooled when passing through the steam generator.

Figure 8: Hot leg coolant temperatures during MSLB



4. Conclusion

Two different coarse mesh 3-D thermal-hydraulic models were developed for the system code TRACE for Exercise 1 of the V1000CT-2 benchmark and their applicability was evaluated using the test data provided in the benchmark specification. The six sector model was also coupled with the PARCS 3-D neutron kinetics model in order to analyze Exercise 2 of the benchmark. In order to be able to use PARCS to analyze Exercise 2 of the V1000CT-2 benchmark the code was modified toutilize the V1000CT-2 cross-section library.

In conclusion, for capturing the loop flow rotation the 6 sector model qualitatively correctly predicted the temperature distribution at the core exit. The results show that the TRACE code is accurate enough to simulate the flow mixing occurring in the downcomer of the VVER-1000 reactor. The Exercise 2 results demonstrated that the changes made in PARCS are correct based on comparison with plant measured data. The obtained results of Exercise 2 with TRACE/PARCS will be further used by the benchmark team for code-to-code comparisons.

References

1) N. Kolev et al, “VVER-1000 Coolant Transient Benchmark, Volume II Specification of the VVER-1000 Vessel Mixing Problem”, OECD NEA, March 2004
2) B. Ivanov et al, “VVER-1000 Coolant Transient Benchmark (V1000-CT). Phase 1 – Final Specification”, OECD NEA/NSC/DOC (2002)6.
3) E. Popov, B. Ivanov and K. Ivanov, “Flow Rotation and Mixing in the Downcomer of a VVER-1000 Reactor”, Submitted for publication in Nuclear Technology, Dec. 2005.
4) “Investigation of the loop flow mixing in the reactor vessel of Kozloduy Unit 6”, Technical Report, Kozloduy NPP, August 1992