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OECD/DOE/CEA VVER-1000 Coolant Transient (V1000CT) Benchmark for Assessing Coupled Neutronics/Thermal-Hydraulics System Codes for VVER-1000 RIA Analysis

B. Ivanov[1], K. Ivanov[1]
S. Aniel[2], E. Royer[2]
N. Kolev[3], P. Groudev[3]

[1]*Dep. Of Mechanical and Nuclear Engineering, Pennsylvania State University, University Park, PA, USA*
[2]*Service Fluides Numériques Modélisation Etudes, CEA, Centre d'Etudes de Saclay, 91191 Gif, France*
[3]*INRNE, Academy of Sciences, Tsarigradsko shausse 72, 1784 Sofia, Bulgaria*

The present paper describes the two phases of the OECD/DOE/CEA VVER-1000 coolant transient benchmark labeled as V1000CT. This benchmark is based on a data from the Bulgarian Kozloduy NPP Unit 6. The first phase of the benchmark was designed for the purpose of assessing neutron kinetics and thermal-hydraulic modeling for a VVER-1000 reactor, and specifically for their use in analyzing reactivity transients in a VVER-1000 reactor. Most of the results of Phase 1 will be compared against experimental data and the rest of the results will be used for code-to-code comparison. The second phase of the benchmark is planned for evaluation and improvement of the mixing computational models. Code-to-code and code-to-data comparisons will be done based on data of a mixing experiment conducted at Kozloduy-6. Main steam line break will be also analyzed in the second phase of the V1000CT benchmark. The results from it will be used for code-to-code comparison.

The benchmark team has been involved in analyzing different aspects and performing sensitivity studies of the different benchmark exercises. The paper presents a comparison of selected results, obtained with two different system thermal-hydraulics codes, with the plant data for the Exercise 1 of Phase 1 of the benchmark as well as some results for Exercises 2 and 3.

Overall, this benchmark has been well accepted internationally, with many organizations representing 11 countries participating in the first phase of the benchmark.

KEYWORDS: VVER, Benchmark, 3-D neutronics/thermal-hydraulic coupling, Main Coolant Pump switching on, Coolant mixing, MSLB

1. Introduction

In recent years the code developers started coupling three-dimensional (3-D) neutron kinetics codes with advanced thermal-hydraulics system codes. The application of such complex computational tools for safety evaluations is conditioned by the assessment of their associated uncertainties. In this context, two coupled code benchmarks have already been initiated. The Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) has completed under the US Nuclear Regulatory Commission (NRC) sponsorship a PWR Main Steam Line Break (MSLB) benchmark [1]. Another OECD/NRC coupled code benchmark has been completed for a BWR turbine trip (TT) transient [2]. In the framework of the US DOE International Nuclear Safety Program a coupled benchmark problem based on Bulgarian Kozloduy NPP (KNPP) data has been developed for the assessment of neutron kinetics and thermal-hydraulic modeling of a VVER-1000 reactor, and specifically for their use in analyzing reactivity transients in a VVER-1000 reactor. Based on the experience accumulated in safety analysis of the Western type reactors (PWR MSLB and BWR TT) this benchmark was extended to an international standard problem under the sponsorship of US DOE, OECD/NEA and CEA, France. The benchmark is labeled as VVER-1000 Coolant Transient benchmark (V1000CT) and consists of two phases, which are described below.

2. Description of the V1000CT benchmark

2.1. Phase 1

The detailed definition of Phase 1 of the V1000CT benchmark can be found in the V1000CT-1 benchmark specification [3]. Phase 1 of the benchmark is based on a comparison with the NPP experiment of a main coolant pump (MCP) start up when the other three pumps are in operation. The experiment was conducted by Bulgarian and Russian engineers during the plant-commissioning phase at KNPP Unit #6 (VVER-1000, model 320) as a part of the start-up tests. This event is characterized by rapid increase in the flow through the core resulting in a coolant temperature decrease, which is spatially dependent. Although the reactivity perturbations in the core are not so strong the benchmark team decided to choose this transient because of the available plant data.

Three exercises are defined in order to verify the capability of system codes to analyze complex transients with coupled core-plant interactions; to test fully the 3-D neutronics/thermal-hydraulic coupling; and to evaluate discrepancies between predictions of coupled codes in best-estimate transient simulations and between coupled codes predictions and plant data.

V1000CT-1 Exercise 1 – Point kinetics plant simulation

The purpose of this exercise is to test the primary and secondary system model responses. The benchmark specification provides all the necessary point-kinetics data. Using this exercise the participants can verify their system input decks and they can eliminate all the deviations coming from the system user modeling, which later could be helpful for the best estimate comparisons.

V1000CT-1 Exercise 2 – Coupled 3-D neutronics/core thermal-hydraulics response evaluation

The purpose of this exercise is to model the core and the vessel only. The benchmark provides inlet and outlet core transient boundary conditions. Using this exercise the participants can verify their coupling schemes and cross section library utilization.

V1000CT-1 Exercise 3 – Best-estimate coupled code plant transient modeling

The third exercise combines elements of the first two. In this exercise the participants must analyze the transient in its entirety, and computation results will be compared to measured plant data. This phase of the benchmark contains also an extreme scenario, which involves a rod ejection in the part of the core cooled by the MCP #3, which will develop very peaked spatial power distribution and nonlinear asymmetric feedback effects. The extreme scenario was developed to test and compare better the predictions of the coupled 3-D kinetics/thermal-hydraulic codes.

2.2. Phase 2

Since previous benchmarks indicate that further improvement of the mixing computation models in the integrated codes is necessary, a coolant mixing and MSLB benchmark for VVER-1000 (V1000CT-2) was defined.

V1000CT-2 Exercise 1: Computation of coolant mixing experiments

This exercise is based on a comparison with a mixing experiment conducted at Kozloduy-6 as part of the plant-commissioning phase. The experiment includes isolation of a steam generator at 9.3% of the nominal power causing single loop heat-up, with all MCP in operation. It is characterized by temperature rise of about 14 degrees and a decrease of mass flow rate by 3.4% in the disturbed loop, affecting the neighboring loops as well. It will be used to test and validate vessel-mixing models (CFD, coarse-mesh and mixing matrix). Vessel boundary conditions and core power distribution along with pressure above the core will be part of the exercise specification. The task is to calculate the core inlet and outlet distributions.

V1000CT-2 Exercises 2 and 3: Main Steam-Line Break (MSLB) 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. Two scenarios will be defined: the first scenario is taken from the current licensing practice and the second is derived from the original one using aggravating assumptions to enhance the code-to-code comparison. The main objective of the study is to clarify the local 3-D feedback effects depending on the vessel mixing. Special emphasis is put on testing 3-D vessel thermal-hydraulic (T-H) models and the coupling of 3-D neutronics/vessel thermal hydraulics. The MSLB is thus divided in two exercises (to be done for the two scenarios): Exercise 2 consists of coupled 3-D neutronics/vessel thermal-hydraulic simulations using specified vessel T-H boundary conditions and Exercise 3 consists of best estimate coupled plant simulations (plant, 3-D vessel and core).

3. Results

The benchmark team has been involved in analyzing different modeling aspects and performing sensitivity studies of the different benchmark exercises. Table 1 and Fig. 1-2 in this section provide a comparison of selected results, obtained with two different system thermal-hydraulics codes, with the plant data for the Exercise 1 of Phase 1 of the benchmark. The PSU results were obtained using the PSU version of the TRAC-PF1/NEM coupled code [4]. The INRNE results [5] were obtained with RELAP5/Mod3.2.

The steady-state results are presented in Table 1 according to the requirements of the benchmark specification. The steady-state results of PSU and INRNE converge within the specified measurement uncertainty band.

The code-to-plant data comparison is given for 129 seconds while the code-to-code comparison is presented for 800 seconds. For the cold leg temperatures, the comparison shows a good agreement between the plant data and the calculated values. The largest difference is observed in loop #3 (Fig. 1) in the interval from 7 to 14 second during the switch on of MCP #3. The predicted temperature in this leg drops to 551 K while such drop of the temperature cannot be observed in the plant data. This phenomenon can be explained as follows. Initially, when the pump is off the direction of the flow in this loop is reversed. After the pump starts, the flow that once has passed trough the SG is forced back and goes trough the SG again, causing the temperature to decrease further. The codes predict the exact situation. However, the measurement did not register this temperature drop because the given experimental points do not correspond to instant temperature measurements but to mean temperatures between the different sampling times and also because of the time delay of the thermocouples.

Table 1 Steady-state results

Parameter	Measured Value	PSU	Deviation	INRNE	Deviation
Core power, MWt	824.00±60	824.00	0.00	824.00	0.00
Prim. side pressure, MPa	15.60±0.30	15.59	-0.01	15.60	0.00
Cold leg 1 temperature, °K	555.55±2.0	555.08	-0.47	554.80	-0.75
Cold leg 2 temperature, °K	554.55±2.0	554.28	-0.27	554.32	-0.23
Cold leg 3 temperature, °K	554.35±2.0	554.49	+0.14	554.57	+0.22
Cold leg 4 temperature, °K	555.25±2.0	554.95	-0.30	554.79	-0.46
Hot leg 1 temperature, °K	567.05±2.0	565.94	-1.11	565.16	-1.89
Hot leg 2 temperature, °K	562.85±2.0	563.30	+0.45	563.73	+0.88
Hot leg 3 temperature, °K	550.75±2.0	551.03	+0.28	550.16	-0.59
Hot leg 4 temperature, °K	566.15±2.0	565.40	-0.75	565.16	-0.99
Core flow rate, kg/s	13611±800	13483.5	-127.50	13503.9	-107.1
Loop 1 flow rate, kg/s	5031±200	5006.70	-24.30	5008.18	-22.82
Loop 2 flow rate, kg/s	5069±200	5039.00	-30.00	5027.07	-41.93
Loop 3 flow rate, kg/s	-1544±200	-1588.4	-44.40	-1535.9	+8.07
Loop 4 flow rate, kg/s	5075±200	5026.20	-48.80	5013.54	-61.46
Pressurizer level, m	7.44±0.15	7.44	0.00	7.44	0.00
Water level in SG1, m	2.30±0.075	2.35	+0.05	2.33	+0.01
Water level in SG2, m	2.41±0.075	2.42	+0.01	2.41	-0.04
Water level in SG3, m	2.49±0.075	2.55	+0.06	2.46	-0.03
Water level in SG4, m	2.43±0.075	2.46	+0.03	2.46	+0.03

The hot leg temperatures calculated by the members of the benchmark team fall within the range of the measurement uncertainty by the end of the transient. The largest difference is observed in loop #2 in the interval from 0 to 20 s (Fig. 2). The predictions of the codes show peak of the temperature, while such a peak is not observed in the plant data. This peak in the temperature could be explained as follows. At the time before the transient starts the temperature of the coolant in hot leg #2 is lower than those in hot legs #1 and #4 because it is affected by the coolant with low temperature coming from the loop #3 (the loop with the reversed flow). Only the temperature in loop #2 is affected because this loop is closest to loop #3 (Fig. 3). At the beginning of the transient, the flow in loop #3 is reverses back and coolant with higher temperature from loops #1 and #4 enters loop #2, which causes the peak of the temperature in the hot leg #2. Later into the transient, the coolant temperature in loops number 1, 2, and 4 is decreasing because of the increasing flow through the core.

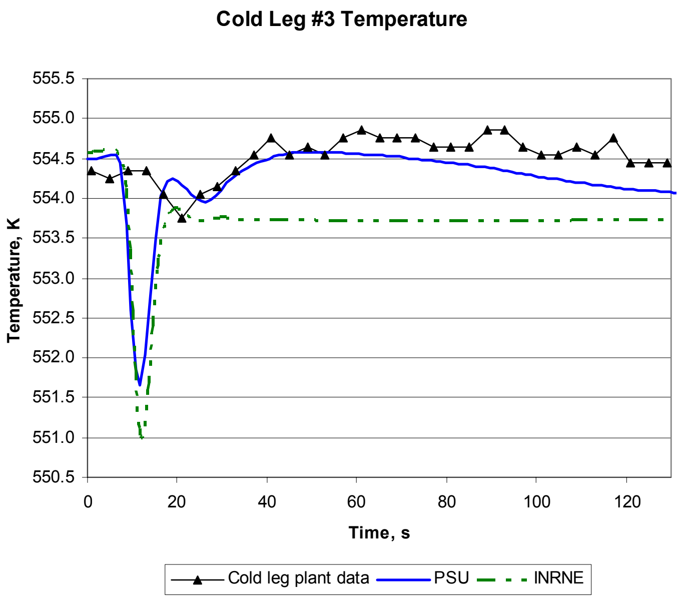

Fig. 1 Cold leg #3 temperature during the transient

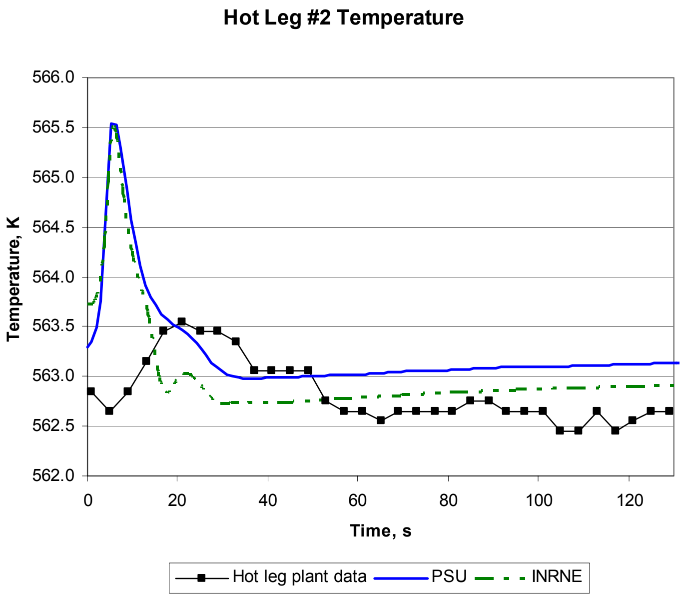

Fig. 2 Hot leg #2 temperature during the transient

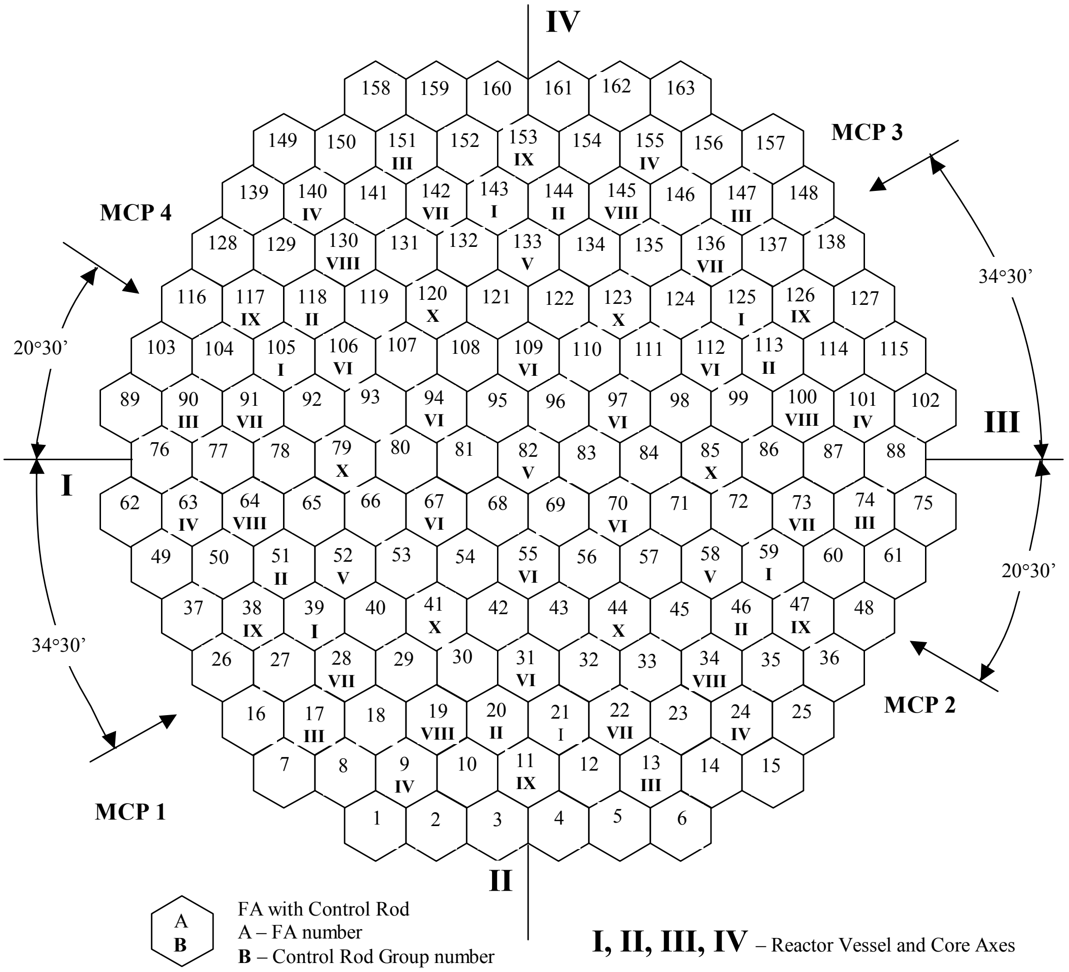

Fig. 3 Cross-section of the reactor core

Fig. 4 shows the comparison of the TRAC-PF1/NEM results for radial power distribution with the available plant data at the initial steady-state. The plant data is given only for selected assemblies because the power was measured only in these fuel assemblies. From this figure it can be seen that the agreement is reasonable and generally the error is less than 5 %. However, the error in several assemblies slightly exceeds 5 %. The largest error is observed in fuel assembly number 60 and it is 7.29 %. This error most probably is due to the uncertainty of the plant measurements.

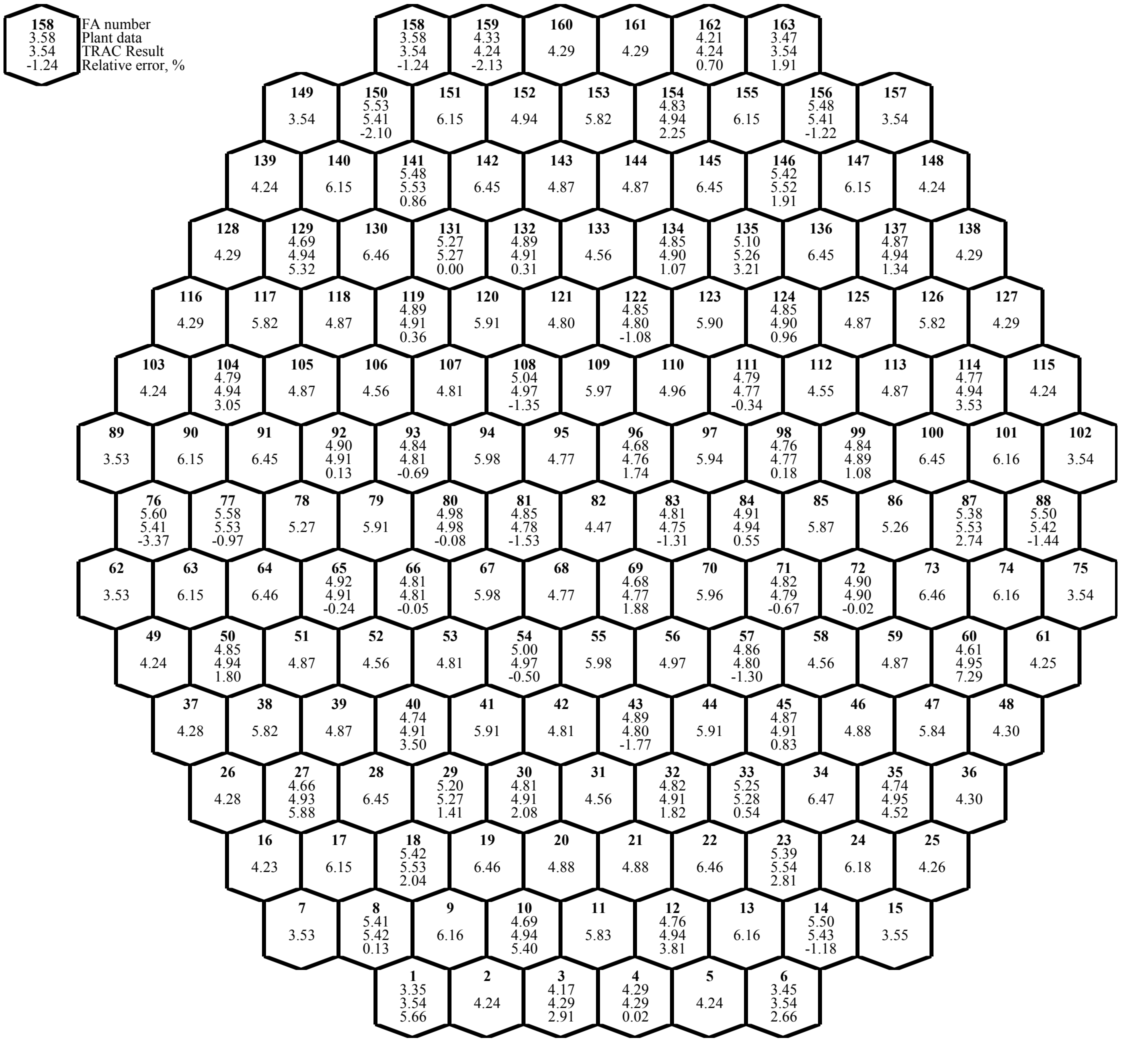

Fig. 4 Comparison of the radial power at the initial steady-state

Another interesting phenomenon observed in our comparative analysis is the difference in the total power time evolution during the transient as predicted by the point kinetics model (Exercise 1) and the 3-D kinetics model (Exercise 3). This comparison is shown in Fig. 5. The difference is about 14 MW in the predicted stabilized power levels after 600 seconds into the transient and it can be explained with conservative assumptions embedded in the point kinetics model predictions. During the transient there are spatial flux redistributions, which affect core reactivity. The point kinetics model is not able to describe these flux redistributions and their impact on the feedback and control reactivities (group X is partially inserted into the core during the transient) and as a result over predicts the total power increase as indicated by the plant data.

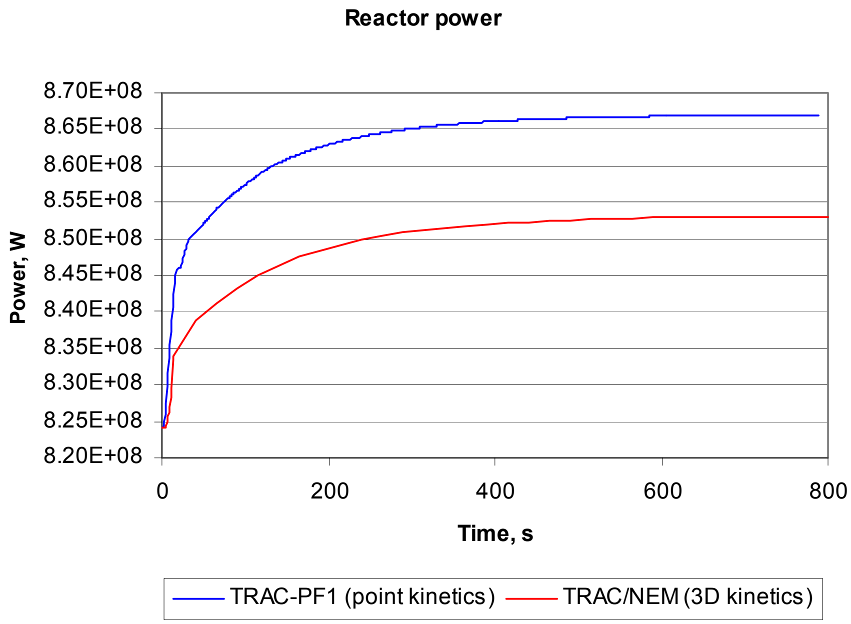

Fig. 5 Comparison of the reactor power time history

4. Status of V1000CT-2

Experimental data show a net counter clock-wise shift (rotation) of "loop flow centers" in different VVER-1000 V320 units flow patterns. The swirl intensity depends on the envisaged unit. It can be concluded that the flow pattern is highly dependent on the Vessel geometry. A geometry description based on design geometrical data will not enable codes to reproduce the swirl and further results post-treatments will be necessary to make valuable code-to-experiment comparisons. Two different fine geometry descriptions of the vessel will thus be given to the participants. They correspond respectively to the VVER-1000 vessel design geometry and to the closest Kozluduy-6 actual vessel geometry description. Giving two geometries will enable the participant to measure the key parameters of the geometry description for a good flow pattern simulation. These data will be available in different formats: a paper one (with tables and drawings) and a computer one (MED format). Preliminary CFD computations are also under progress with TrioU code.

5. Conclusion

Overall, this benchmark has been well accepted internationally, with many organizations representing 11 countries participating in the first phase of the benchmark. The schedule of the OECD/DOE/CEA V1000CT benchmark includes the following activities in near future: preparation of a draft of the specification for Exercise 1 of Phase 2 (by the end of February 2004); submitting results by the participants for Exercises 1 and 2, Phase 1 (by the end of February 2004); and organizing and conducting the Second V1000CT Benchmark workshop in conjunction with the AER WGD Meeting – 5-8 April 2004 in Bulgaria

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