TRANSIENT SIMULATIONS IN VVER-1000 – COMPARISON BETWEEN DYN3D-ATHLET AND DYN3D-RELAP5

U.Grundmann, S. Kliem, Y. Kozmenkov, S.Mittag, U. Rohde, F.-P. Weiss,
Forschungszentrum Rossendorf

ABSTRACT

Simulations of a real transient of an operating VVER-1000 power plant have been performed using DYN3D-ATLET /Gru95/ and DYN3D-RELAP5 /Koz01/ code systems in the frame of activities aimed at a validation of the neutronic / thermal-hydraulic coupled codes. The transient initiated by a main coolant pump (MCP) switching off, when three of the four MCPs of the plant are in operation (scenario of the VALCO project) is chosen for the simulation. The same models of the plant (except the core nodalization) but two different libraries of macroscopic cross-sections have been used in compared calculations. Additionally, the compared code systems are based on the different - external and internal - coupling techniques. This paper contains a brief description of the coupled codes and the plant model as well as a comparison between the results from simulations.

1. INTRODUCTION

In recent time, taking advantage of rapidly growing computer technologies, various coupled three-dimensional neutron kinetics and one-dimensional thermal-hydraulic (T-H) best-estimate code systems have been developed over the world by several research teams. An integration of neutron kinetics and T-H advanced codes into the code systems leads to a more detailed, more accurate and, as a result, less conservative prediction of the reactor plant parameters. A wider range of reactor transient and accident scenarios can be analysed using the coupled code systems, owing to their enhanced capabilities of representing the transient behavior of the standard uranium-dioxide fuel as well as advanced fuels, being developed for improving the operational and safety features of LWRs or / and the burning of plutonium in thermal reactors.

Currently, in the framework of various international projects, intense efforts are directed at the comprehensive analysis of prediction capabilities of the developed coupled code systems. These activities include (1) overall testing of the coupling interface, (2) verification of coupled code systems by solving international benchmark problems (conducting a code-to-code comparison) and (3) extended validation of the coupled codes against measured nuclear power plant (NPP) transients. The recent examples of co-operation in this field are the EU FP5 (VALCO) project on validation of coupled neutronics / thermal-hydraulics codes for VVER reactors and the joint FZR (Germany) – IPPE (Russia) research project on application of coupled codes for transient analysis in VVER-type reactors.

2. BASIC FEATURES AND EVALUATION OF THE COUPLED CODES

The integration of the DYN3D /Gru96/ and ATHLET /GRS02/ codes was entirely performed at FZR, whereas the interface for coupling DYN3D and RELAP5 /All92/ codes was developed in co-operation of FZR and the Russian Institute of Physics and Power Engineering (IPPE). Both coupled code systems incorporate the same code of three-dimensional neutron kinetics – DYN3D. A more recent modification of this neutronic code is coupled with ATHLET, allowing to model both hexagonal and rectangular geometries of fuel assemblies (FA). Presently, DYN3D-RELAP5 coupled code system is capable of modeling FAs of hexagonal geometry only. However, both geometries are scheduled to be included into the updated future version of DYN3D-RELAP5.

In addition to the transient neutronic simulations, the stand-alone DYN3D code is capable to perform calculations of (1) fuel burn-up distributions in the core, (2) distributions of the equilibrium Xe and Sm concentrations, (3) spatial decay heat and (4) the core thermal-hydraulic parameters. All these capabilities, except the capability of fuel burn-up calculation, are available for the considered code systems as well. The stand-alone DYN3D code should be used for the fuel burn-up calculations prior to the transient simulations.

Both ATHLET and RELAP5 thermal-hydraulic system codes are based on the one-dimensional, nonhomogeneous and nonequilibrium models for the two-phase flow and capable of modelling nuclear reactor transients and accidents in a wide range of scenarios. The stand-alone ATHLET code utilizes a point and one-dimensional neutron kinetics model, while the NRC versions of the stand-alone RELAP5 system code employs a point-kinetics model only. The capabilities of the original stand-alone system codes are available for coupled-code users.

DYN3D and ATHLET codes have been integrated in two different ways, using so-called "internal" and "external" coupling techniques. An internal integration technique means that both neutron kinetics and thermal hydraulics of the core are simulated by the code of neutron kinetics, and the system code simulates all plant components outside the core. In the case of an internal coupling only neutronic model of the neutron kinetics code is integrated with the thermal-hydraulic system code. An internal coupling technique has been only used to integrate DYN3D with RELAP5. It was selected primarily due to the advantages of the closed implicit solution of thermal-hydraulic equations and unrestricted application of the RELAP5 models, including modelling capabilities of the control and trip systems, to the core simulation.

To the present time several reactor plant transients and international benchmarks aimed at the evaluation of the coupled codes have been successfully analyzed using DYN3D-ATHLET and DYN3D-RELAP code systems. Being developed later, DYN3D-RELAP5 coupled code has been applied to a less number of exercises, compared with the number of validation and verification problems solved by the DYN3D-ATHLET code system. Table 1 contains the list of VVER-related calculations performed by the internally coupled DYN3D-ATHLET code system. All transients and benchmarks presented in this table concern VVER-440 and VVER-1000 reactors. VVER-related calculations performed by the internally coupled DYN3D-RELAP5 code system are listed in Table 2. Only one real plant transient has been simulated using the DYN3D-RELAP5 code system by now (shadowed line in Table 2).

Table 1. Overview of VVER-related calculations (externally coupled DYN3D-ATHLET)

No.	Simulation Problem	Type of reactor	Scenario
1	Commissioning experiment at Balakovo-1	VVER-1000	Switching off 1 of 4 working main coolant pumps (MCP)
2	Accident with delayed SCRAM at Greifswald-5	VVER-440	Switching off 1 of 3 working MCP at 50% power, manual SCRAM
3	Transient of the EU-PHARE SRR-1/95 project at Lovisa-1	VVER-440	Load drop of 1 from 2 working turbogenerators
4	Transient of the EU-PHARE SRR-1/95 project at Balakovo-4	VVER-1000	Switching off of 1 from 2 working feed water pumps
5	Transient of the EU VALCO project at Kozloduy-6	VVER-1000	Switching on of 1 from 3 working MCPs
6	V1000-CT transient at Kozloduy-6 (work in progress)	VVER-1000	MCP switching on
7	5th dynamic AER benchmark	VVER-440	Symmetric main steam header break
8	6th dynamic AER benchmark	VVER-440	Asymmetric main steam header break

Table 2. Overview of VVER-related calculations (internally coupled DYN3D-RELAP5)

No.	Simulation Problem	Type of reactor	Objective	Specific feature
1	Ejection of the central CR group	ABV (VVER-type)	Testing of the coupling interface	Natural circulation of the primary coolant
2	5th dynamic AER benchmark	VVER-440.	Verification of thermohydraulic models	Code-to-code comparison with results obtained using externally coupled code DYN3D/ATHLET
3	LB LOCA	VVER-640	Decay heat model of DYN3D	ISTC project on ROX-fuel for VVERs
4	Ejection of central CR	VVER-1000	New type of cross-section library developed in IPPE	Core model only
5	Transient of the EU VALCO project at Kozloduy-6	VVER-1000	Code system validation against experiment	1st simulation of the real plant transient

3. REFERENCE TRANSIENT AND REACTOR PLANT MODEL

The reference transient chosen for comparison calculation is the commissioning experiment at the 6-th unit of Kozloduy NPP (VVER-1000) documented in the framework of the EU FP5 (VALCO) project. This is the first real plant transient, which has been simulated by the DYN3D-RELAP5 coupled code system.

The transient is initiated by the coast-down of the 1st loop MCP at the moment, when 3 of 4 MCPs (namely, 1st, 2nd, and 4th) are in operation. The MCP of the 3rd primary loop has been switched off about 90 minutes earlier during the first phase of conducted start-up experiments, and, according to the VALCO project specification, this period of unit operation is not required to be included in simulation. The transient scenario is shown in Table 3.

Table 3. Sequence of main events

Time, s	Event
0	MCP of the 1st primary loop is switched off (one of three operating MCPs)
0.5	10-th group of control rods starts its downward movement from 73% position to decrease reactor power
20	Set point "low level in SG1" (–100 mm) is reached and the 2nd auxiliary feed water pump (AFWP-2) is put into operation; AWFP-1 is operating during the whole experiment
31	10-th control group reaches the lower position of 55 %
52	Switch off of the 1st heater group of pressurizer
58	First opening of the pressurizer spray valve (maximum 21% at 75th second, closure at 83rd second)
88	Second opening of the pressurizer spray valve (maximum 7% at 98th second, closure at 103rd second)
380	End of transient

The following reactor parameters have been measured during the course of the Kozloduy-6 experiment and are available for comparison with the results of computer simulations:

- initial and final axial distributions of the reactor neutron power,
- initial and final radial distributions of the neutron power,
- initial and final distributions of the core outlet temperature,
- neutron power,
- boron acid concentration in the primary coolant,
- pressure drop over main coolant pumps,
- hot and cold leg temperatures,
- reactor upper plenum pressure,
- pressurizer pressure and water level,
- pressure at the secondary side of steam generators,
- main steam header pressure,
- feedwater levels in steam generators.

Additionally, according to the specification of the VALCO project, the following unmeasured plant parameters have to be compared:

- mass flow rate through the core,
- loop mass flow rates,
- mass flow rates through the main steam lines.

Table 4 represents measurement accuracy of the main thermal-hydraulic parameters.

Table 4. Absolute errors of measurement at the Kozloduy-6 unit

Parameter	Measurement range	Measurement error
1. Pressure, MPa	0.0 - 19.61	± 0.3 MPa
2. Pressure drop, MPa	0.0 - 0.98	± 0.02 MPa
3. Temperature, C	0.0 - 350.0	± 2.0 C

The computer model of the V-320 plant, which has been used in the both compared calculations, incorporates 4 separate primary coolant loops, steam generators and main steam lines up to their connection points to turbines. Each fuel assembly of the core model has its own hydrodynamic channel within 60-degree sector of symmetry. The total number of the modeled core hydrodynamic channels, including 8 radial reflector channels, is 36. At the elevation level of the hot leg nozzles the upper plenum has been symmetrically divided into two equal volumes without direct exchange of coolant between them. Within each of these two volumes the mixing of coolant is assumed to be ideal. The dynamic pump models of ATHLET and RELAP5 are applied to simulate hydraulic behavior of the MCPs. This model describes MCP by the empirical set of homologous curves. The homologous pump characteristics employed in both validation calculations correspond to those defined in the NEA VVER-1000 Coolant Transient Benchmark [6]. The operation of feedwater pumps is modeled as time-dependent boundary conditions, using corresponding experimental data.

There are two differences in the models of reactor plant used in DYN3D-ATHLET and DYN3D-RELAP5 calculations. The first difference concerns axial nodalization of the core hydrodynamic channels. The core models of DYN3D-ATHLET and DYN3D-RELAP5 codes utilize 20 and 11 hydrodynamic axial nodes, respectively. Each nodalization includes two axial reflector layers - the top and the bottom reflectors of the core. The number of the fuel (neutronic) axial nodes is the same in compared calculations and equals 18.

The second difference concerns macroscopic cross-section libraries used in compared calculations. VVER-1000 cross-section library generated by the NESSEL code is used in the DYN3D-ATHLET simulation, whereas the library for the DYN3D-RELAP5 simulation is generated by WIMS. The libraries are also differing in the cross-section approximation techniques.

4. COMPARISON OF RESULTS

Prior to the transient simulations, the calculations of fuel burn up distribution in the core have been performed at 171.6 FPD using the stand-alone DYN3D code. Then, the initial state of the plant and the MCP coast down transient has been simulated by the coupled code systems.

Comparisons of the initial (steady-state) and final parameters of the reactor plant are presented in the Tables 5 to 6 and in the figures 1 and 2. Close predictions of the normalized radial power distributions are given by the coupled codes. The maximum discrepancy in calculated values of the normalized FA powers does not exceed 1.5% for both initial and final states of the core. A good agreement is achieved between the calculated and measured values of the FA maximum power (marked by asterisks in Table 5).

Table 5. Comparison of calculated normalized radial power distributions

a) initial state

MEASUREMENT
8
1.2300*

FA no.	**28**						
DYN3D-ATHLET	0.6734						
DYN3D-RELAP5	0.6856						
FA no.	**26**	**27**					
DYN3D-ATHLET	1.1364	0.8217					
DYN3D-RELAP5	1.1310	0.8318					
FA no.	**23**	**24**	**25**				
DYN3D-ATHLET	1.2248	0.9715	0.8475				
DYN3D-RELAP5	1.2132	0.9641	0.8569				
FA no.	**19**	**20**	**21**	**22**			
DYN3D-ATHLET	1.0049	1.0060	1.1473	0.8478			
DYN3D-RELAP5	1.0001	0.9962	1.1433	0.8572			
FA no.	**14**	**15**	**16**	**17**	**18**		
DYN3D-ATHLET	1.0036	0.9827	1.0065	0.9722	0.8223		
DYN3D-RELAP5	1.0066	0.9789	0.9967	0.9649	0.8324		
FA no.	**8**	**9**	**10**	**11**	**12**	**13**	
DYN3D-ATHLET	1.2191	1.0037	1.0053	1.2260*	1.1372	0.6737	
DYN3D-RELAP5	1.2310*	1.0066	1.0006	1.2145	1.1318	0.6860	
FA no.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
DYN3D-ATHLET	0.9965	1.0232	1.0253	1.1488	1.0310	1.0385	1.0002
DYN3D-RELAP5	1.0065	1.0323	1.0321	1.1517	1.0226	1.0259	1.0050

b) final state

MEASUREMENT
8
1.2000*

FA no.	**28**						
DYN3D-ATHLET	0.6698						
DYN3D-RELAP5	0.6781						
FA no.	**26**	**27**					
DYN3D-ATHLET	1.1280	0.8168					
DYN3D-RELAP5	1.1196	0.8228					
FA no.	**23**	**24**	**25**				
DYN3D-ATHLET	1.2204	0.9668	0.8425				
DYN3D-RELAP5	1.2088	0.9574	0.8481				
FA no.	**19**	**20**	**21**	**22**			
DYN3D-ATHLET	1.0102	1.0057	1.1408	0.8428			
DYN3D-RELAP5	1.0080	0.9962	1.1345	0.8484			
FA no.	**14**	**15**	**16**	**17**	**18**		
DYN3D-ATHLET	1.0130	0.9879	1.0061	0.9675	0.8173		
DYN3D-RELAP5	1.0201	0.9866	0.9966	0.9581	0.8234		
FA no.	**8**	**9**	**10**	**11**	**12**	**13**	
DYN3D-ATHLET	1.2279*	1.0130	1.0106	1.2215	1.1288	0.6702	
DYN3D-RELAP5	1.2453*	1.0202	1.0084	1.2101	1.1204	0.6785	
FA no.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
DYN3D-ATHLET	1.0065	1.0326	1.0355	1.1636	1.0337	1.0336	0.9922
DYN3D-RELAP5	1.0213	1.0465	1.0472	1.1731	1.0271	1.0200	0.9929

* maximum values

Table 6. Comparison of reactor steady-state parameters

Parameter	Measurement		DYN3D-ATHLET		DYN3D-RELAP5	
	Initial state	Final state	Initial state	Final state	Initial state	Final state
Core power, MW	1949	1530	1947	1510	1955	1506
Boron acid concentration, g/kg	3.150	3.150	2.980	2.980	3.235	3.235
Upper plenum pressure, MPa	15.71	15.61	15.72	15.69	15.73	15.67
Cold leg 1 temperature, °C	287.5	287.8	285.2	286.3	286.2	285.8
Cold leg 2 temperature, °C	285.0	288.4	282.7	285.5	283.1	285.4
Cold leg 3 temperature, °C	284.4	287.9	284.8	286.3	285.0	285.8
Cold leg 4 temperature, °C	287.0	288.1	286.4	287.1	285.6	286.3
Hot leg 1 temperature, °C	315.0	278.2	311.4	274.9	311.3	274.9
Hot leg 2 temperature, °C	304.5	312.5	300.5	308.9	303.4	309.4
Hot leg 3 temperature, °C	277.0	276.7	279.2	278.6	278.1	276.9
Hot leg 4 temperature, °C	312.6	310.4	311.4	312.1	311.3	311.4
Loop 1 mass flow rate, kg/s	5168	-1038	4970	-1015	4898	-1006
Loop 2 mass flow rate, kg/s	5142	5500	5013	5251	4955	5244
Loop 3 mass flow rate, kg/s	-1570	-1015	-1603	-1044	-1569	-1003
Loop 4 mass flow rate, kg/s	5245	5667	5064	5327	4905	5229
Main steam header pressure, MPa	5.923	5.923	5.924	5.918	5.923	5.917
SG 1 pressure, MPa	6.051	5.874	6.016	5.896	5.969	5.906
SG 2 pressure, MPa	5.962	6.090	5.963	6.002	5.949	5.966
SG 3 pressure, MPa	5.884	5.913	5.923	5.916	5.920	5.912
SG 4 pressure, MPa	6.051	6.110	6.012	6.019	5.971	5.971
Pressure difference in MCP 1, kPa	472.7	61.8	476.7	59.5	481.3	60.4
Pressure difference in MCP 2, kPa	456.0	374.6	460.8	395.6	480.5	417.4
Pressure difference in MCP 3, kPa	162.8	61.8	148.1	63.0	147.0	60.1
Pressure difference in MCP 4, kPa	478.6	372.7	482.6	420.1	481.9	418.2

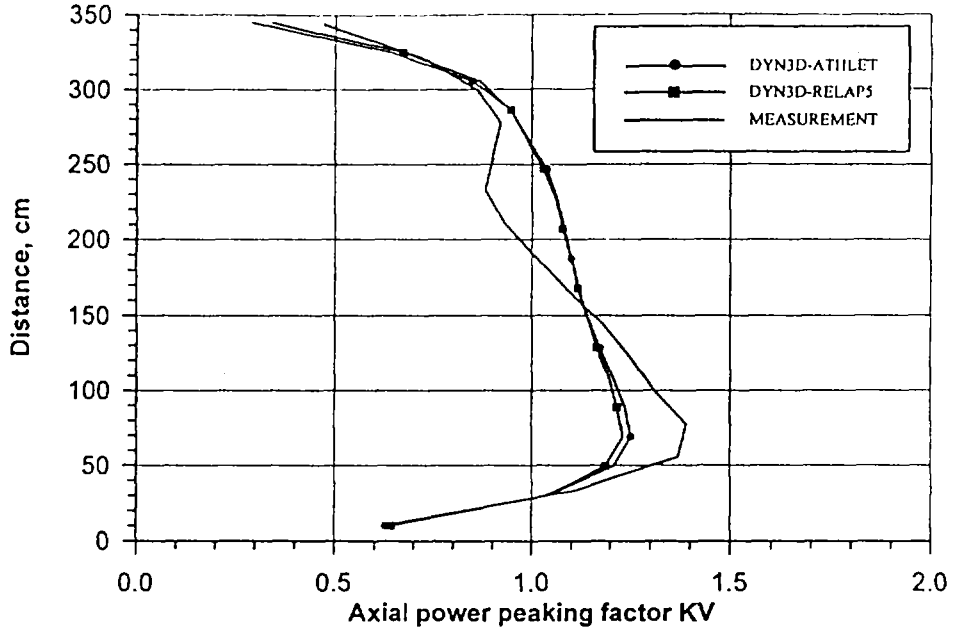

Fig.1 Normalized axial distribution of neutron power (initial state)

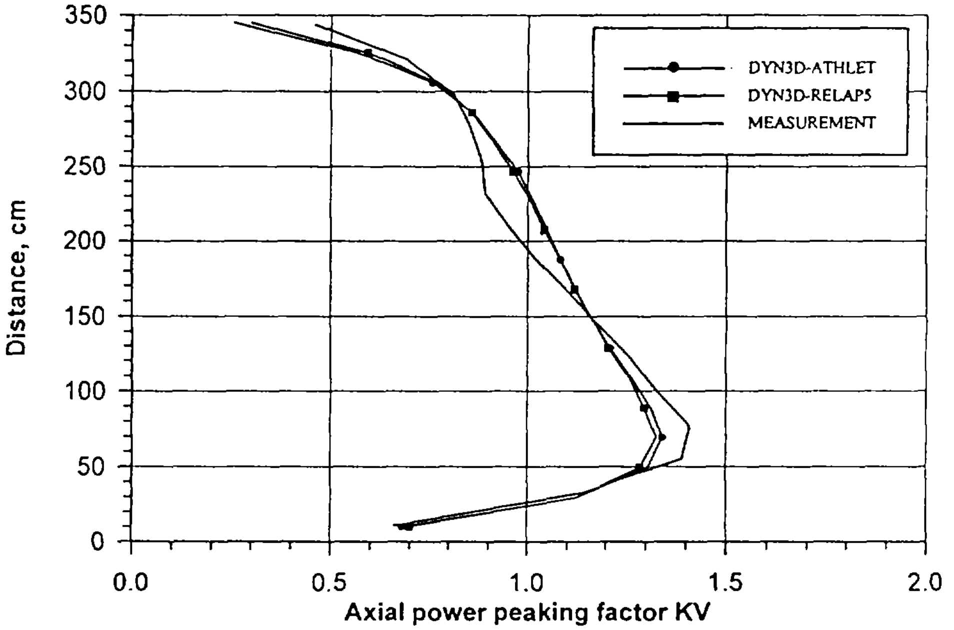

Fig.2 Normalized axial distribution of neutron power (final state)

The deviations in this parameter are much less than 1% for the initial state and don't exceed 3.8% at the end of the transient. Both codes correctly predict the location of the maximum power assembly within the core at the final state (FA no. 8), but differ in the predictions on the initial location. For the initial state the fuel assembly's numbers predicted by the DYN3D-RELAP5 and DYN3D-ATHLET code systems are 8 and 11, respectively. The values of normalized power for these assemblies are very close in the DYN3D-ATHLET calculation. The application of different cross-section libraries as well as different thermal-hydraulic models in compared calculations can explain the discrepancy in the initial location of the "hot" fuel assembly.

Both above-mentioned factors are also responsible for a difference between calculated values of the critical boron concentration in the primary coolant, which are compared in Table 6. Most of the initial thermal-hydraulic parameters presented in this table are in a satisfactory agreement with the corresponding plant data, i.e. their discrepancies lay within the ranges of the measurement errors.

Normalized axial power distributions at the beginning and the end of the simulated transient are shown in figures 1 and 2. A code-to-code comparison for both initial and final axial power profiles demonstrates a very close agreement, whereas a better agreement with the plant data is achieved for the final state. Profiles of the normalized axial power have been calculated by the coupled code systems assuming equilibrium distributions of the Xe and Sm concentrations in the core, while at the starting point of the real plant transient they were not strictly equilibrium.

300 seconds of the transient have been simulated using DYN3D-ATHLET and DYN3D-RELAP5 coupled code systems. Figures 3 to 7 show a code-to-code comparison of the most representative simulation results and their validation against the plant measurements.

Figure 3 shows a decreasing of the reactor power due to the movement of the control rod group No. 10 in the core. The calculated neutron powers demonstrate a rather good agreement with the measured data. Differences in the employed cross-section libraries, core hydrodynamic nodalizations and thermal-hydraulic models used in compared simulations do not cause noticeable deviation between the neutron power predictions. Only two measured values of the power are available for comparison starting from the 80-th second of the transient.

A realistic behavior of the calculated hot leg temperatures (fig. 4) confirms validity of the chosen upper plenum nodalization. Predicted temperatures are in a close agreement with the experimental data except the hot leg temperature at the 1st reactor loop. Obtained results of calculations have not been filtered by a low-pass filter to model a real thermocouple measurement. As reported in /Mit00/, it is the main reason for the observed deviations between the calculated and measured temperatures at the 1st loop.

The dynamic pump models of the system codes provide adequate simulation of the operating and switched off main coolant pumps, which is proofed by the comparison of calculated and measured pump pressure differentials (fig. 5). More accurate results have been obtained for the stopped main coolant pumps of the 1st and the 3rd primary loops. Nearly the same value of the 1st MCP coastdown duration (about 115 seconds) was predicted by both coupled code systems.

Figure 6 represents a comparison of the primary coolant pressure in the reactor upper plenum. Caused by the MCP coastdown, the primary pressure starts to increase at the 40th second of the transient and reaches the maximum value in the interval between the 60th and the 80th seconds. A lower primary pressure is predicted by the DYN3D-RELAP5 code system during the whole simulation. It can be explained by a higher heat transfer rate and, as a consequence, a higher rate of steam production in steam generators of the 2nd and 4th working loops (fig. 7). Measured data are not available for these parameters.

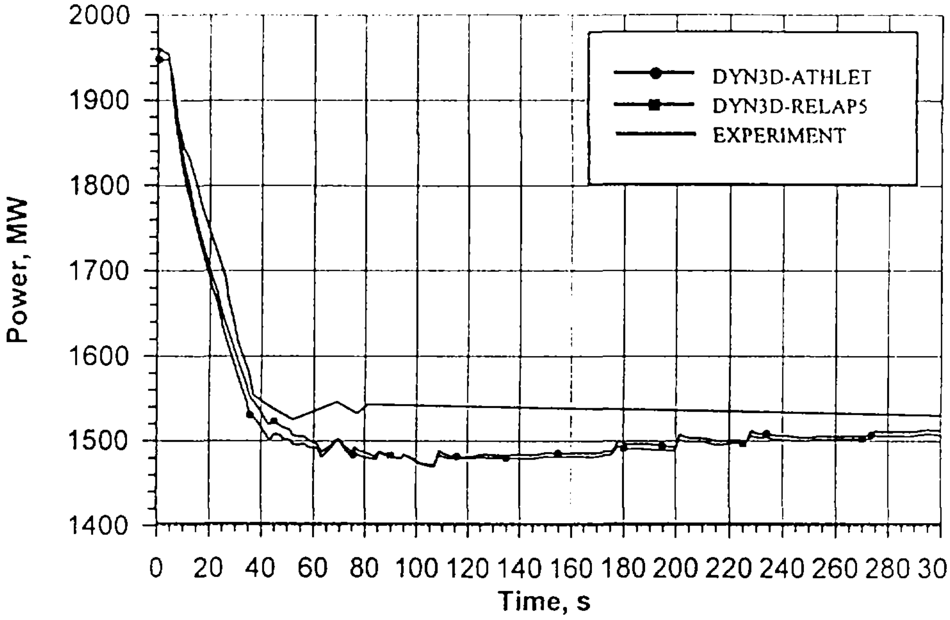

Fig. 3 Neutron power

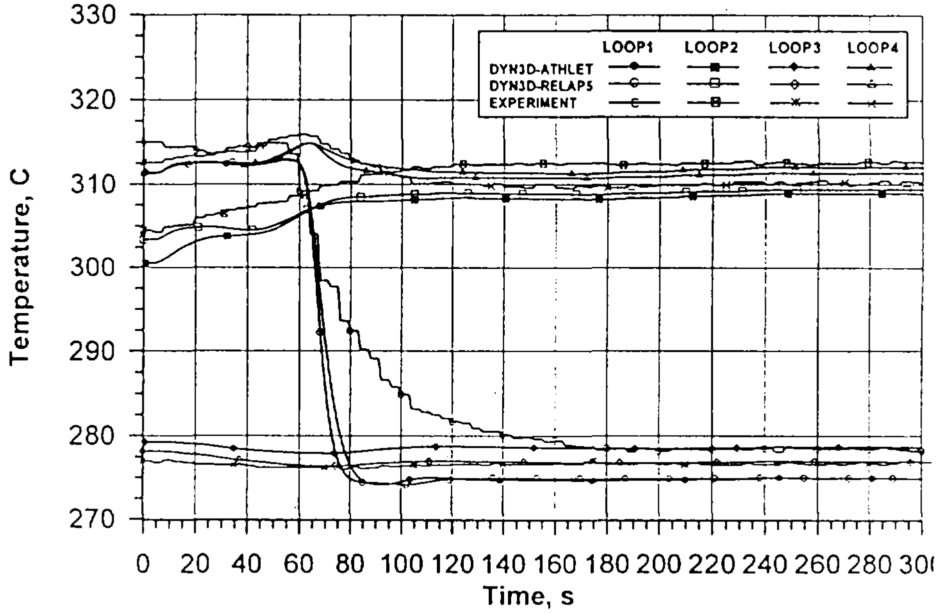

Fig. 4 Hot leg temperatures

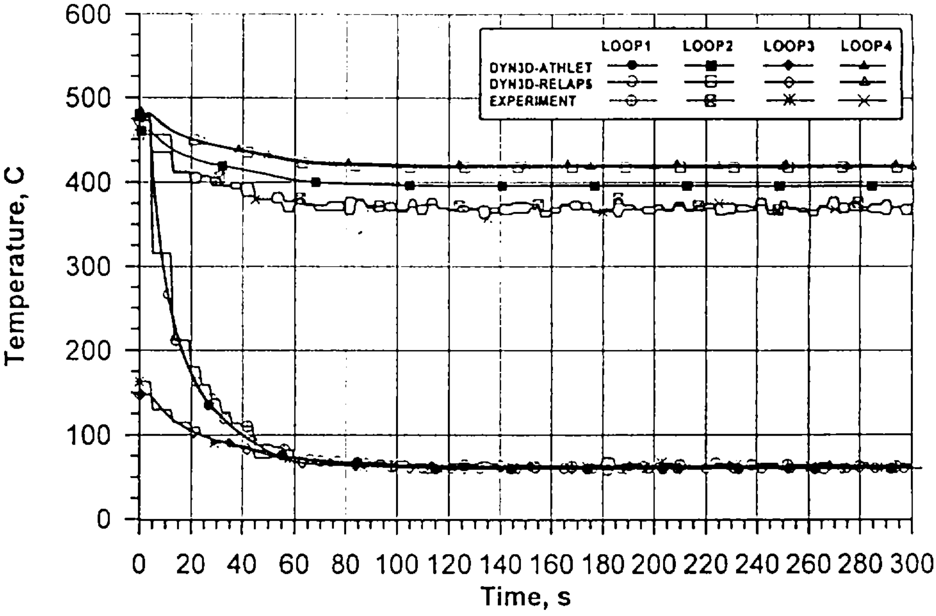

Fig. 5 Pressure drop over coolant pumps

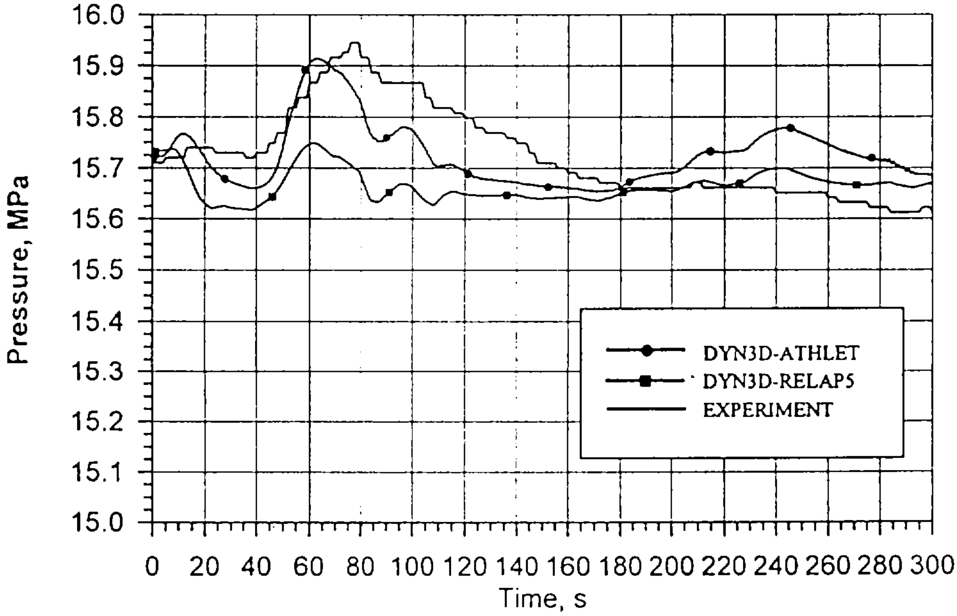

Fig. 6 Upper plenum pressure

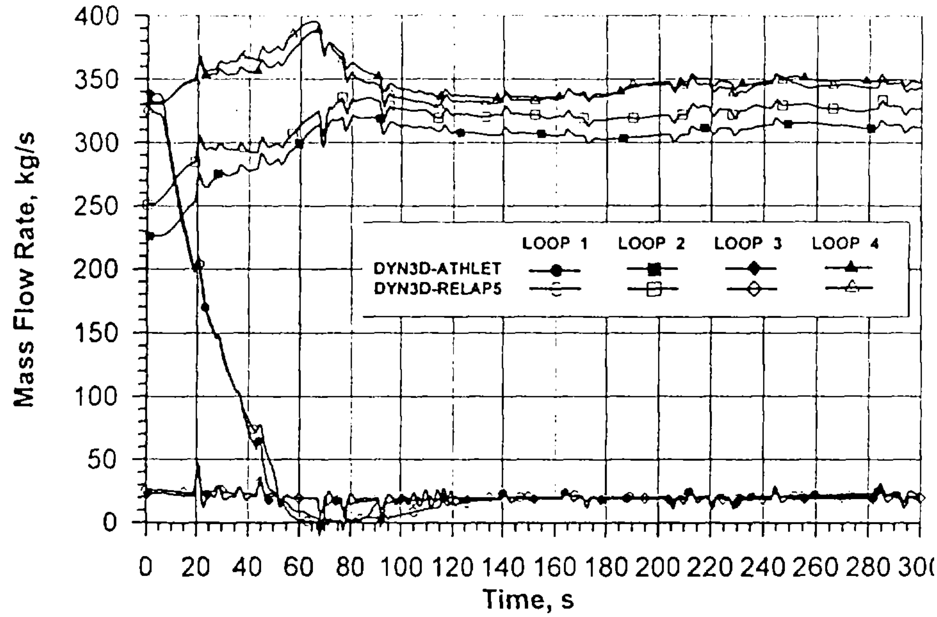

Fig. 7 Main steam line mass flow rate

CONCLUSIONS

The Kozloduy-6 VVER-1000 start-up experiment was analyzed by the DYN3D-ATHLET and DYN3D-RELAP5 coupled code systems. In this experiment one of the three initially operating main coolant pumps was switched off and the reactor power reduced due to a relocation of the control rod group. It was the first simulation of a real plant transient conducted by the internally coupled DYN3D-RELAP5 code system and aimed at its validation. Both a validation against experimental data and code-to-code comparison between calculated results was performed using two coupled code systems.

Except the differences in the axial nodalization of the core hydrodynamic channels and in the employed libraries of macroscopic cross-sections, the same computation models of the reactor plant were utilized in the compared simulations. An important role of the upper plenum nodalization in prediction of the cold and hot leg temperatures was shown. The loop temperatures depend on the efficiency of the primary coolant mining in the reactor upper plenum. Both code systems produced satisfactory predictions of the measured transient parameters. A close agreement between calculated results was demonstrated.

As the next step in validation of the presented coupled code systems, a simulation of the VVER-1000 coolant transient benchmark (V1000CT-1) will be carried out. This exercise, as the previous one, is based on the real Kozloduy-6 experiment.

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