Analyses of the MSLB Benchmark V1000CT-2 by the Coupled System Code ATHLET-BIPR8KN

Sergey P. Nikonov [1], Siegfried Langenbuch[2], Michael P. Lizorkin[1], Kiril Velkov[*2]
[1] *RRC KI, 123182 Moscow, Russia*
[2] *GRS mbH, 85748 Garching, Germany*

Abstract

Within the activities of OECD/NEA is being initiated the second phase of the VVER-1000 Coolant Transient Benchmark (V1000CT-2). It considers the best estimate analyses of a Main Steam Line Break (MSLB) of a VVER-1000 NPP with two exercises. The analyses have been performed with the coupled system code ATHLET-BIPR8KN which enables to perform realistic simulation of three-dimensional neutron kinetics and thermal-hydraulic processes in VVER NPP. Results are presented and analysed for the two proposed scenarios. These results are supplemented by sensitivity studies varying the number of the thermo-hydraulic channels (THC) in the core and by comparisons with point kinetics calculations. This work is of considerable importance for the validation of the coupled system code ATHLET-BIPR8KN in case of asymmetric core inlet conditions.

KEYWORDS: VVER-1000, MSLB, ATHLET-BIPR8KN, Coupled Code

1. Introduction

All exercises of the V1000-CT Benchmark address the problems of flow mixing in the reactor pressure vessel. The main objective of the best-estimate MSLB analysis (Exercise 3) is to compare code-to-code simulation results for coupled 3D kinetics/thermal-hydraulics system codes after they have been checked on real plant measured data with non-uniform loop flow mixing in the reactor vessel which is done within the previous activities of Phase 1 [1] and Exercise 1 of Phase 2 [2]. Basic NPP data is taken from the Bulgarian Kozloduy Nuclear Power Plant Unit 6 where special experiments have been performed to study the mixing of coolant flows in the reactor vessel of a VVER-1000 V320. The V1000CT-2 MSLB transient is determined by a double break of a main steam line (MSL) between the steam generator (SG) and the steam isolation valve, outside the containment and it causes a very strong asymmetric cooling of the core. Two scenarios are defined: the first one is near to the current licensing practices and aims to maximise the consequences for a return to criticality, and the second one - considered as pessimistic one - is derived by additional conservative assumptions to enhance code-to-code comparisons.

2. Coupled code system ATHLET-BIPR8KN

The thermal-hydraulic system code **ATHLET** (**A**nalysis of **TH**ermal-hydraulics of **LE**aks and **T**ransients) is being developed by the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH for the analysis of the whole spectrum of leaks and transients in PWRs and BWRs [3]. The code is applicable for western LWR designs as well as for Russian VVER and RBMK reactors. The main code features are the advanced thermal-hydraulics, the modular code architecture, especially the separation between physical models and numerical methods,

[*] Corresponding author, Tel. +498932004428, Fax.+498932004599, E-mail: vek@grs.de

the pre- and post-processing tools, and the portability to the prevalent computer platforms.

The computer code for 3D neutron kinetics **BIPR8KN** [4] is being developed in the Department of Physics in the NRI RRC KI. The code calculates the core power and 3D neutron flux distribution versus time caused by reactivity perturbation of different nature, e. g. control rods movement or propagation of cold or unborated water slug in the core, taking into account two prompt neutron energy groups and six delayed neutron groups including feedback effects.

Both codes have been coupled through an universal interface build in the system code ATHLET applying the method of internal coupling [5].

3. Initial and boundary conditions of the benchmark

The following conservative assumptions have been defined: The reactor core is at the end of cycle 8 (EOC) and 3000 MW hot full power (HFP). All integral plant parameters (pressure, temperatures, mass flows …) correspond to the nominal reactor power state. The automatic power controller and all limitation controllers are in operation. Steam dump to condenser (BRU-K) and house loads are supposed to operate, also the steam dump for internal load (BRU-CN) is available. The pressurizer (PRZ) volume control system and high and low pressure injection systems (HPIS and LPIS) are available. No credit of HPIS boron reactivity insertion is considered. The SG inventory is near the maximum value. The two most efficient control rods remain stuck out of the core (assumed to be in the affected sector). The total control rod scram worth is reduced supposing that one control bank does not drop into the core. The feed water pumps fail to trip (control valve sticks in open position) after receiving the trip signal, but the main feed water flow to the affected SG-4 is terminated by a closure of the feed water isolation valve. The off-site electric power is available.

The reactor core is operated with a three-year core loading and is modelled with the real geometrical and neutron-physics characteristics of all 163 fuel assemblies. Burnable absorbers are used in 54 fuel assemblies. The macroscopic cross section libraries for all available fuel assembly types are generated with an own spectral code system developed for BIPR8KN code. The reflector composition is described with diffusion parameters and zero flux on the outer surface.

The transient is initiated by a break of the MSL, D580 mm, 25 m away from SG-4 location. Scram takes place in 0.3 sec after the steam line break signal is detected; turbine trip starts 10s after the scram signal. In Scenario 1, a trip of the main circulation pump (MCP) of the affected loop is assumed, the other three MCPs remain in operation. In Scenario 2, all MCPs remain in operation and additionally the scram worth is reduced. This is achieved by increasing the number of control rods remaining stuck at the core top. The simulation time is 600s.

4. Nodalization

The NPP nodalization scheme, the applied core mapping schemes and the modelling details of the reactor pressure vessel, primary and secondary sides of the Kozloduy NPP are described in details in [6]. Neutronically the core is always modelled 1:1 (one node per assembly in X-Y plane). Thermal-hydraulically calculations have been performed with 163 thermal-hydraulic channels (THC) (1:1 mapping) for the core without cross flows (CF) and with 7 THC in the core (6 at the periphery and one at the centre) - once with and once without cross flows. For all cases, reactor vessel downcomer is modelled with 6 THC with cross flows. Point kinetics core calculations are also performed for comparison.

5. Discussion of the results

A zero transient calculation of one thousand sec is performed in order to reach a stable steady state initial condition for the whole NPP. The power histories of both scenarios are presented in Fig.1 and the pressure histories in Fig.2. The transient is determined by the following events' and control signals' sequence: With the opening of the MSL break at 0s a signal is generated for further opening of the feed water control valve (requirement of the specification) and another one of closing the feed water isolation valve. At 0.052s the difference of coolant saturation temperature between the primary and secondary sides reaches 75^{o}C. The pressure decreases very fast in the steam line (SL) of the SG-4 below 4.9 MPa and coolant temperature in the primary side stays higher than 200^{o}C. Reaching of these three set points causes the following three actuations of the safety system: closing of the fast isolation valve on steam line of SG-4; generation of the so called 'NPP protection signal' and switching off the make-up system.

At 0.07s the pressure in SL-4 decreases below 4.4 MPa which leads, in case of Scenario 1, to MCP-4 trip. In case of Scenario 2 MCP-4 stays in operation. After this time the two scenarios have different time histories of the main parameters.

The Scenario 2 is discussed in more detail, it continues in the following way: At 0.363s a scram signal of protection level 1 is generated and the control rods start to move downwards with a delay of 0.3s; at 1.045s the check valve of SL-4 is closed. Due to the constant decrease of primary pressure, PRZ heaters number 1,2,3 and 4 are switching on respectively at 1.83s, 2.29s, 2.85s and 3.46s. At 7s after the break time, a rise of power occurs and 46% return to power is reached at 45s (see Fig.1). At approximately 10s are closed the fast isolation valve in SL-4 and the turbine stop valve with delay of 10s. At the same time the steam dump for internal loads starts to open. At 12.27s the auxiliary feed water pumps are turned on due to water level lower than 100 mm detected in SG-1,2,3 and coolant temperature in the primary side greater than 150^{o}C. Steam dump to condenser (BRUK) opens at 18.61s due to the rise of pressure in the steam collector above the set point of 6.67 MPa. At 30.06s (30s delay after generation of the 'NPP protection signal') are starting the HPIPs. The processes stabilise after about 580s when the PRZ heaters number 4 and 3 are switching off sequentially.

Additional analyses have been performed for both scenarios in order to study the influence of the number of parallel THCs in the core. In addition to the 1:1 mapping schema, two more calculations with the coupled code have been performed with 7 THC in the core region (6 THC at the periphery and 1 in the central part) with and without cross flows. Results of BIPR8KN are compared also with point kinetics calculations.

Comparisons of the transient results for the cold and hot legs' temperatures of Scenario 2 are presented in Fig.3-Fig.10. It can be seen that the temperature differences of the hot and cold legs for the case with 7 THC with and without cross flows are negligible. The reason for this is that each of THC in the core is very big and comprises many assemblies with different power generating properties but only a mean value results for the reactivity feedback parameters which do not differ considerably compared with the neighbouring THC values. The pressure differences between the THCs at different core axial levels remain very small and thereby the cross flow driving force is also very small. Compared to the 7 THC results, this is not the case for results obtained with a 1:1 schema and/or PK. The difference in cold leg temperature prediction reaches 3.5^{o}C between models with 7 and 163 THC (Fig.3-Fig.6) and it is even higher (5^{o}C) for the hot legs (Fig.7-Fig.10). The differences are even much higher comparing the 163 THC schema with PK (13^{o}C respectively 15^{o}C for the hot leg). Comparing the maximum local fuel temperatures in case of 1:1 mapping and 7 THC, a difference of 85^{o}C is observed in the affected part of the core. The influence of the numbers of parallel THC in the core on the results can be seen best in Fig. 11 where the power histories for all calculations are compared. The return to power peak is highest by the model with 7

THC and lowest in the case of PK presentation of the core.

Contrary to Scenario 2, in case of Scenario 1 no return to power is observed (Fig.1). Comparison of reactor power history for different core mapping schemes (Fig. 12) shows very small differences. The same small differences are observed for the hot and cold leg coolant temperatures.

All results presented in this paper are performed with a realistic mixing model of ATHLET code on the base of a coarse mesh nodalization of the reactor pressure vessel (6 THC in the downcomer, lower and upper plenums and 7 THC in the active core). Some additional studies, presented in [7], showed that the way of modelling (finer mesh nodalization) of the fluid mixing in the down comer, upper and down plenums can affect additionally strongly the transient parameter histories.

6. Summary

The paper describes the results of the coupled system code ATHLET-BIPR8KN for the MSLB cases of the OECD/NEA V1000-CT2 Benchmark. The ATHLET-BIPR8KN model developed for the VVER-1000 Unit 6 in Kozloduy NPP is able to represent correctly the overall plant response. In case of Scenario 2 (MCP-4 remains in operation) a return to power is observed, while in Scenario 1 (MCP-4 trips) no return to power occurs. Additional studies were performed to determine the importance of the core mapping schemes on the integral and local NPP parameters. It is concluded that a 1:1 mapping scheme should be applied for a precise prediction of transient parameter values. Application of cross flows to describe the mixing flow phenomena in the reactor pressure vessel is of great importance. By reasonable number of THCs in the core and strong asymmetries at its inlet, cross flows should be modelled to describe correctly the in-core mixing. Additional developments are going on to study the influence of a more detailed modelling of the reactor downcomer, lower and upper plenum on the accuracy of the simulated transient.

The benchmark is an important contribution to the validation of the coupled system code ATHLET-BIPR8KN in case of asymmetric core inlet conditions.

References

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Fig.1 Power history for the both scenarios

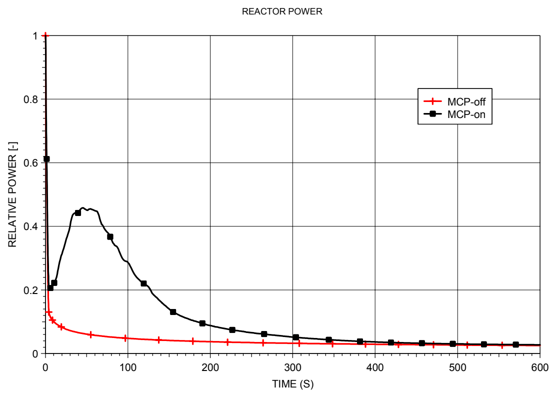

Fig.2 Primary pressure for the both scenarios

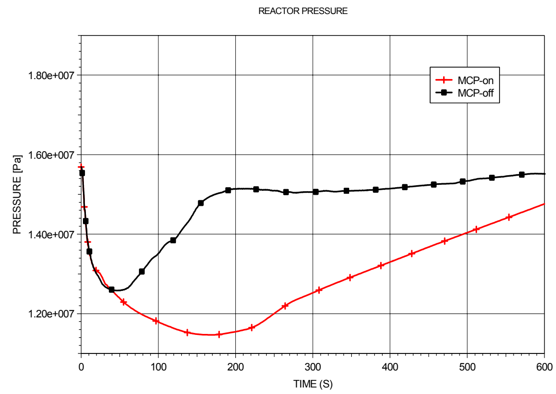

Fig. 3 Comparison of cold leg #1 coolant temperature in case of 163 THC, 7THC with and without CF and point kinetics

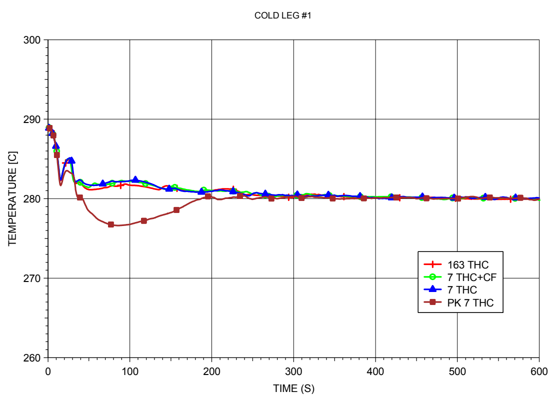

Fig. 4 Comparison of cold leg #2 coolant temperature in case of 163 THC, 7THC with and without CF and point kinetics

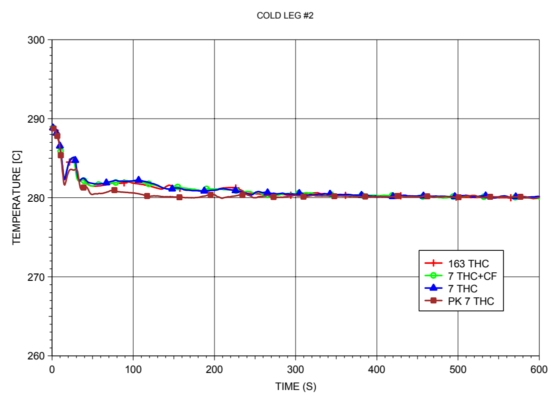

Fig. 5 Comparison of cold leg #3 coolant temperature in case of 163 THC, 7THC with and without CF and point kinetics

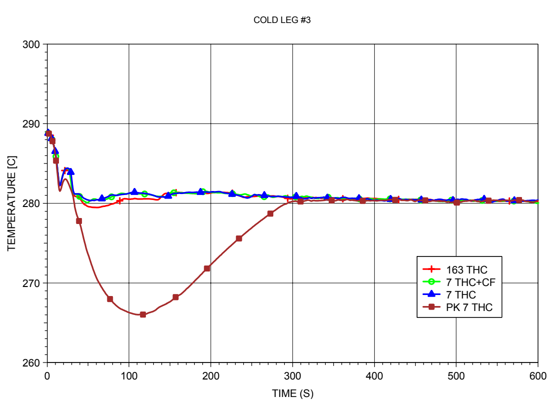

Fig. 6 Comparison of cold leg #4 coolant temperature in case of 163 THC, 7THC with and without CF and point kinetics

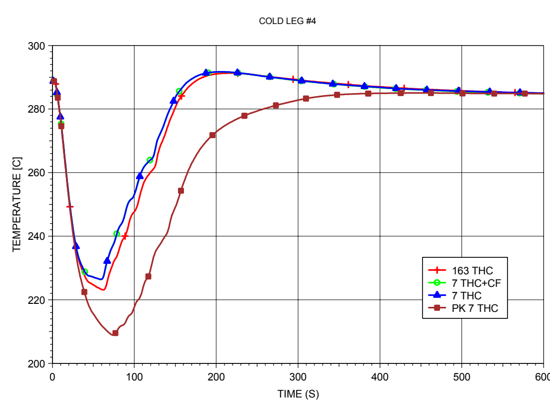

Fig. 7 Comparison of hot leg #1 coolant temperature in case of 163 THC, 7THC with and without CF and point kinetics

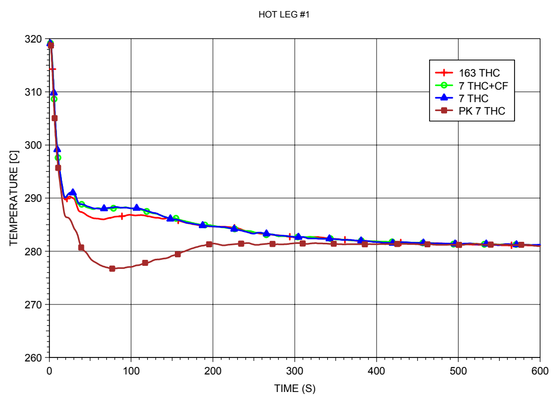

Fig. 8 Comparison of hot leg #2 coolant temperature in case of 163 THC, 7THC with and without CF and point kinetics

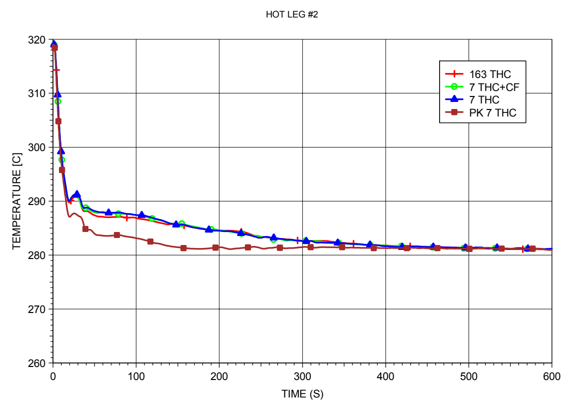

Fig. 9 Comparison of hot leg #3 coolant temperature in case of 163 THC, 7THC with and without CF and point kinetics

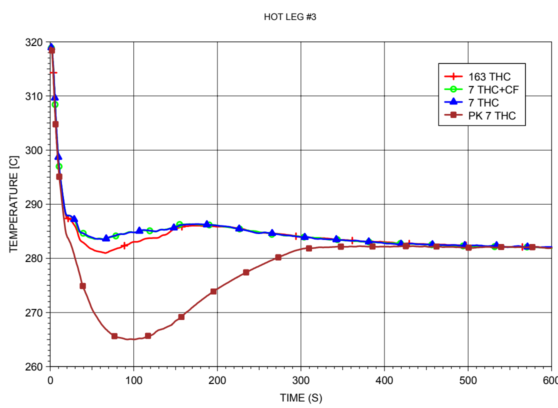

Fig. 10 Comparison of hot leg #4 coolant temperature in case of 163 THC, 7THC with and without CF and point kinetics

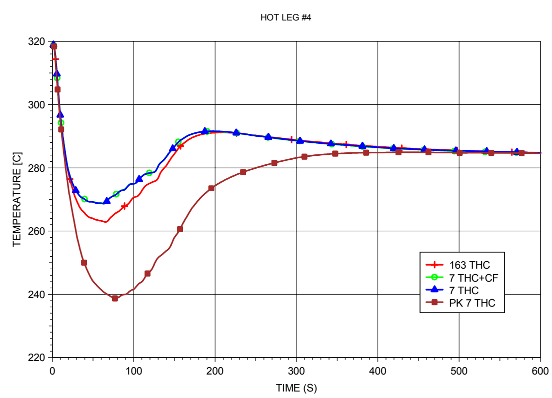

Fig. 11 Comparison of power histories for scenario #2 in case of 163 THC, 7THC and without CF and point kinetics

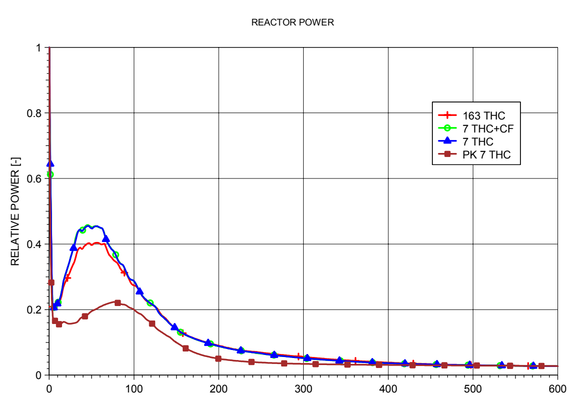

Fig. 12 Comparison of power histories for scenario #1 in case of 163 THC, 7THC with with and without CF and point kinetics