CEC PHARE PROJECT SRR1/95: IMPROVEMENT OF THE VERIFICATION OF COUPLED THERMOHYDRAULICS / NEUTRON KINETICS CODES

DYN3D BURNUP AND STEADY STATE CALCULATIONS

Sören Kliem, Siegfried Mittag, Ulrich Rohde, André Seidel, Frank-Peter Weiß

1. Introduction

The Commission of the European Community (CEC) has been funding projects aimed at a long-term collaboration in the field of reactor safety research and technology between the EU member states and East European countries within the PHARE programme. PHARE originally meant: **P**oland and **H**ungary - **A**ssistance in the **R**econstruction of the **E**conomy, but the programme was later extended to assist other East European countries, too.

The principal objective of the **S**afety **R**elated **R**esearch project SRR1/95 was the verification of those coupled thermal-hydraulics - neutron kinetics codes, that are currently used for modelling the behaviour of the Russian pressurized water reactors VVER during transients and accidents. The simulation of transient processes and the comparison of the results obtained by coupled codes with measured transient data is of particular interest. The higher the degree of code validation, the more reliable will be the analyses of possible abnormal states in the NPP, and the better is the safety assessment of these reactors.

This report provides a survey of the project participants, the codes to be validated and the measured NPP data, that have been documented for code validation. Prior to the transient calculations, the stationary core state from which the transient started has to be calculated. The comparison of the measured steady-state parameters to the calculated values was the first step of code validation. Only after that, transient simulations should be carried out.

2. International Project Team

The project work was performed by a Consortium consisting of Forschungszentrum Rossendorf e.V. (FZR) Germany, VTT Energy (Finland), Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Germany and AEA Technology, UK, the Contractor FZR being the leading company.

The Nuclear Research Institute (NRI) Řež (Czech Republic), Atomic Energy Research Institute Budapest, (AEKI), Russian Research Center "Kurchatov Institute" Moscow (KI), Scientific & Technical Centre on Nuclear and Radiation Safety Kiev (STCNRS), and the Institute of Nuclear Research and Nuclear Energy Sofia (INRNE) were the East European Subcontractors in the project, Imatran Voima (Fortum) Oy (IVO) Power Engineering Ltd., Finland was a direct Subcontractor of VTT Energy.

The Consortium brought together organisations that have been at the forefront of thermal-hydraulics and neutron kinetics code development and application for many years. The chosen Subcontractors were able to provide transient data measured in operating VVERs.

3. Codes

In the Institute for Safety Research of FZR, the code DYN3D has been developed and coupled to the thermal-hydraulics code ATHLET developed by GRS [1]. DYN3D is a three-dimensional two-group nodal neutron kinetics code that is widely used for VVER core analyses in Eastern Europe. The code was transferred to Bulgaria, the Czech Republic, the Slovak Republic, and the Ukraine in the framework of an IAEA project. The coupled code system ATHLET-DYN3D is also being transferred to the countries mentioned.

KI has developed the three-dimensional two-group neutron kinetics code BIPR8 [2]. This code and earlier versions of it are used in Russian NPP operating VVER. KIKO3D [3] is a similar code, developed by AEKI. Both neutron kinetics code have been coupled to ATHLET.

VTT developed the thermal-hydraulics / neutron kinetics (three-dimensional, two groups, nodal expansion method) code system SMABRE / HEXTRAN [4,5]. VTT has been applying the code system to the Finnish VVER-440 reactors.

4. NPP transients

The following transients (experiments) have been provided by the Subcontractors and documented for code validation [6]:

VVER-440:

- Drop of the power of one of the two turbo-generators from full power down to house load level (Loviisa-1, documented by IVO),
- Coast-down of three of six working main coolant pumps at 55 % of nominal power (Dukovany-2, documented by NRI),

VVER-1000:

- Failure of one of the two working feed water pumps at nominal power (Balakovo-4, documented by KI),
- Drop of the turbo-generator power from nominal value down to house load level (Zaporoshye-6, documented by STCNRS),
- Coast-down of two from four working main coolant pumps at 90 % of nominal power (Kozloduy-6, documented by INRNE).

For each reactor type, the first-mentioned transient has been chosen for the code validation in the framework of the current project. The remaining transient files are available to later validation work.

5. The Loviisa-1 VVER-440 transient

5.1 Transient description

The transient was initiated by the load drop of one turbo-generator, i. e. the electric power output of the plant was suddenly reduced by half [7]. At the moment of generator drop, the nuclear power production in the reactor core was still at 100 %. Shortly after transient initiation, the reactor control system started to reduce the reactor power by inserting the group number six of the neutron-absorbing control assemblies. Thus neutron power was reduced down to 60 % within some 100 seconds. As a result of power reduction, the hot leg temperatures of the primary circuit decreased. Moreover, the cooling of the primary circuit by the steam generator is reduced because of the increasing steam pressure at the secondary side. Therefore, the cold leg temperature first increased significantly. Some 20 seconds later this temperature also started decreasing. The primary circuit pressure first increased, too, but was quickly reduced by spraying in the pressurizer. Later on, the reducing nuclear power decreased the pressure, so that the pressurizer heaters were switched on to stabilize pressure at its nominal level. On the secondary side, pressure also started increasing sharply, but was quickly brought back to normal by opening the turbine bypass valves, before the dropping nuclear power took effect here, too.

5.2 Burnup and steady-state calculations

The described transient was measured in the 21st cycle of the Loviisa-1 VVER-440. The burnup distribution at the beginning of cycle 19 was provided by IVO together with the shuffle schemes and operation history up to the start of the transient. Each participant in the validation carries out his own burnup calculation to get the actual burnup distribution and the steady-state reactor parameters as an input for the transient calculation. Only FZR (DYN3D) results will be presented in this report.

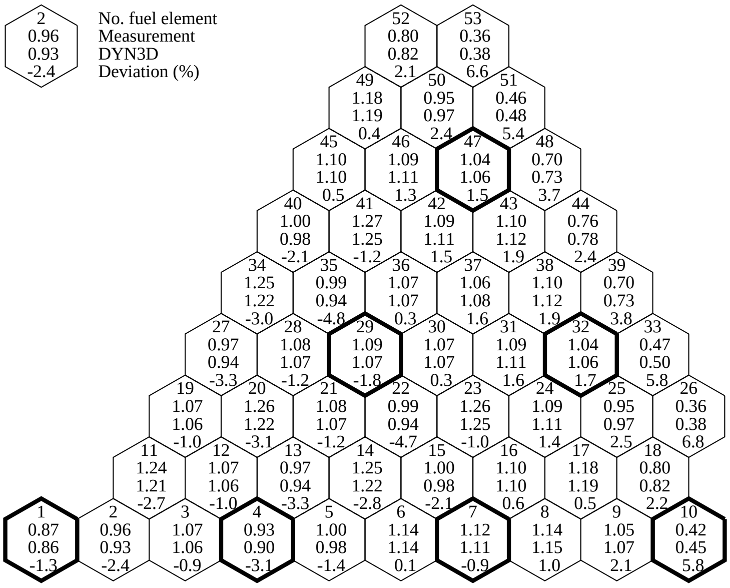

Fig. 1: Normalized power distribution before transient

The critical boron concentration calculated by DYN3D for the state at 71 full power days of cycle 21, i. e. for the burnup state at which the transient started, amounts to 5.60 g/kg (g boric acid per kg water), which is near to the measured value of 5.53 g/kg [7].

The DYN3D burnup distribution for this state was compared to the distribution calculated by IVO applying the Finnish standard fuel cycle lay-out code HEXBU-3D. The mean deviation of fuel assembly burnup between DYN3D and HEXBU-3D is 0.9 %, the maximum deviation is 3.2 %. This agreement is satisfying.

Self-powered neutron detector measurements were done by IVO [7] in the stationary state prior to the transient to reconstruct the three-dimensional power distribution. Fig. 1 presents the comparison of assembly powers calculated by DYN3D to these experimental values for a 60-degree symmetry sector of the reactor core. Significant deviations are found near the core edges, i. e. in a region of low power densities. Fig. 2 shows the axial power distribution in assembly 41, where the highest assembly power has been measured.

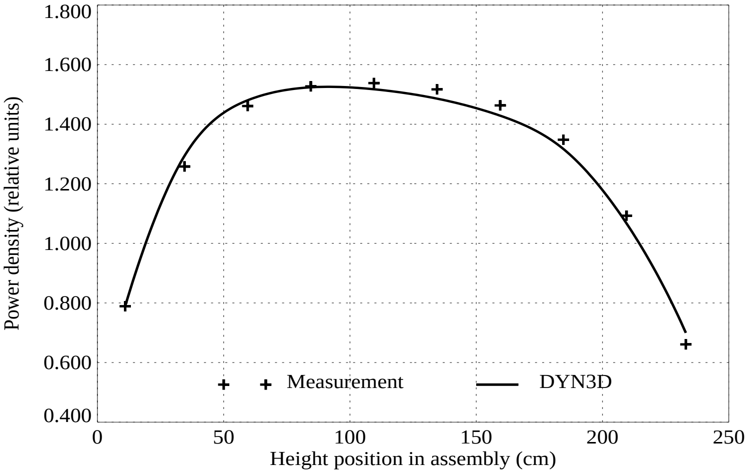

Fig. 2: Axial power distribution in the hottest assembly

In fig. 3, the fuel assembly outlet temperatures calculated by DYN3D are compared to the values measured in the steady state before the transient start. The core coolant inlet temperature at this state was at 265.5 $^{\circ}$C, the thermal power was 1495 MW. The measured outlet temperatures are averages over the six core symmetry sectors. The deviations between calculated and measured temperatures correspond to the differences in the assembly powers (cf. fig. 2). The highest temperature deviation is found in fuel assemblies 22 and 35.

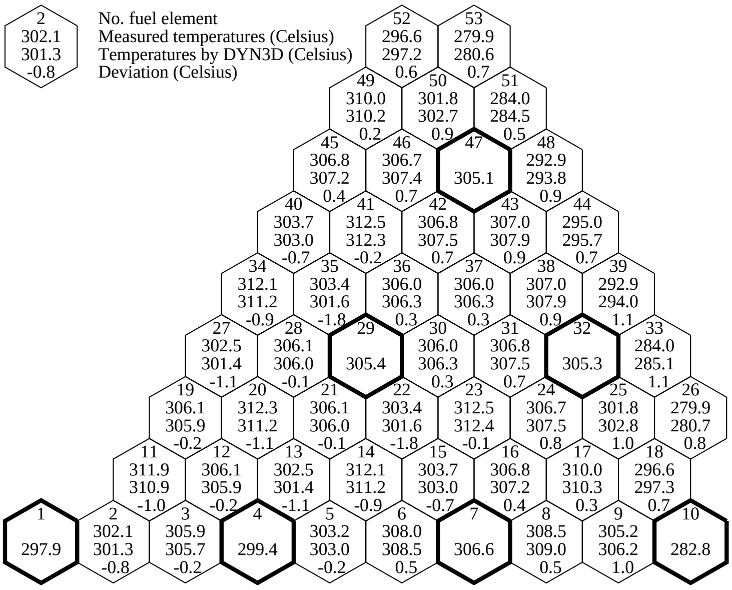

Fig. 3: Fuel assembly outlet temperatures before transient

Altogether, there is a satisfying agreement between the DYN3D results and the measured values.

6. The Balakovo-4 VVER-1000 transient

6.1 Transient description

The failure of one of the two working feed water pumps at full power was the initiating event for the transient [8]. The power control system responded by dropping the first control rod group from top to bottom within four seconds. Group No. 10, that had been at the axial position of 275 cm, started inserting in at the rate of 2 cm/s. As a result of dropping group No. 1, the neutron power decreased to about 63 % of the nominal value within 10 seconds. The slow insertion of group No. 10 down to a position of 140 cm resulted in a power of about 45 %. The reactor power was stabilized at this level by the automatic power controller.

The thermal power of the primary circuit followed the neutron power decrease with a delay of about 20 seconds. The differences between the temperatures of the hot legs and the corresponding cold legs of the four main coolant pumps decreased proportionally to the thermal power reduction, as all four pumps continued working.

In the secondary circuit, where the transient had been initiated, the flow rate through the second feed water pump that was still in operation, was increased by some 50 % within 16 seconds after the failure of the first pump, in order to partly compensate the deficient feed water flow. In the following, the flow rate of the second pump was reduced again to match the decreasing thermal power of the primary circuit.

6.2 Burnup and steady-state calculations

A DYN3D burnup calculation was carried out over 152 full-power days of the 1st cycle. The calculated critical boric acid concentration for the full-power state before the transient amounts to 2.77 g/kg, which underestimates the measured value by 0.23 g/kg [8].

KI provided three-dimensional core power distributions derived from self-powered neutron detector measurements in the stationary states before and after the transient [8]. Fig. 4 shows the assembly-wise normalized power density distribution (before the transient) calculated by DYN3D in comparison with the reference values, that have been given for the assemblies equipped with SPNDs. The maximum deviation is about 3%. In fig. 5, a comparison is presented

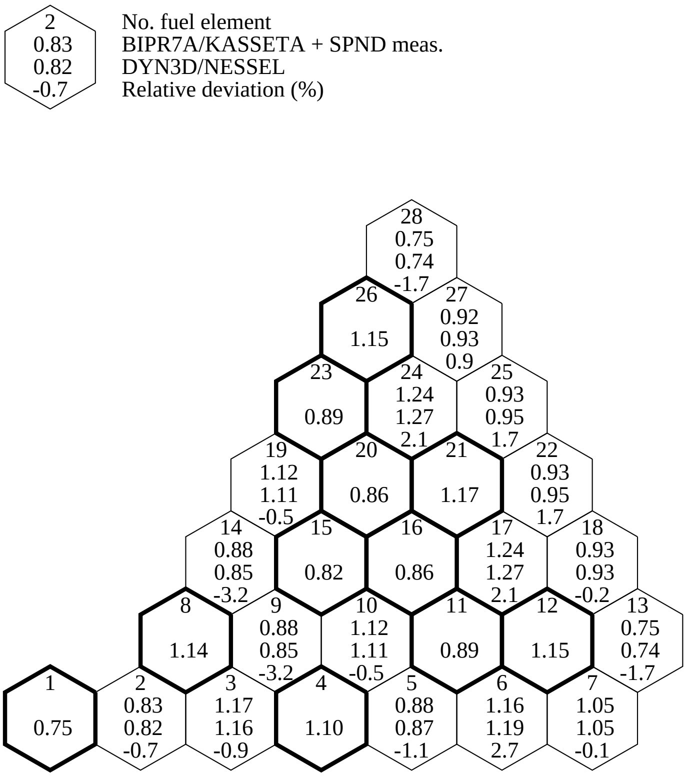

Fig. 4: Normalized power distribution before transient (Balakovo)

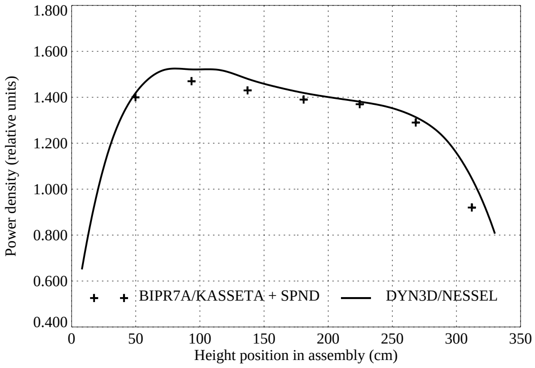

Fig. 5: Axial power distribution in assembly 17

for the axial power distribution within the hottest fuel assembly. In the stationary state after the transient, the agreement is worse. The maximum deviation in the assembly-wise power distribution is 5.3 %. A significant overestimation of the axial power distributions by DYN3D has been observed in the upper core part. But in all, a satisfying agreement between the calculated and measured values has been reached.

7. Conclusions

The comparisons of sections 5.2 and 6.2 can be considered as successful validation of the burnup and steady-state versions of DYN3D for VVER-440 and VVER-1000 cores. Corresponding calculations were carried out by the other project participants, applying the neutronics codes HEXTRAN, BIPR8 and KIKO3D. For most of these calculation results, the degree of agreement to the measurements is roughly the same as that reached by DYN3D. The main results of the whole project, especially coupled-codes calculations, are provided in [9,10].

References

[1] U. Grundmann, D. Lucas, S. Mittag and U.Rohde (1995), Weiterentwicklung und Verifikation eines dreidimensionalen Kernmodells für Reaktoren vom Typ WWER und seine Ankopplung an den Sörfallanalysecode ATHLET, Rossendorf, Report FZR-84

[2] P. Fomitchenko, M. Lizorkin, L. Gilvanov et al. (1993), Coupling of the thermal- hydraulic system code ATHLET and the 3D-neutronics model BIPR8, RRC KI Moscow, GRS Garching (Germany), Interim report

[3] G. Hegyi, K. Velkov, I. Trosztel et al. (1998), Kopplung von ATHLET mit dem ungarischen 3D-Kernmodell KIKO3D, Garching (Germany), Report GRS-A-2547

[4] R. Kyrki-Rajamäki (1995), Three-dimensional reactor dynamics code for VVER type nuclear reactors, Espoo (Finland), VTT Publications 246

[5] J. Miettinen (1998), SMABRE Code Manual, Volume 1: SMABRE System Models and Numerical Methods, Espoo (Finland), VTT Publications

[6] R. Kyrki-Rajamäki, S. Mittag (1998), Collection and review of VVER transient measurement data, Rossendorf, Technical Report on CEC PHARE project SRR1-95, FZR/SRR195/RREV1.2

[7] H. Kantee (1998), Drop of one turbine to house load level experiment on Loviisa-1 NPP, Rossendorf, Technical Report on CEC PHARE project SRR1-95, IVO/SRR195/LOV1.1

[8] S. Danilin (1998), Experimental data of the transient caused by turning off one feed water pump from working two, Rossendorf, Technical Report on CEC PHARE project SRR1-95, KI/SRR195/ED2.0

[9] S. Mittag, S. Kliem, F. P. Weiss, R. Kyrki-Rajamäki, A. Hämäläinen, S. Langenbuch, S. Danilin, J. Hadek, G. Hegyi, A. Kuchin, and D. Panayotov (2001), Validation of

coupled neutron kinetic / thermal-hydraulic codes, Part 1: Analysis of a VVER-1000 transient (Balakovo-4), Annals of Nuclear Energy 28/9, pp. 857-873

[10] A. Hämäläinen, R. Kyrki-Rajamäki, S. Mittag, S. Kliem, F. P. Weiss, S. Langenbuch, S. Danilin, J. Hadek, and G. Hegyi (2001), Validation of coupled neutron kinetic / thermal-hydraulic codes, Part 2: Analysis of a VVER-440 transient (Loviisa-1), Annals of Nuclear Energy, accepted for publication