PREDICTION OF MEASURED SPND READINGS WITH THE COUPLED CODE SYSTEM ATHLET-BIPR-VVER

S. P. Nikonov
RRC “Kurchatov Institute“, Russia

K. Velkov and A. Pautz
GRS mbH, Germany

ABSTRACT

The paper describes the capability of the coupled code system ATHLET-BIPR-VVER to predict local core parameters. Compared are Self-Powered Neutron Detector (SPND) measured signals in 64 assemblies at seven axial layers in a VVER-1000 core with values predicted by the coupled system code ATHLET-BIPR-VVER.

The measured data for this study is being taken from the recently launched OECD/NEA Benchmark “Switching-off of One of the Four Operating Main Circulation Pumps at Nominal Reactor Power at NPP Kalinin Unit 3”.

Comparisons are performed during the entire transient. The data is statistically analyzed and the influence of some parameters on the results is studied. In almost all cases an overestimation of the simulated SPND results in the down part of the core and an underestimation in the upper part of the core is observed. Potential sources of errors are discussed in the paper and some remedies are given for further studies on this subject.

This work is also a preparation for performing a detailed uncertainty and sensitivity analysis in the frame of the OECD/NEA Benchmark on uncertainty and sensitivity methods (UAM).

INTRODUCTION

The performed analysis is dedicated to the problems connected to the validation of the coupled system code ATHLET-BIPR-VVER calculations on measured VVER-1000 in-core data. The main emphasis is on the comparison of the simulated SPND readings with measured data on NPP Kalinin-3 during the transient: switching-off of one of the four operating main circulation pumps (MCP) at nominal power. During the transient the power is automatically reduced to 67%. Very good and detailed measured data is being collected during the transient which is intended to be applied for validation purposes of the coupled system code ATHLET-BIPR-VVER.
The joint work of RRC ‘Kurchatov Institute‘ and GRS mbH on the coupled code simulation of Kalinin-3 transients has started in 2006 and first results were reported in [1]. This work was in fact an elaboration of a proposal for a new international coupled code benchmark including uncertainty analysis for VVER-1000 reactors on the base of NPP Kalinin-3 measured data. At that time the analysis performed by RRC KI and GRS on the CEA-NEA/OECD VVER-1000 Coolant Transient Benchmark connected with the study of the fluid mixing phenomena in the reactor pressure vessel at NPP Kosloduy Unit #6 has been successfully concluded. The experiment – isolation of one steam generator, was performed at 9% power and led to asymmetric fluid temperature distribution at core inlet. The common KI/GRS results are reported in [2]. On the basis of comparisons with experimental measurements (Phase #2, Exercise #1) the fluid mixing phenomena at assembly heads were estimated and mixing coefficients were introduced in the thermal-hydraulic core outlet models of the coupled system code ATHLET-BIPR-VVER. The knowledge and experience of calculating the mixing coefficients introduced in the ATHLET objects - ‘assembly head’ was applied successfully in the case of Kalinin-3 MCP switching-off transient calculations. The comparison of the calculated results with the in-core thermocouple measurements showed rather good agreement [3, 4].

On the basis of the experience gained and feasibility studies performed by KI and GRS on the available measured data, OECD/NEA took the guidance and organization of an international benchmark for coupled codes and uncertainty analysis in modelling: “Switching-off of one of the four operating main circulation pumps at nominal power at NPP Kalinin Unit #3” [5, 6]. Results presented in this study are directly connected with the benchmark and even are a step forward in the preparation of the on-going OECD/NEA benchmark on UAM.

**PROBLEM DEFINITION**

One of the goals of the benchmark is to predict the local power density values at those positions where the SPND are located during the entire transient. The measured data for comparison is available with a time resolution of 1 s. The study which is presented in this paper is only the first phase of solving a very complicated problem. The basic data that we use for comparison is the set of SPND linear power readings of 64 assemblies with measurements at 7 axial layers in each assembly at 1 second time intervals during the transient duration of 300 s. The large amount of data gives a very good possibility for performing statistical estimations. The difficulties to solve the problem properly stem from the fact that the SPND readings in fact are electrical currents non-linearly proportional to the neutron flux which after
filtering procedures, different approximations, corrections and normalizations are transformed
to linear power densities applying different transformation coefficients for different detector
readings. In addition the coefficients are not constant values and are changing during the
reactor operation and they depend on some other factors. We are using for our comparison
already electronically and mathematically treated data for which it is very difficult to estimate
its final ‘measured’ accuracy.

**TRANSIENT EVOLUTION**

Main scenario sequences recovered from the measured data histories can be systematized so:

- Manually switching-off MCP #1 at t=0s.
- After the signal ‘one pump out of operation’ which is generated after 1.41 s, reactor
  limiting controller starts to decrease the power to a level of 67.2 %.
- The following sequence of actuations for reactor limiting controller and automatic reactor
  power controller is recorded:
  - At t=1.41 s the reactor limiting controller starts to decrease the reactor power. Control
    rod bank (CRB) #10 starts to move downwards. When the CRB #10 reaches 50 %
    insertion depth (at about 60 s) the CRB #9 also starts to enter the active core according to
    the control rod movement algorithm.
  - Protection system level #1 of the automatic reactor power controller switches from
    option ‘T’ (keeping the secondary loops’ parameter constant) to option ‘H’ (keeping
    neutron power constant)
  - Control rod controller decouples from automatic reactor power controller.
- At t=71 s the reactor power load-off procedure is finished and power reaches a level of
  67.2 % P_{nom}. At this moment the position of the CRB #10 is at 43.4 % and remains there
till the end of the transient. CRB #9 is inserted into the core and reaches at 71 s the
position of 93.1 % and stays there till 180 s. After that, it returns back to 100 %. The
automatic reactor power controller is again switched on to the control rod controller with
option ‘H’ and it starts to keep the power level in the range of 66.2 - 67.3 % P_{nom}.

**DISCUSSION OF THE SIMULATED RESULTS AND COMPARISONS**

The analysis is performed with the coupled system code ATHLET-BIPR-VVER with
a detailed nodalization of the reactor pressure vessel. The main results of the simulation and
comparisons with the measured data with the exception of the SPND data comparisons are presented and discussed in [7]. The topic of interest for this paper is only the prediction, comparison and statistical study of the SPND measured readings and calculations.

Figure 1 shows the integral power evolution during the transient which is automatically decreased by the power controller to a level of 67 % $P_{\text{nom}}$ to meet the operational and safety requirements of the NPP operation with one switched off MCP. The power reduction is a result of the control rod insertion. At the beginning of the transient the CRB #10 is first moved downwards and after 60 sec the insertion of CRB #9 (Fig. 2) takes place. The power decrease and the rod banks’ insertion are recorded by the SPND sensors located in 64 assemblies in 7 layers (a small number of SPND were out of order during the experiment and have hence been excluded from our data processing and any further comparisons). Examples of comparisons of predicted with ATHLET-BIPR-VVER system code local powers with the SPND measurements are shown in Fig. 3 - 8. Figures 3 and 4 show the comparison of the axial power distributions before and after the transient for assemblies #12 and #14. Figures 5-7 show the comparisons with the SPND readings during the whole transient recorded with a time step of 1 sec for sensors located at three different axial core layers (#1 – bottom, #4 –middle, #7 – top of the core) for 3 different assemblies (#69, #12 and #1). Figure 8 demonstrates the axial power profile change and its comparison with the sensors’ readings for assembly #30 which is located near the control rod bank #10. Three time points are selected for comparison; $t=0$ s - beginning of the transient, $t= 25$ s – the moment of reaching the half insertion length of the CRB #10 and $t= 150$ s – the beginning of power stabilization and no more movement of CRB #10.

Figures 3-8 indicate that the system code ATHLET-BIPR-VVER is able to predict the local power values quite well, but to quantify the accuracy an additional statistical analysis has been performed on the results.

The main results of the performed statistical analysis are summarized in Tables 1 and in Fig. 9-11. The estimations have been conducted in two steps. At first are being performed comparisons between the measured SPND data and those predicted by the system code ATHLET-BIPR-VVER without any corrections, after which some hypothetical corrections are introduced into the analysis. The relative deviations (RD) and standard deviations (SD) estimated with the formulas 1 and 2 are being calculated for the whole set of available measured points (64 assemblies with 7 layers for 300 s).
The achieved results for the comparison in all measured points for all transient time steps are summarized in Table 1. The total SD has a value of 5.213% and the maximum RD is in the range of -5.4% to +5.5%.

Table 1 Layerwise RD and SD for all SPND readings at all time points

<table>
<thead>
<tr>
<th>LAYER</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEVIATION, %</td>
<td>-5.377</td>
<td>-4.436</td>
<td>-3.334</td>
<td>-3.320</td>
<td>-2.239</td>
<td>0.007</td>
<td>5.506</td>
<td>-1.926</td>
</tr>
</tbody>
</table>

Figures 9 is an example for the time history of the RD for each SPND layer of assembly #12, while Fig. 10 shows the same time history of the RD but for all assemblies with SPND sensors. The maximum RD is in the range of -8% to +11%. The corresponding SD for all SPND assemblies is shown in Fig. 11. From the analysis of these curves it can be observed that they can be divided in three time intervals with different behavior of the statistical parameters:

1. Directly before the transient initiation RD is within the range of -8% to +7% and SD from +3% to +9%.

2. During the insertion of the CR bank #10 (from 0 s to 70s) the RD is within the range of decreased low boundary (compared to the steady state calculations) of about -6% and increased upper boundary of 11% and the SD from unchanged lower boundary 2% to increased upper one of 11%.

3. After the moment of CR bank #10 insertion stop (t > 70 s) the RD stabilizes in the range of -5 to +5 % and SD stabilizes in the range of 3 to 7%.

4. Almost for all assemblies a negative RD is observed for the first core layer of SPND locations (bottom part of the core) and a positive RD is denoted in the last (upper) core layer (#7) of SPNDs. That shows that the calculated power distributions are overpredicted at the bottom part of the core and underpredicted it in the upper part.
Similar results but only for steady state comparisons and for other NPPs with VVER-1000 reactor are reported in [8]. Analyzing our results a kind of a systematic error can be observed for the SPND readings which leads to the idea of implementation of a correction factor in the form of an axial shift of the SPND locations. It is not very clear and still not yet proved what can be the origin of this shift, whether it is a measurement or a simulation problem. To study the influence on the results, an axial shift within the range of -30 to +30 cm for all SPND locations is performed in order to find out the minimum SD value. Figure 12 shows the results after performing a systematic shift of the SPND locations in case of: steady state calculation (t=0s, red curve); end of the transient (t=300s, blue curve); t=20s – middle of control rod bank movement; for all time-steps - 64x7x300 data points (black curve). If the data is compared with the one in Table #1 it can be seen that the implementation of a 3 cm shift in the direction towards the bottom of the core increases the accuracy of the SPND system code prediction and SD decreases approximately by 0.3%. For the duration of CRB #10 movement SD decreases even by more than 2% which suggests that one reason for applying this shift may be connected with the CRB positions or their modeling.

Figure 13 shows the error distribution function for RD of the whole data set versus \(\sigma\) (Formula #2). For comparison purposes, the normal distribution (Gauss) of the error function is also plotted. The error function is a tool to estimate the probability of the studied parameter within a given interval of deviation (the area under the curve of the interval) and in our case it represents the part (%) of the measurement points with a given value of deviation. Concerning the form of the curve, the experimental one is very near to the theoretical but shifted towards the region of negative \(\sigma\) which indicates that a large fraction of the measured data is located on the graphic below the calculated data which in fact confirms the above reported results.

The explanation of the observed differences is not a simple task and is an object of our future detailed work connected with performing systematic uncertainty and sensitivity studies and analysis. According to our experience and first estimations the differences may be attributed to the following reasons and considerations:

1. Small number of axial nodes of the active core model in BIPR. The results are simulated only in 10 axial layers and the value for the power comparison at the axial points where the SPNDs are located is achieved through spline approximations.

2. The degree of realistic modeling and calculation of the thermal-hydraulic (TH) feedback parameters for the BIPR neutronic model. The TH feedbacks are results
of direct or indirect functions and are influenced by a large number of parameters and model descriptions of the whole core and also of approximations made by modeling of separate local effects, as for example the flow mixing phenomena in the reactor pressure vessel or the exact modeling of the operation of the power controller, its set points, etc.

3. Correct generation and homogenization of the nuclear cross section data and its uncertainties and correctly defining the fuel burnup in each assembly at the time moment when the measurements have been performed.

4. Correctly taking into account the fuel burnup dependence on the fuel heat conductivity properties.

5. Correctly taking into account of the coolant temperature of the ‘cold’ water located in the control rod guide tubes (approximately 7% of the assembly cross section water area) for the calculation of the water densities needed as feedback parameters for the nodal cross section calculations in the neutronic code BIPR-VVER.

6. Due to the reported axial power profile shift, the lengths of the upper and lower reflector zones and also the way the XS are being generated and validated for them must be carefully studied.

7. How exact can the position of each SPND in each assembly at each axial layer be defined.

8. More information is needed about the quality and accuracy of the measured SPND data, the accuracy achieved through all SPND signal processing procedures as: noise removal, SPND burnup compensation, induced cable current effects, SPND current-power transformation procedure, power used for normalization, methodological errors, etc.

**SUMMARY**

The performed comparisons with the measured SPND linear power densities in Kalinin-3 NPP showed good agreement with the coupled code predictions. A systematic shift of the axial power distribution is observed, with the source of the deviations currently difficult to be identified. The reason can be a still undefined problem by the in-core measurements or by the ATHLET-BIPR-VVER modeling. This study is the preparation for performing in the near future uncertainty and sensitivity analysis which are expected to yield some answers or explanations for the observed deviations.
The detailed modelling features of the coupled code system ATHLET-BIPR-VVER allow predicting the local power densities within a rather good accuracy even though the ATHLET code is based on a one-dimensional thermal-hydraulic pipe model only. The on-going development of the coupled system code ATHLET-BIPR-VVER is expected to increase the time-space core parameter prediction capabilities.

ACKNOWLEDGEMENT
The work was partly performed within projects supporting the scientific and technological co-operation with Russia of the German Federal Ministry of Economics and Technology.

REFERENCES
5. V. A. Tereshonok, S.P. Nikonov, M.P.Lizorkin, K.Velkov, A. Pautz, K.Ivanov, International Benchmark for Coupled Codes and Uncertainty Analysis in Modelling: Switching-off of one of the four operating main circulation pumps at nominal power at NPP KALININ UNIT 3, 18th Symposium of AER on VVER Reactor Physics and Reactor Safety, Hungary, Eger, Oct. 6-10, 2008
6. NEA/NSC/DOC(2009)7, OECD Benchmark First Workshop for Kalinin-3 Coupled Code Calculations and Uncertainty Analysis in Modelling (K1), University Park/State College, PA, USA, April 27-28, 2009

7. S. Nikonov, M. Lizorkin, V. Tereshonok, Velkov K., A. Pautz, OECD Benchmark on Measured Data at NPP Kalinin Unit 3 and GRS/RI Results by the Coupled System Code ATHLET/BIPR-VVER, Annual Meeting on Nuclear Technology, May 12-14, JT 2009, Dresden, Germany


Fig. 1 Comparison of the integral power evolution

Fig. 2 Comparison of CRB #10 and #9 movement histories
Fig. 3  Comparison of axial power distributions for assembly #12 at t=0 s and t= 300 s

Fig. 4  Comparison of axial power distributions for assembly #14 at t=0 s and t= 300 s
Fig. 5  Comparison of power histories of assembly #69 for three axial SPND location layers

Fig. 6  Comparison of power histories of assembly #12 for three axial SPND location layers
Fig. 7  Comparison of power histories of assembly #1 for three axial SPND location layers

Fig. 8  Comparisons of axial power profile changes of assembly #30 (located near to CRB #10) at 3 different time moments – before, during and after CRB movement
Fig. 9 Layerwise relative deviation histories of assembly #12

Fig. 10 Layerwise relative deviation histories of all SPND readings for all time moments
Fig. 11 Layerwise standard deviation histories of all SPND readings for all time moments

Fig. 12 Standard deviation change as a function of SPND locations’ axial shift
Fig. 13 Comparison of the error distribution function for RD of the whole data set versus with the theoretical Gauss distribution