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The Process of Asymmetric Boron Dilution at Zero Power of VVER-1000 on Kudankulam NPP and it Simulation

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Abstract - *Experimental studies during reactor start-up play an important role at the commissioning of new units. Successful tests allow confirming the reactor compliance with the design and give important information for computer codes verification and validation. The paper presents some experimental results that may address to the inhomogeneous boron dilution process of pressurized water reactors. The result was obtained at the real VVER reactor unit of Kudankulam NPP in India. During the physical start-up stage at hot zero power of both Kudankulam NPP units special tests were performed to assess the efficiency of the Quick Boron Injection System (QBIS). In the course of test three out of four QBIS tanks had been promptly opened and it lead to asymmetrical injection of boric acid into the core. Authors believe the process of the asymmetrical injection of boric acid may be useful for verification and validation of coupled neutronic and thermo-hydraulic codes widely used for safety analysis [1].*

I. INTRODUCTION

The process of the inhomogeneous boron dilution has been studying since 1990s [2]. Now it becomes an essential part of safety analysis for pressurized water reactors [3] and particularly for VVER reactor [4]. Complex models included coupled three-dimensional neutron kinetics and thermo-hydraulic codes are typically used in such analysis [5]. Models related to boron dilution process were validated based on facility test. New opportunity for complex coupled code validation gives the test carried out at Kudankulam NPP during hot zero power stage.

For the first time in the operation of VVER, an additional quick boron injection system (QBIS) was added to the project of reactor plants for the Kudankulam NPP (VVER-1000/412) to help managing beyond-design-basis accidents without scram. [6-8]. This passive system is designed to bring the reactor to a subcritical state in case of failure of the reactor control and protection system (CPS) with the emergency protection (EP), by fast injection of a concentrated boric acid solution into the primary circuit. The system has four independent channels, each of which includes a tank of boric acid solution with a concentration of 40 g/kg that is connected to each circulation loop in parallel to the main circulation pump (MCP), as shown schematically in Fig. 1.

When the fast-acting valves on the pipes connecting the QBIS tanks to the primary circuit are opened, the boron solution is displaced by the coolant due to a differential pressure in the MCP [7, 8]. The design of QBIS tanks for different projects is available at [8]. The efficiency of the system is determined by its ability to quickly inject into the primary coolant boric acid solution in an amount that provides the necessary level of subcriticality.

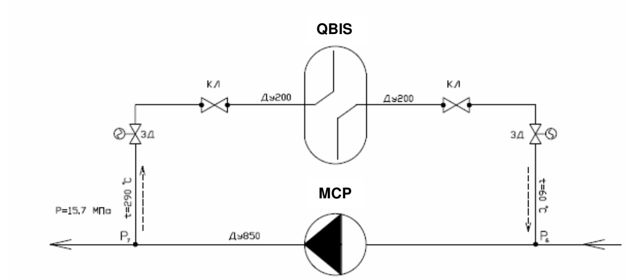

Fig. 1. Circuit diagram of the quick boron injection system channel of the Kudankulam NPP, from [8].

II. ZERO POWER TESTS AT KUDANKULAM NPP

The efficiency of the system in terms of introducing negative reactivity was experimentally confirmed at the reactor start-up stages for Units 1 and 2 of the Kudankulam NPP. The success criterion for the test at hot zero power state is assumed to be the value of subcriticality achieved.

According to the test program, the shut-off valves of the QBIS were opened simultaneously on three loops in response to a command from the Main Control Room (MCR); valves on the fourth loop remained closed. During the test at Unit 2 in July of 2016 the tank remained shut-off in loop No. 4.

For the start-up test the hardware and software measurement complex (HSMC) was used that included two ionization chambers (ic) (KNK4 type, 3He), which were located in the ex-core channels, as shown schematically in Fig. 2. In addition, regular temperature sensors, level gages, flow meters of the unit monitoring, control and diagnostic system were in operation.

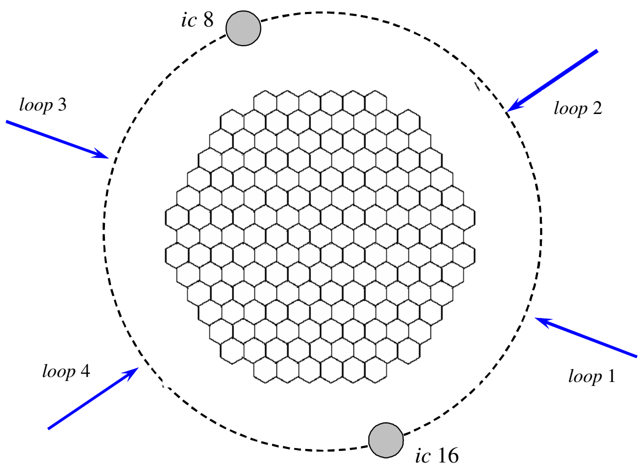

Fig. 2. Diagram of ion chambers layout during the QBIS testing at Units 1 and 2 of the Kudankulam NPP

Some experimental data recorded during the test in Unit 2 of the Kudankulam NPP performed on 18.07.2016 are provided in fig. 3-6. Before the beginning of the test, the reactor was in the critical condition, the current concentration of boric acid in the primary circuit was 7.5 g/kg, and the coolant temperature was about 282 °C. A signal to open the fast-acting valves of the QBIS was sent from the unit MCR at 20:50:13 local time by pressing the respective switches on the control panel. The volume of QBIS tanks on each loop is 7.8 m3, initial concentration of boric acid in them was approximately 40 g/kg, and the temperature was about 65 °C.

Fig. 3 shows graphs of changes in currents of the ic and readings of the reactivity meters during the tests.

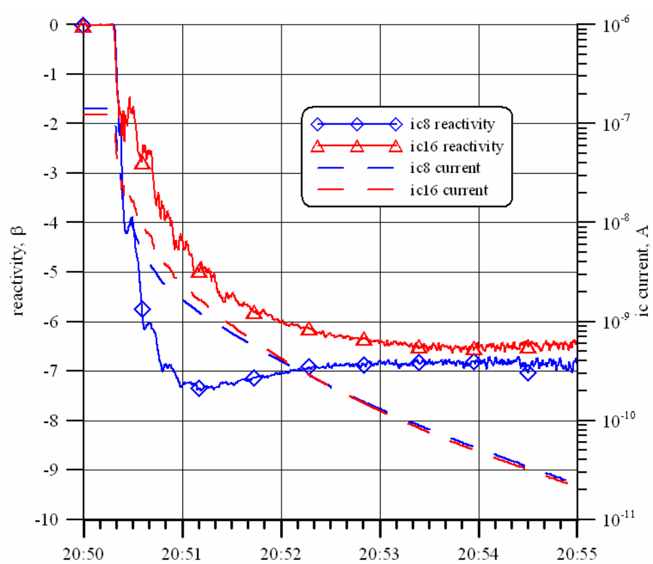

Fig. 3. Reactivity meter readings and currents of ion chambers during the QBIS test at Unit 2 of the Kudankulam NPP.

As from the graphs of fig. 3, the readings of both reactivity meters began to change intensively 6-7 seconds after the QBIS valves opening. However, the readings of the reactivity meters differ reflecting a substantial spatial non-uniformity of boric acid delivery to the core. The readings of the reactivity meters asymptotically approach each other, but do not merge completely during the time available in the test.

The graphs shows a periodic disturbances of reactivity meter readings, which are related to the passage of the coolant with a higher concentration of boric acid through the core. Specific peaks and decays of reactivity in the readings of the two ion chambers are slightly shifted.

It should be noted that the appearances of the reactivity curves for ic8 and ic16 is different. A significant difference in reactivity values was caused by the influence of spatial non-uniformity of the disturbance made by boron dilution. In addition, the reactivity graph obtained of the current of ic8 shows in general a smooth change, while readings of ic16 cause frequent disturbances of reactivity.

We believe that these disturbances are not related to noise and interference affecting only ic16, but they are likely to be caused by the nature of boron dilution process. Reactivity is influenced not only by the concentration of boron acid but also by the coolant temperature; the influence is both on the flux distribution in the core area close to the ic and the conditions of fast neutron transport from the core to the ic channels.

According to fig. 2, ic16 is located in an area affected by the coolant of loops 1 and 4. The coolant temperature and the concentration of boron acid in these loops are substantially different. Their combined influence on the neutron flux in a selected area of the core and on the properties of the downcomer region, may cause disturbance of the current of ic16.

Delivery of a cold coolant to three out of the four loops leads to non-uniform change in average temperatures, both in cold and hot legs, as shown in fig. 4. Readings in hot heg 2 of the loop are recognized unreliable and are not shown in the figure.

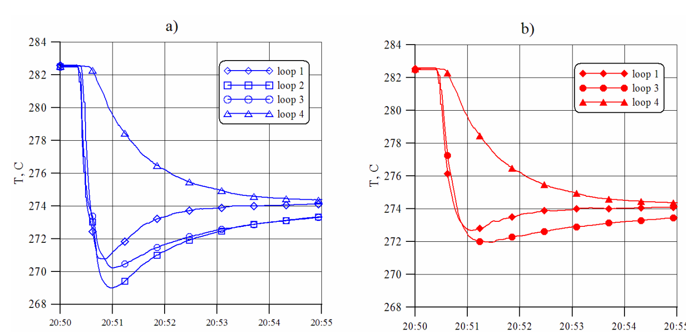

Fig. 4. Change in average coolant temperatures of individual loops during the QBIS test at Unit 2 of Kudankulam NPP: a) cold legs; b) hot legs.

III. PROCESS SIMULATION

The process of asymmetric boron dilution, which was observed during the QBIS test in the Kudankulam NPP, was simulated using the system code ATHLET/BIPR-VVER [9-11]. The transient processes were calculated in ATHLET/BIPR-VVER complex including a three-dimensional description of neutron kinetics and a quasi-three-dimensional description of the thermal hydraulics in the facility. The equipment simulated by the software complex includes all the basic components and systems of the reactor system. Flexibility in creating the nodalization scheme enables to account for effects of coolant mixing in the steam generators and the reactor housing with asymmetric operation of the loops.

Fig. A1 of the Appendix shows the calculation (nodalization) scheme of the reactor system with VVER-1000 for calculations using ATHLET/BIPR-VVER complex [9-11]. The calculation scheme contains functionally interrelated components of the primary and secondary coolant equipment. The primary circuit is represented by four circulation loops. Each loop has three macro parts: a hot leg, steam generator tubes, a cold leg with the MCP. Each macro part is divided into design volumes. The loop connection places are the upper collecting coolant-mixing chamber above the core and the upper part of the coolant downcomer region at the reactor inlet. Within the reactor, the following parts are simulated: the downcomer region, the lower pressure mixing chamber, the core with all the assemblies, the upper collecting mixing chamber with perforated plate, PPB and the space under the reactor head, the input and output loop connections. The pressurizer is connected to the hot leg of the loop through a surge line.

The QBIS is simulated by means of standard ATHLET tools as four identical channels consisting of a 7.8m3 tank with boric acid and pipelines (D = 200 mm). The pipelines include valves with an opening time of 1 s. Each QBIS channel connected to the cold leg of the corresponding loop. In addition, we introduced a model of ex-core ionization chambers, which enabled to simulate readings of ic8 and 16 and calculate the reactivity; ion chambers model is taking into account change of coolant temperature in downcomer.

The ability of the QBIS to displace boric acid solution to the primary circuit was experimentally tested in studies on models [6, 8], and also on Unit 1 of the Kundakulam NPP in course of hot run tests [7, 8]. The tests resulted in obtaining experimental dependences of the boric acid concentration at the system output, presented in fig.6 as 'experimental' graph. Graph of simulated boric acid concentration change at the outlet of the modeled system is also shown in fig. 5 ('model').

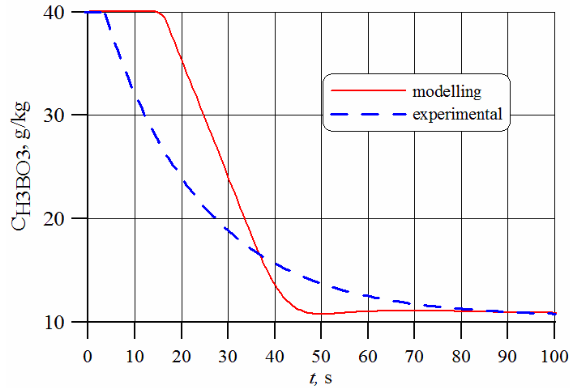

Fig. 5. Change of boric acid concentration at the outlet of the QBIS during the test.

As seen in fig. 5, the model of the QBIS shows a change of the boric acid concentration, which is closer to the "piston like expel" than the experiment. Thus, in the model, the delivery of boric acid to the primary coolant is more intense than in the experiment.

Fig. 6 shows the results of reactivity meter reading simulation. The calculated reactivity meter readings from ic 16 (located closer to loop 4) generally coincide with the experimental ones. For ic 8, the calculated values differ significantly in the initial section. This difference apparently related to the simulation features of the boric acid solution displacement from the QBIS tanks specified in fig. 5. In the simulation, a more intensive delivery of boric acid to the area adjacent to ic 8 (see fig. 2) results in a sharper fall in the current of the ic and loss of reactivity.

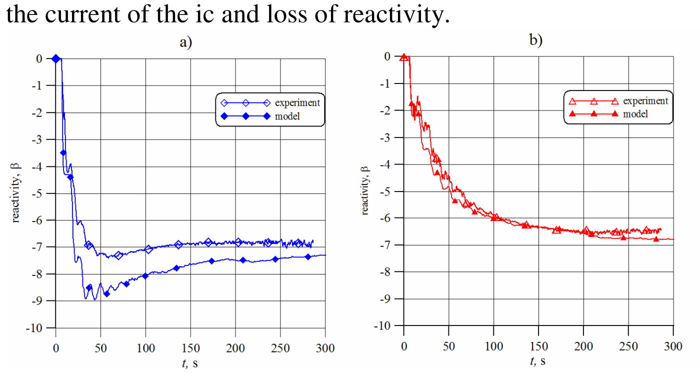

Fig. 6. The experimental and simulated reactivity meter readings: a) ic 8; b) ic 16.

Disturbances of reactivity connected with the passage of the coolant with a higher boric acid concentration through the core, are also seen in readings of the model and generally coincide with the experimental data in terms of time. It can also be distinguished four or five cycles with typical losses of reactivity in the 'experimental' graph. In the model, the losses are sharper and there are six or seven distinct cycles, which also indicate a slower diffusion of the "slug".

In general, the readings from ic 16 located (closer to loop 4) are simulated precisely. According to the figures of the Appendix, the concentration of boric acid in the initial section is almost unchanged in loop 4. Periodic disturbances in the reactivity of ic 16 are connected with the coolant of loop 1 and with a general change of the flux in the core. However, it should be noted that the graph of the model has no short-term disturbance of high amplitude, unlike the 'experimental' graph.

The results of simulation of boric acid concentration change across the reactor and in the primary circuit are represented in Figures A2-A3 of the Appendix. According to these data, a substantial spatial non-uniformity of boric acid concentration distribution in the core persists throughout the test period. The concentration of boric acid in loop 4 and the adjacent area is always lower than in the other loops.

Fig. 7 shows the experimental and calculated values of the average coolant temperatures for the loops. The rate of the solution displacement from QBIS tanks influences both the temperature and the concentration of boric acid. According to the graphs for loops 1-3 in fig. 7, colder coolant delivered from the tanks more intensively in the model than in reality. Additionally, the results of the experiment and the calculation for the average temperature of loop 4, where the QBIS tank was not opened, might indicate that the model underestimates the mixing of the coolant, and the cold coolant of loops 1-3 ingress in loop 4 more intensively.

An experience of the process simulation with ATHLET/BIPR-VVER codes and some sensitivity studies [12] point the most influential parameters of the model. The most important characteristics is the QBIS tank outflow, which affect reactivity meters readings and coolant temperature behaviour as well. The model of reactor vessel mixing affects all coolant temperature characteristics and also important for spatial distribution of slug in the core. Reactivity meters model is also crucial for correct simulation; this model has to include terms for downcomer parameters accounting.

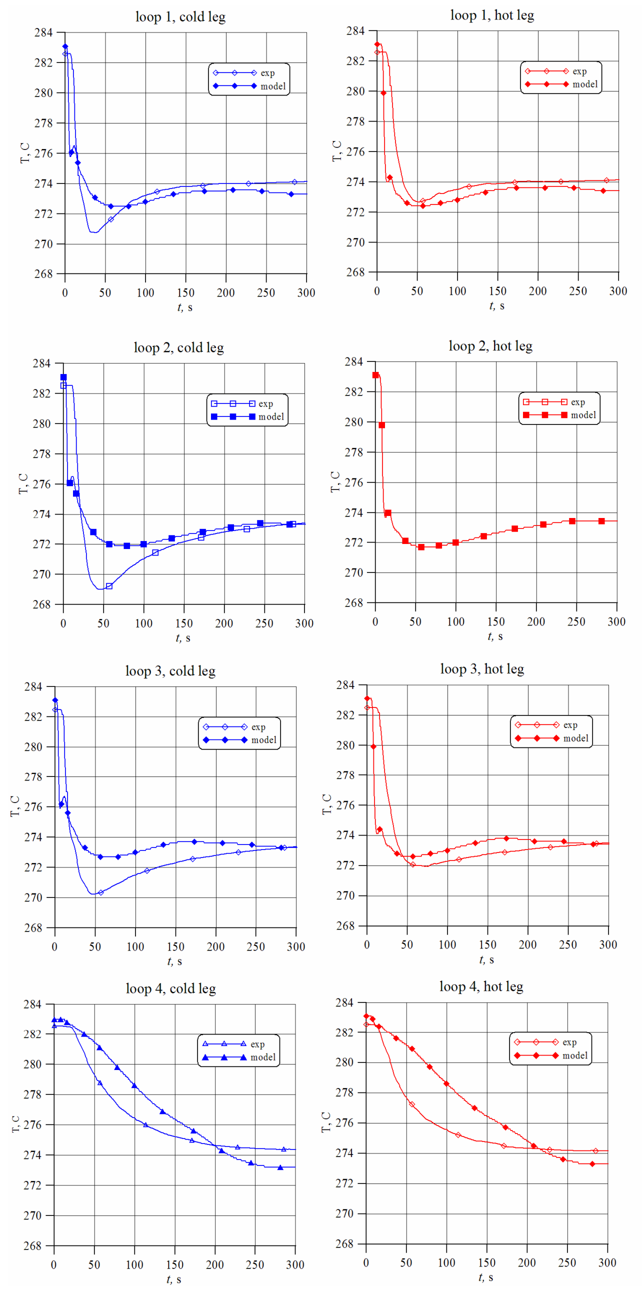

Fig. 9. The experimental and calculated average coolant temperature in all four loops.

IV. CONCLUSIONS

Unique tests of the quick boron injection system were performed at the units of the Kudankulam NPP during the reactor start-up, where an asymmetric boron dilution in the core there was observed. The experimental data recorded by the special instrumentation and the regular monitoring, control and diagnostics systems enable to analyze the process in the reactor system.

The authors believe the test data may be useful for verification of dynamic codes and improvements of the calculation models. An example of ATHLET/BIPR-VVER simulation confirms it.

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APPENDIX A: SOME SIMULATION RESULTS

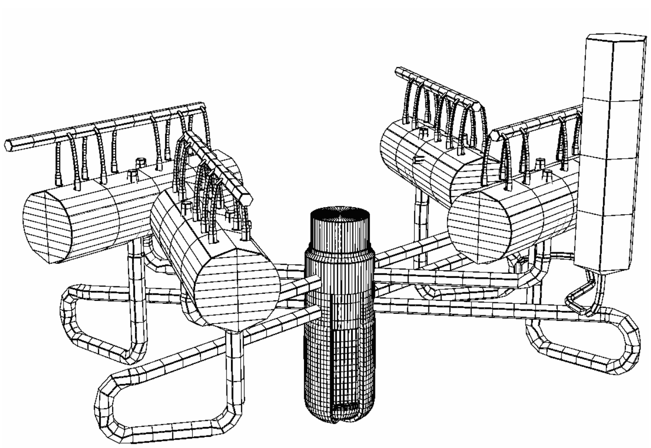

Fig. A1. Design model of the primary circuit of the VVER-1000 reactor system for ATHLET/BIPR-VVER code

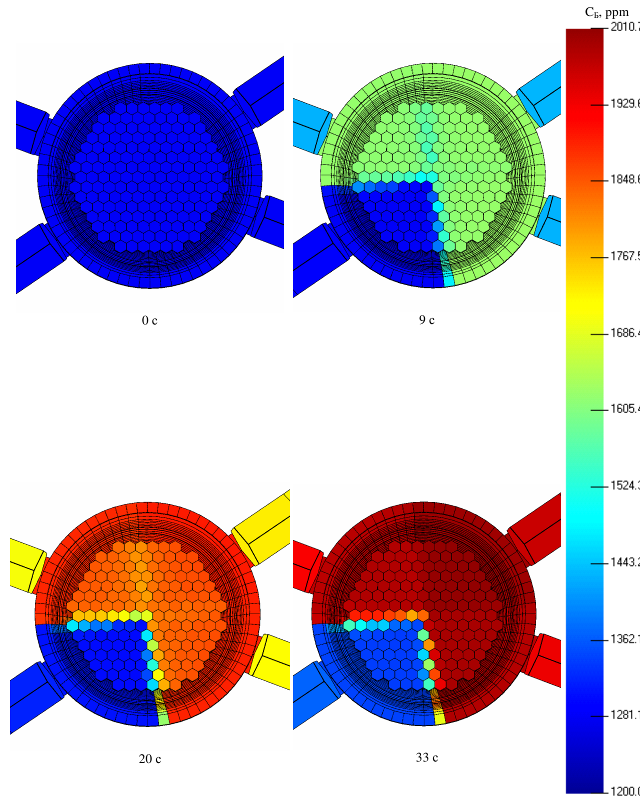

Fig. A2. Spatial distribution of the boric acid concentration in the reactor system of the Kudankulam NPP, Unit 2, during the test of the QBIS (0 – 33 s)

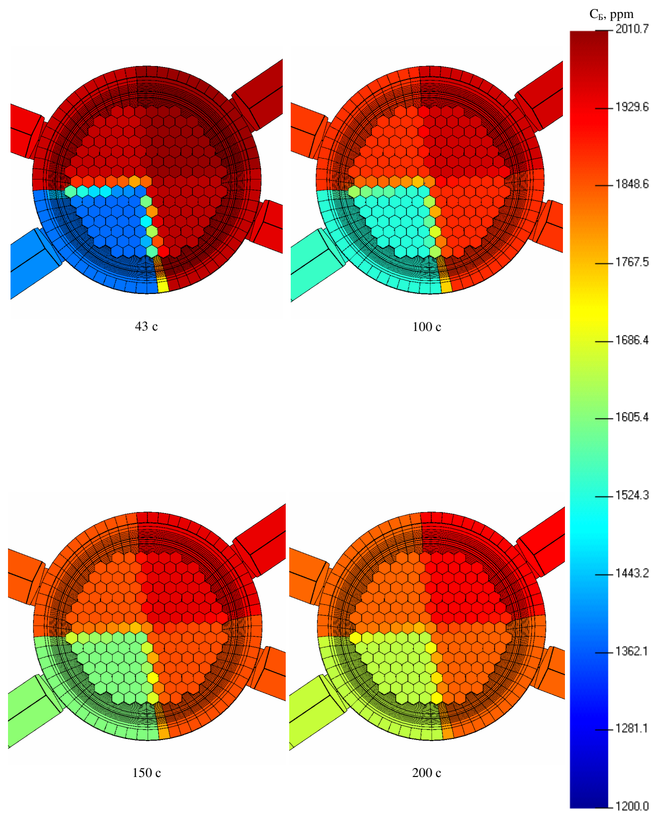

Fig. A3. Spatial distribution of the boric acid concentration in the reactor system of the Kudankulam NPP, Unit 2, during the test of the QBIS (43 – 200 s)

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