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Fast-Acting Boron Injection System (FABIS)

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PROJECT PARTNERS

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OBJECTIVES

The objective of the FABIS project was to show that a fast shutdown of the reactor is feasible in the existing and future BWRs with a fast-acting boron injection system (FABIS). FABIS is needed since there is a risk in the existing BWRs that the nuclear fission process can't be stopped by the active fine motion control rod drives or by the passive scram system if there is a common cause failure in the control rod drive system. To reduce this risk, a diverse fast-acting boron injection system (FABIS) is proposed which injects sodium pentaborate into the Reactor Pressure Vessel (RPV). See Figure 1 for the principle flow diagram of the system.

FABIS takes boron from a large tank where it is heated to 250 °C. Heating ensures the densities of the boron solution and water in RPV is the same. With a second set of heaters, the upper 20 % of the water are heated to 331-335 °C (130-140 bar). About 10 % of the boron tank is filled with saturated steam. After activation of FABIS, steam expands and more steam is produced from saturated boron solution due to the pressure reduction. The boron solution flows through pipes inside RPV up to the upper side of the lower core plate. There the boron solution flows through smaller pipes adjacent to the lower core plate into the core bypass through about 100 small nozzles. This guarantees a homogeneous distribution of boron in RPV.

THE RESEARCH PERFORMED AND METHODS ADOPTED

The FABIS project included five work packages (WP1-WP5). The project aimed at answering to the following four questions:

1. <u>How much time is needed for the injected boron solution to be spread both axially and radially over the core in such a way that the fission process stops completely?</u>

The first two work packages (WP1 and WP2) answered to this question with PHOENICS [1] calculations and mixing experiments. Framatome ANP was responsible of WP1 and WP2. The main parameters in the calculations were the mass flow of the core bypass, diameter, flow velocity and direction of the local ejection nozzles and the pulse of the entrance flow to the core bypass. Calculations gave the optimum combination of the parameters leading to fast mixing. The experiments of WP2 verified the calculational results. The test rig was built of perspex in 1:1 scale and colored water simulated the boron solution. In the rig, it was possible to observe the mixing process by optical means and to use video to record the process.

[1] PHOENICS Version 3.4, 2002, Cham UK, Wimbledon.

2. Is there boron in the core entrance flow when the injection is stopped?

A series of TRAB-3D [2] analyses of WP3 answered to this question. VTT was responsible of WP3. TRAB-3D is a lumped parameter code, which includes 1D or 3D neutronics core models and 1D or node models for RPV hydraulics. The analyses were needed since re-criticality of the core could take place if the mixing is insufficient. If the internal recirculation flow in RPV decreases with decreasing steam production and with decreasing speed of the main circulation pumps, the recirculation period will become longer. If the injection of boron solution ends earlier than this recirculation period, pure water may enter the core bypass and the boron solution could be washed out of the core.

3. What are the forces acting onto the lines between the boron solution tank and the RPV due to thermal shocks and pressure waves inside the lines?

In WP4, experiments at Lappeenranta University of Technology (LUT) studied the flow between the boron tank and RPV (see Figure 2). The volumetric scale of the test rig was 1:6 and the maximum pressure 80 bar. The experiments started with high pressure in the boron tank and low pressure in RPV. The valves in the connecting line between the tanks were opened and water from the boron tank was injected to RPV. The second aim of the tests was to find out which part of the inventory of the boron tank must be heated to the saturation temperature and pressure to reach the desired pressure level at the end of the test.

4. How can the results be transformed from the laboratory to the full scale?

The experiments of WP2 and WP4 used different temperatures, pressures and dimensions of the components than in the full-scale FABIS. The purpose of WP5 was to check, using dimensional analysis and engineering judgement, whether the results of the tests must be transformed due to the scale effects. WP5 ended with a system description, with detailed flow diagram and data sheets for the main components so that the realization of the system in a real BWR plant could be done. Framatome ANP was responsible of WP5.

MAIN ACHIEVEMENTS

Calculation of Mixing Process

WP1 included mixing calculations with the PHOENICS code with different jet and bypass flow rates, bore openings and injection angles and with 1 or 2 jets in representative section models. The calculated concentration profile in the gap between the fuel assemblies was sufficiently homogeneous along the core active zone for the optimal parameter combination. Figure 3 shows the calculated values across the core height for the injection/by-pass flow ratio of 4 % and for injection velocity and angle of 20 m/s and 20°. Although the bypass design and distribution is important it arose that small modification to the bypass did not affect the results, since most of the boron mixes already below the fuel assemblies. Hence, if the design is changed, the mixing in the bottom part must be studied carefully keeping the minimum boron concentration deviations as close as possible to the mean. Rather uniform boron distributions with the mean values of 4 % could be achieved with relative low injection rates

[2] A. Daavittila and H. Räty. Validation of TRAB-3D. In: FINNUS Final Report, VTT Research Notes 2164. Espoo, Finland, 2002 (http://www.vtt.fi/pro/tutkimus/finnus/index.html), pp. 127-133.

of about 0.25 kg/s, being 4 % of the bypass flow rate. Because of this a rather low boron storage volume is needed.

Mixture Tests
The main components of the test rig of WP 2 were
– model of scale 1:1, made of acrylic plastic (perspex),
– 6 control rod guide tube heads with upper part of the control rods and bypass slots,
– 24 full length FAs with foot and bypass holes, and
– separate water circuits for FA bypass flow, control rod bypass flow and boron injection.

The test rig was built to include 2 different sections of the injection positions, one with converging and one with diverging jets. In 1:1 scale, the tests were performed with original mass flows and flow velocities and no further scaling was needed. WP2 started with pretests to check the performance of the rig, to adjust the flow rates of the injection system and the bypass flow pumping units, and to check the measurements. In the second phase, LASER light slit tests were performed at different model cross sections and recorded on video to observe mixing of boron (simulated by particle seeded water) and coolant at three elevations. A series of tests with colored water was also run and recorded on video to observe the overall mixing behavior.

Mixture Calculations
A CASMO-4 study of the effects of the inter-assembly bypass boron distribution showed the homogeneity achieved with the planned boron injection was satisfactory. With the maximum boron density variation of factor of 2, the required additional boron to compensate the remaining heterogeneity was less than 5 %. Figure 4 shows the boron heterogeneity weight factor for a 3 cm long boron slug of 600 and 800 ppm in the bypass. The TRAB-3D steady-state calculation at the beginning of an equilibrium cycle resulted in an initial bypass boron concentration of 0.04 w-%, if the core should remain subcritical also during the second recirculation, when the boron is distributed homogeneously to RPV and the injection is stopped. This leads to 9.4 % sodium pentaborate solution in the boron tank, clearly less than the planned 13 %. In the TRAB-3D transient calculations, RPV was safely borated at the end of the injection after 150 seconds. Figure 5 shows the calculated fission power for the first 40 seconds of a turbine trip transient. In the Case 1, FABIS was activated immediately after the scram. In the Case 2, a delay of about 10 s was assumed. The analyses were made assuming the pumps are kept running at the minimum speed. If the pumps are stopped, the flow in the core by-pass stops almost totally. In this case, more studies are needed to confirm the function of the system.

Tests of the Flow between the Boron Tank and the RPV
Figure 2 shows the principle view of the test rig at LUT for the experiments of WP4. The rig consists of a boron tank, RPV, three electric heaters, piping, two fast opening valves, an orifice device, measurement instrumentation and data acquisition system. The instrumentation included two differential and three absolute pressure sensors, temperature measurements, valve position sensors and three strain gauges. WP4 included a series of pre-tests for testing and practicing the operation of the rig, and 7 final tests. The tests followed the actual operation of the full-scale FABIS system. The initial parameters were 65-80 bar, 15-180 °C (280-295 °C at the top) in the boron tank and 5-15 bar, 152-198 °C in RPV. The opening of the valves in the blowdown line actuated water injection from the boron tank. The time difference for opening the valves in the blowdown line was 0.3 s. Before each test, the tanks

were filled with water. The blowdown line was full of water at atmospheric pressure. The water in the boron tank was heated to the desired temperature with the lower heater. Electrical heaters were also used to pressurize the boron tank and RPV. Opening the valves in the blowdown line actuated the water injection. During the tests, the whole water inventory of the boron tank was injected. The initial volume fraction of saturated water in the boron tank varied between 21-31 %. See Figure 6 for the measured pressure in the tests with different initial pressures, boron tank water levels and mass of saturated water in the boron tank.

After opening the first valve, a pressure wave propagated between the valves. When the initial pressure in the boron tank was 65 bar, a 30 MPa tension stress on the outer wall of the blowdown pipe in circumferential direction was observed. Initial pressure of 80 bar caused a 40 MPa tension stress. When the fluid started to flow in the pipe, the inner wall temperature changed faster than at the temperature at the outer wall. This caused thermal stresses. When the inner wall temperature was below the outer wall temperature, a tensile stress occurred on the outer wall. The maximum tension stress was 75 MPa. When the temperature on the inner wall was lower than on the outer wall, compression stress occurred. The maximum value for compression stress of – 130 MPa was measured after the second valve. These stress values didn't risk the integrity of the blowdown pipe.

Transformation of the Test Results to the Actual Plant
WP5 of the FABIS project included analyses to transfer the test results to the real plant conditions. Two different investigations were done, since the forces induced by the pressure waves and thermal shock do not appear simultaneously. The first analyses assessed the effects of the propagating pressure waves on the piping system between the boron tank and RPV. The second assessed the effects due to the thermal shock by injecting the hot boron solution to the cold pipes. The pressure wave analysis showed higher pressures in the piping system than in the tests of WP4. The reason was the too rough time step of the data acquisition in the tests. A check analysis using the same integration time step showed a good agreement between the tests and analysis. In this way the test results, the analysis method and the transferability to the real plant were validated. A further investigation concerning fatigue due to the thermal shock and maximum operating conditions was done showing that all loads on the real system are within allowable limits.

DISSEMINATION AND EXPLOITATION OF THE RESULTS

The FABIS system is a part of a new generation nuclear power plant. It provides a cost-effective way to improve safety of the existing and new nuclear power plants. FABIS system is a part of the safety systems of the SWR 1000 nuclear power plant, one of the plants offered to TVO in Finland as an alternative for the fifth Finnish NPP.

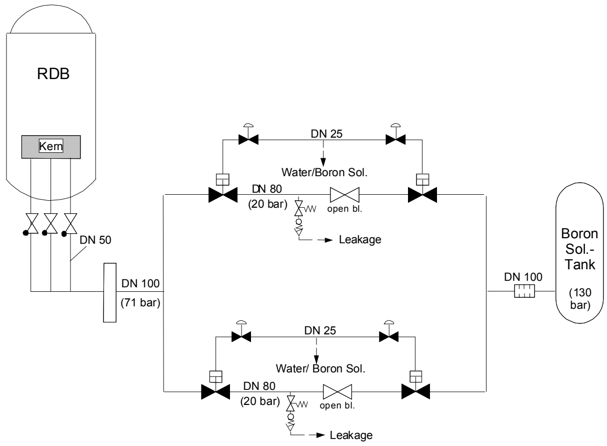

Figure 1: Principle flow diagram of the Fast-Acting Boron Injection System, FABIS

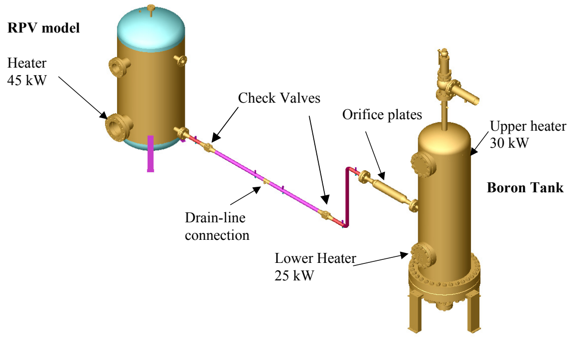

Figure 2: Principle view of the test rig of WP 4

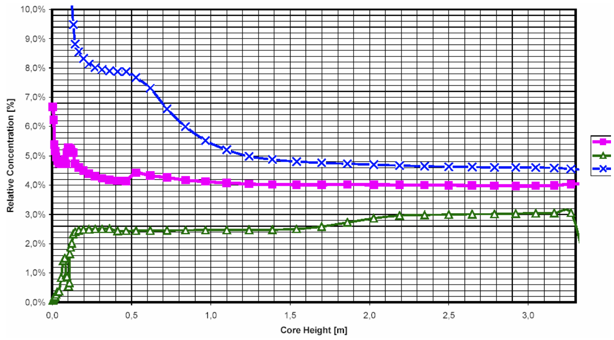

Figure 3: Relative boron concentration (mean, min., max.) across core height. Case I: injection/bypass ratio 4 %, inj. veloc./angle: 20 m/s, 40 deg.

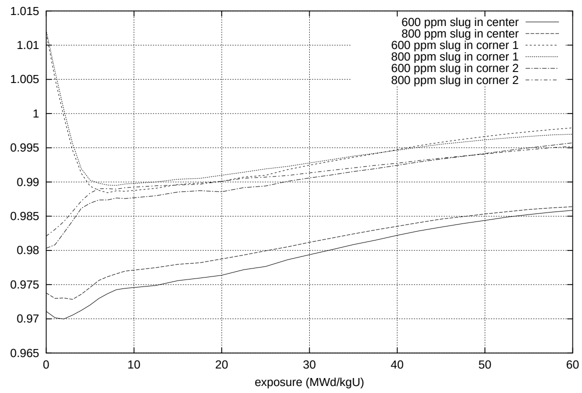

Figure 4: Boron heterogeneity weight factor for a 3 cm slug of 600 and 800 ppm boron concentration

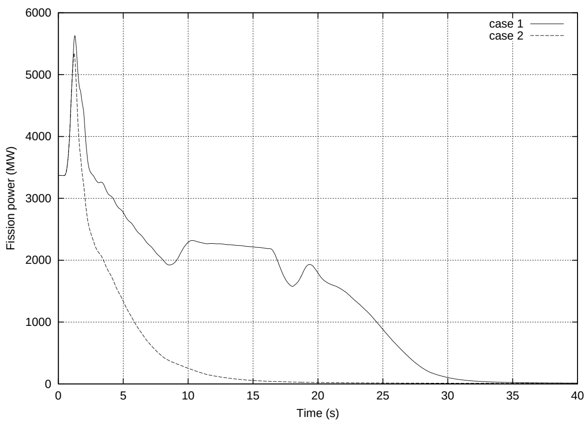

Figure 5: Fission power for the first 40 seconds in the TRAB-3D calculations

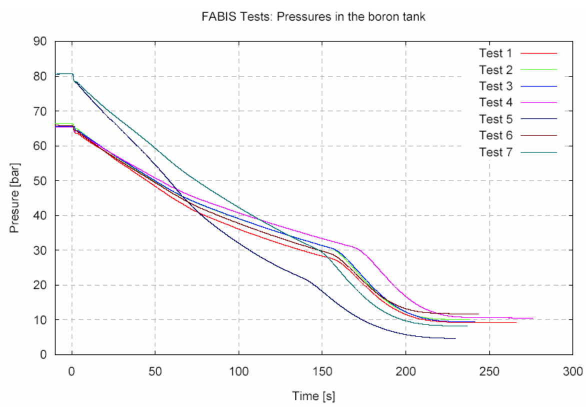

Figure 6: Depressurization of the boron tank in the experiments of WP4