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APROS COUPLINGS FROM CORE TO CONTAINMENT

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ABSTRACT

APROS simulation environment is able to describe the1-D and 3-D neutronics of the reactor core. It is also able to describe the thermal hydraulics of the core and circuits either with 5-equation or 6-equation thermal hydraulics. It can also describe the plant automation and electrical systems, as well as the behaviour of the containment.

The peculiar feature of APROS in comparison to other coupled systems is that all parts in the coupled system are described with the same code instead of coupling two or three separate codes together with information exchange between the separate codes. The most recent possibility is the coupled calculation of the process and the containment. The more traditional coupling, the coupling of the process containing both the process description and the automation description with more or less detailed description of the 3-D core either for safety analysis or real-time simulation purposes has been discussed in previous work, such as reference [1].

The paper presents and discusses the capabilities of the code in coupling the plant process and automation description with the plant containment description with two example transient cases. An improved boron concentration solution with second order upwind discretisation has been recently included in APROS. An example on the increased accuracy acquired in the 3-D core model has been included.

KEYWORDS: Core, neutronics, thermal hydraulics, coupling, boron, APROS

1. INTRODUCTION

APROS (Advanced PROcess Simulator) is a multifunctional simulation environment for the dynamic simulation of nuclear and conventional power plant processes and for the simulation of industrial process dynamics. It has been developed by VTT Technical Research Centre of Finland and Fortum Nuclear Services Ltd since 1986 [2]. APROS simulation environment consists of an executive system, model packages, equation solvers, a real-time database and interface models. The model packages containing the physical models and process components related to them are grouped into general and application specific packages. The key feature of APROS is that the same packages can be used in various simulation applications. In addition to the general packages, like thermal hydraulics, each application needs an application specific package. The APROS plant models are currently created and used in most applications via GRADES graphical user interface.

In APROS nuclear reactor core one- or three-dimensional two energy group neutronics model is connected with homogeneous, five- or six-equation thermal hydraulic model. The three-dimensional model is a finite-difference type model. The core model has been described in detail in [3]. An essential feature of APROS core model is the flexible combination of the neutronics with thermal hydraulic channels. APROS core models have been designed to be an integral part of the simulation environment with the same requirements of on-line calculation, interruption of simulation, modification of the model and continuation of the simulation with the modified model, as the other models of the simulation environment.

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2. COUPLING OF PLANT MODEL AND CONTAINMENT

The coupling of plant model and containment is discussed with two example cases. The purpose of the first example is to ensure that the basic solution in APROS is sound. The second example is from coupled plant and containment calculation for a double-ended guillotine break in steam line of a BWR plant.

2.1 Liquid discharge to the containment

A liquid discharge to the containment has been simulated with the containment and six-equation models of APROS and compared to the calculations made with the VTT's in-house SUPLES program [4]. SUPLES is a fairly simple numerical program which solves the containment mass balance, pressure and temperature either after all discharge water has been put in the control volume at a time or as a function of time. Because the solving procedure of SUPLES fully executes the thermal equilibrium and the steam tables of the program are quite accurate (compared to IAPS Formulation 1982), it can be well used as a numerical reference in restricted, idealized cases for the validation of the containment analyses.

The purpose of the example case is to ensure that the basic solution of APROS is sound [5]. In the experiment, a constant liquid flow of 1550 kg/s with enthalpy of 1324 kJ/kg was injected within 90 seconds into a containment volume of 50 000 m3. The initial pressure, temperature and relative humidity were 0.1 MPa, 20 °C and 50%, respectively.

In the containment model, one node (volume 50000 m3) was used in the simulation. The diameter of mist droplets was assumed to be 0.1 mm. In the six-equation model, two nodes were used in order to simulate the dropping of water to the pool. The simulation models are illustrated in Figures 1 and 2.

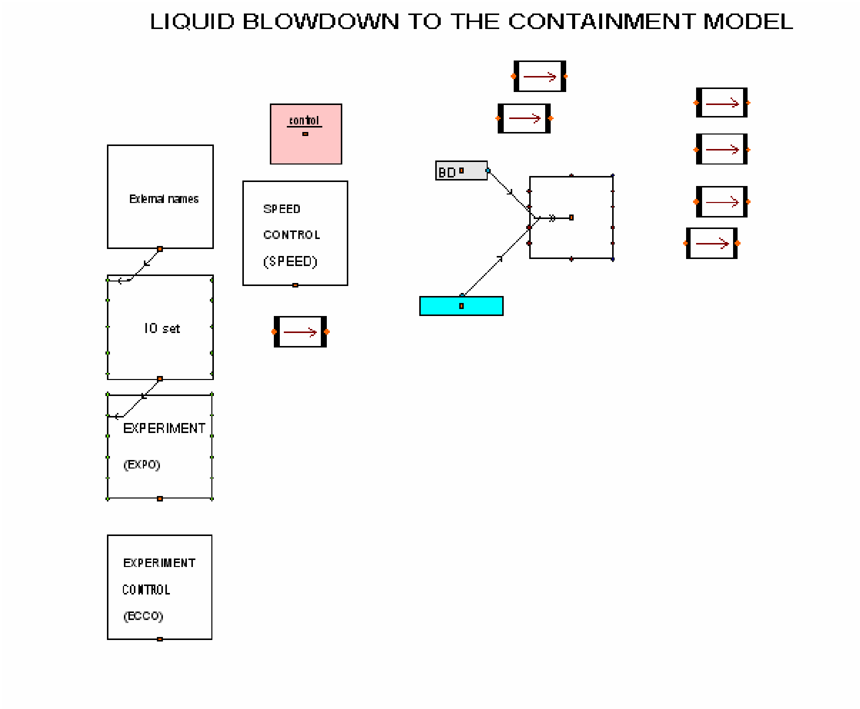

Figure 1. Simulation model of liquid discharge into the containment model.

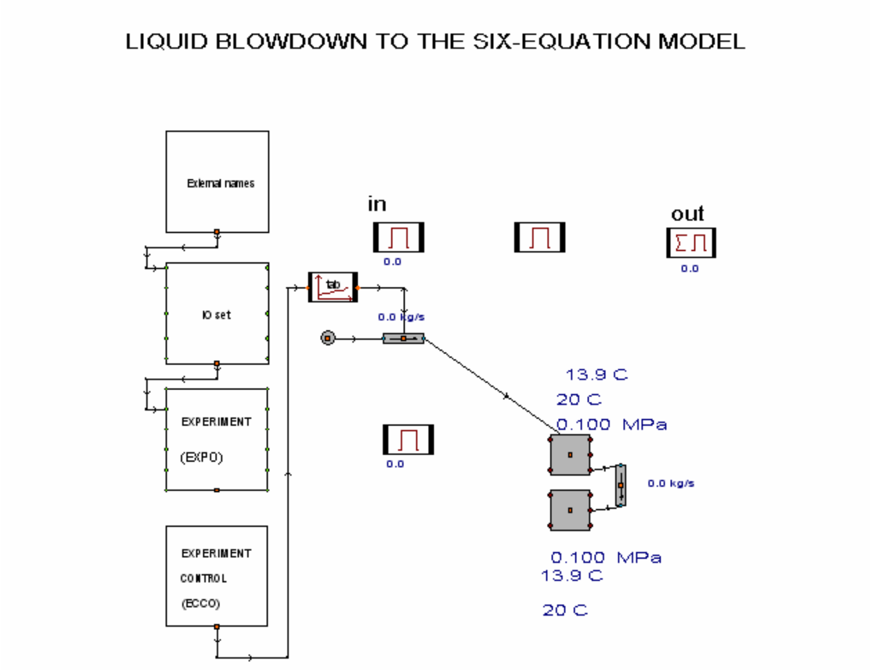

Figure 2. Simulation model of liquid discharge into the six-equation model.

The simulation results of the compared models are quite close to each other. The major difference is the higher gas temperature calculated by the six-equation model. The interfacial heat transfer and friction models used by the six-equation model lead to superheating of steam, whereas the steam temperature calculated by the other models is close to the saturation temperature. Figures 3 and 4 show the results obtained for pressure and gas temperature. The transient has been included in the validation of successive APROS versions, and the results for the most recent versions 5.04 and 5.05 [5] are shown in the Figures.

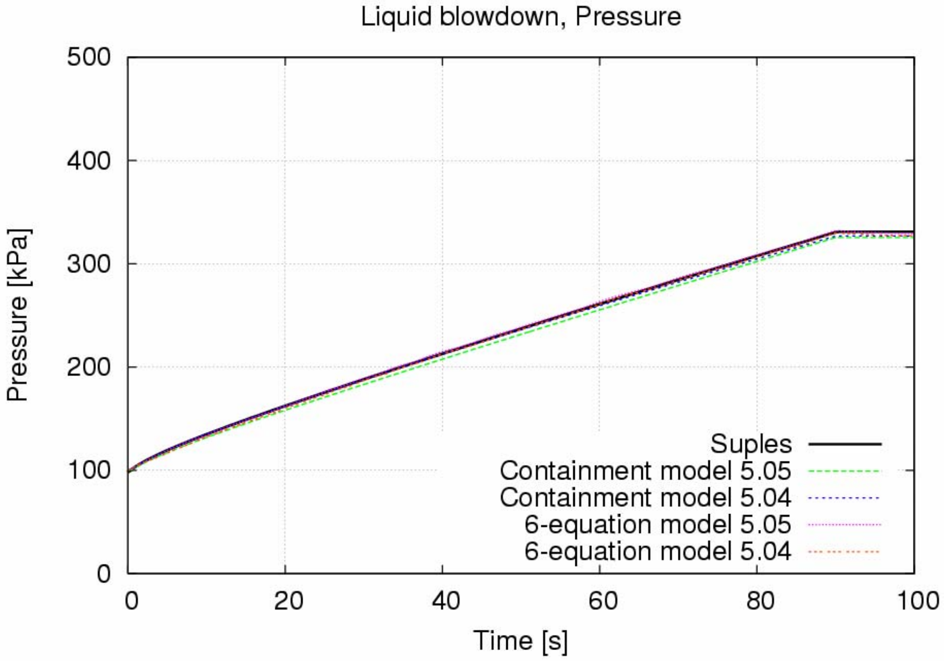

Figure 3. Pressure calculated with APROS in comparison with SUPLES code.

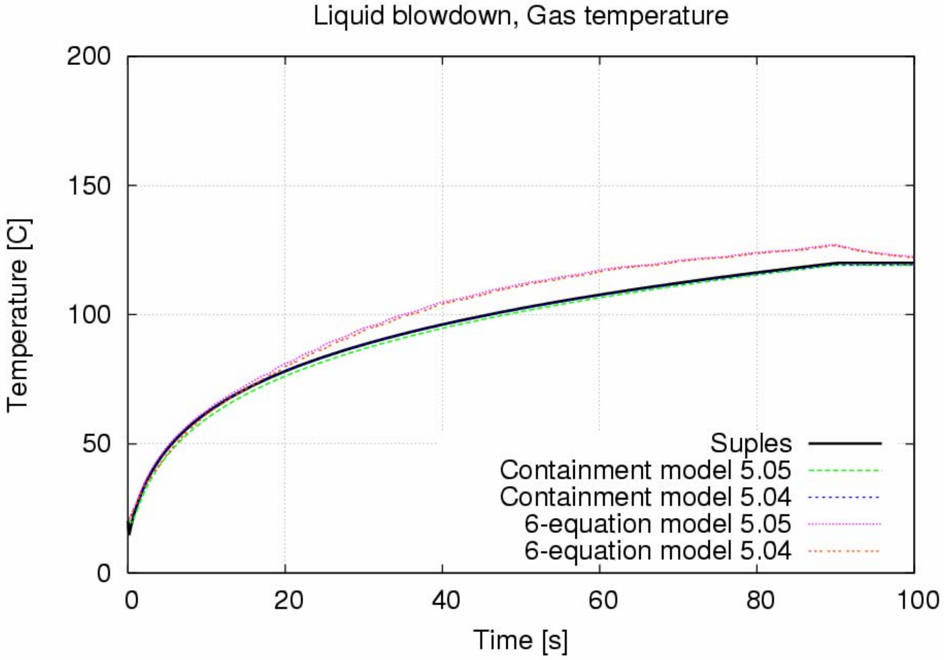

Figure 4. Gas temperature calculated with APROS in comparison with SUPLES code.

2.2 Coupled process containment calculation

The simulation model of the Olkiluoto nuclear power plant (a boiling water reactor plant) includes the reactor core, steam lines, feed water lines and containment modelled in detail. The auxiliary systems and controllers of the plant are modelled in the extent needed for typical design basis accident analyses. The reactor vessel, steam lines, feed water lines, relief system and part of the auxiliary feed water system are modeled with the six-equation model. The spray and shut-down systems and part of the auxiliary feed water system are modeled with the homogeneous model. The containment model uses its own solution system.

The validation case [5] discussed is a double-ended guillotine break in steam line 2 of the plant. The steam line break is modelled with two valves connected to the dry well node of the containment model. The flow area of each valve is 0.163 m^2. The break is initiated by opening the valves. Figure 5 shows the APROS model of the steam line.

APROS results have been compared in with the results obtained in the same transient case with the results of GOBLIN [6] and COPTA[6] codes that are considered to give the best available reference on the qualitative as well as quantitative physical behaviour in this transient.

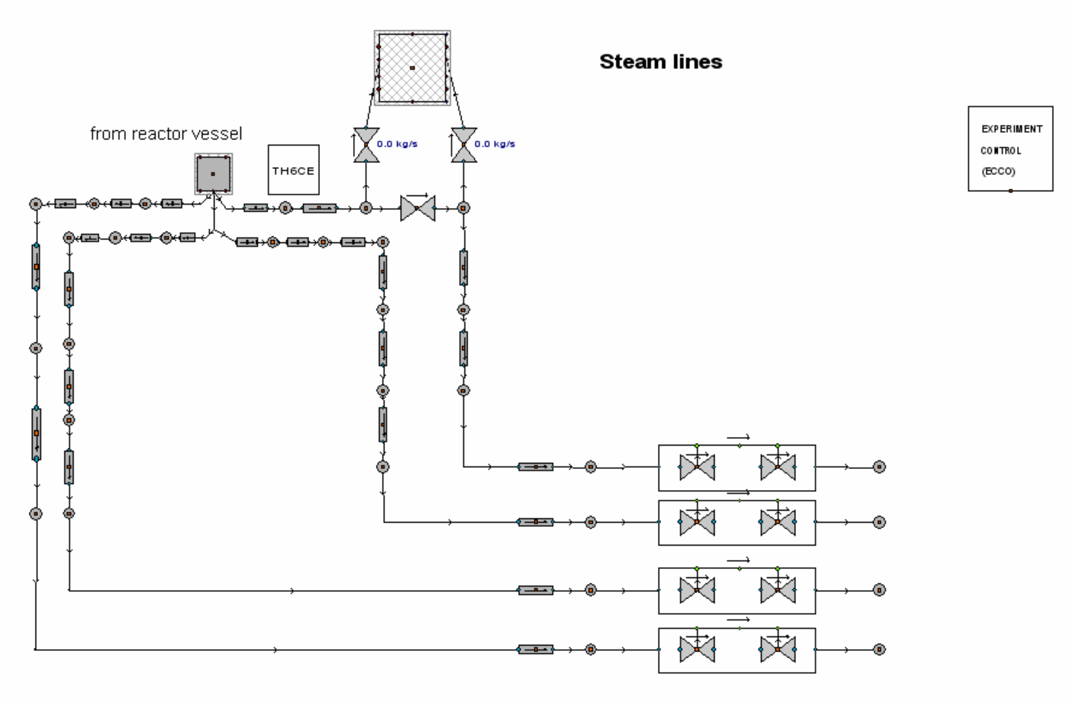

Figure 5. APROS Steam line model of Olkiluoto nuclear power plant with break valves

In the transient the inner isolation valve of the broken steam line is assumed to stay open. Two out of four lines in the containment spray system, core spray system and auxiliary feed water system are in use. During the first 3600 seconds of simulation the containment spray is distributed between the drywell and wetwell nodes. After that the whole spray flow goes to the drywell.

Reactor scram occurs shortly after the break valves in the steam line are opened and the reactor power decreases rapidly. The reactor pressure starts to decrease rapidly and there is some flow through the valves of the pressure relief system in the beginning of the transient. Feed water flow ceases very quickly. The recirculation pumps are first ramped down to the minimum speed of 550 rpm and tripped 9 seconds after the reactor scram. The containment spray system starts about 20 seconds after the beginning of the transient and the auxiliary feed water flow about 40 seconds after the beginning. The core spray starts to deliver water to the reactor vessel when the pressure has fallen below the shut-off head of spray pumps.

When the auxiliary feed water system is started for the first time, two loops are in use. When the water level in the reactor vessel goes over 5.0 meters, core spray and auxiliary feed water flows are stopped. When the level goes below 3.6 meters, one loop of the auxiliary feed water is started. The auxiliary feed water flow is alternately started and stopped during the rest of the transient.

The main difference between APROS and COBLIN and COPTA results is the behaviour of the water level of the reactor vessel and consequently the amount of the break mass flow [5]. The break flow calculated by GOBLIN between 20 and 100 seconds is considerably higher than the flow simulated by APROS. The level in the GOBLIN calculations rises higher and there is more water in the break flow than in the APROS calculation. There are also small differences in the containment behaviour in the successive APROS versions.

The overall behavior of the containment during the whole transient is similar in the APROS and COPTA calculations [5]. The cyclic behavior of the containment pressures and temperatures is caused by changes in the break flow and is predicted by both codes. The auxiliary feed water system is alternately turned on and off according to the liquid level in the reactor vessel.

Figures 6-8 indicate the results for some of the main parameters of the transient.

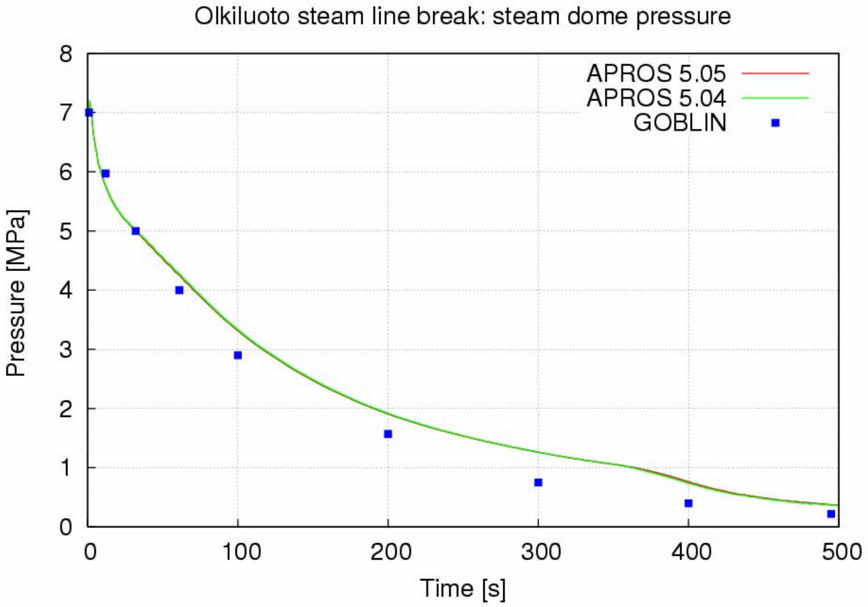

Figure 6. Steam dome pressure during the first 500 seconds.

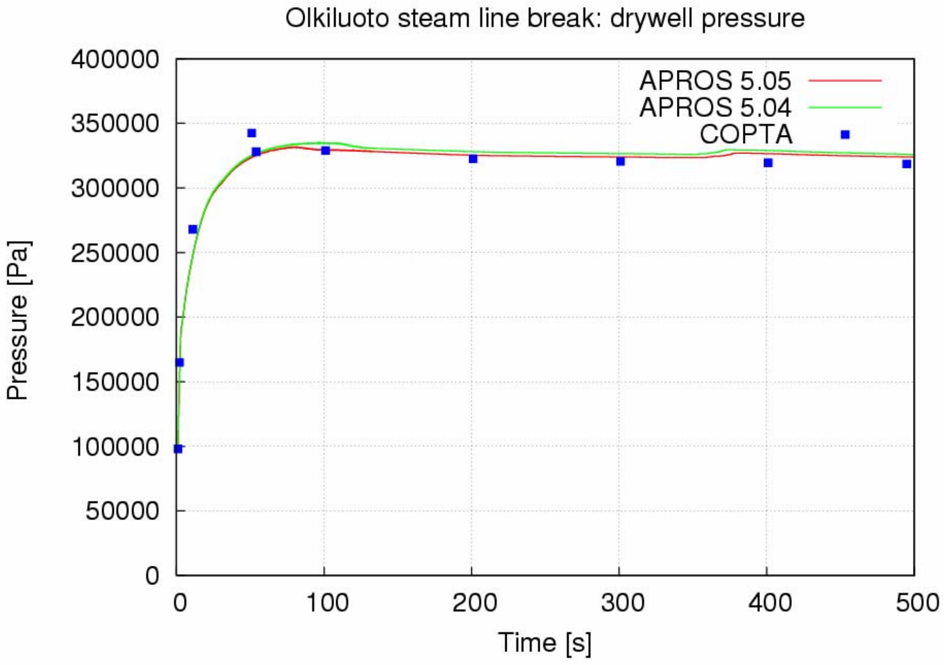

Figure 7. Drywell pressure during the first 500 seconds.

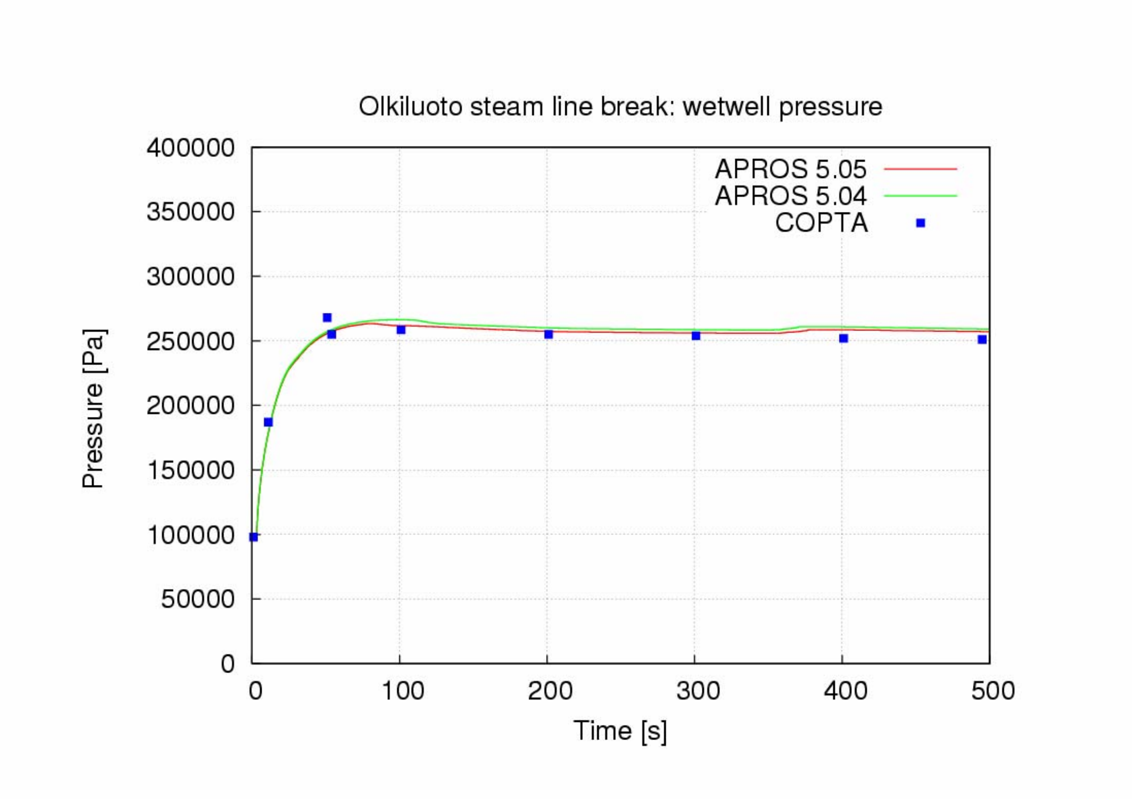

Figure 8. Wetwell pressure during the first 500 seconds.

3. COUPLED 3-D CORE AND CIRCUIT WITH IMPROVED BORON FRONT DESCRIPTION

The accurate simulation of a sharp boron front entering e.g. the core of a pressurized water reactor has not been possible in APROS. The problem has been handled with dense nodalization and small time steps. However, due to the first order upwind discretization scheme, the boron front is smoothened when the fluid proceeds over several calculation volumes. In version 5.05 the problem has been solved by using second order upwind discretization scheme in the concentration solution. A similar problem in simulating the propagation of a temperature front has been solved by using a second order space discretization for the enthalpy solution [7].

The simulation model of the Loviisa nuclear power plant (a pressurized water reactor plant of type VVER) includes all the major subsystems of the Loviisa 1 unit [5]. The primary circuit and core have been modelled for various purposes either with the five-equation or the six-equation model and the secondary circuit with the homogeneous model. One picture from the simulation model (part of the primary circuit) is shown in Figure 9.

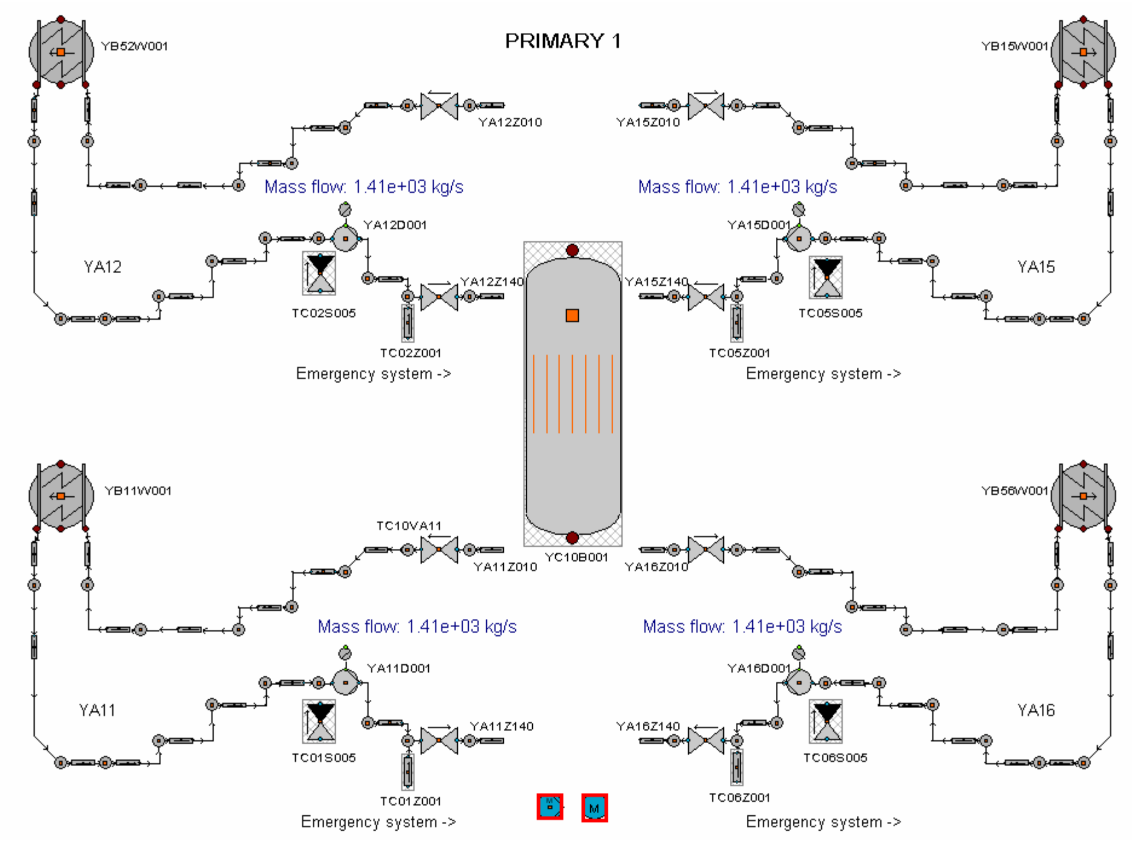

Figure 9. Primary circuit of the simulation model of the Loviisa nuclear power plant

The example transient studies the effect of boron plug propagation in the 3-D core with the improved boron front propagation model in comparison with the traditional description used until now in APROS. The 3-D core consisted of 313 fuel assemblies divided into 10 axial nodes and placed into 53 one-dimensional thermal hydraulic flow channels modeled with the five-equation thermal hydraulic model.

In the example a boron plug of 200 ppm was instantaneously induced into the core. Figure 10 shows the smoothening of the boron concentration over the successive core nodes with the first order discretisation and the improvement in the sharpness of the front with the second-order discretisation. Figures 11 illustrates the situation in three successive core nodes during the same instant tin the first order discretisation. The corresponding results for the second-order discretisation scheme have been shown in Figure 12.

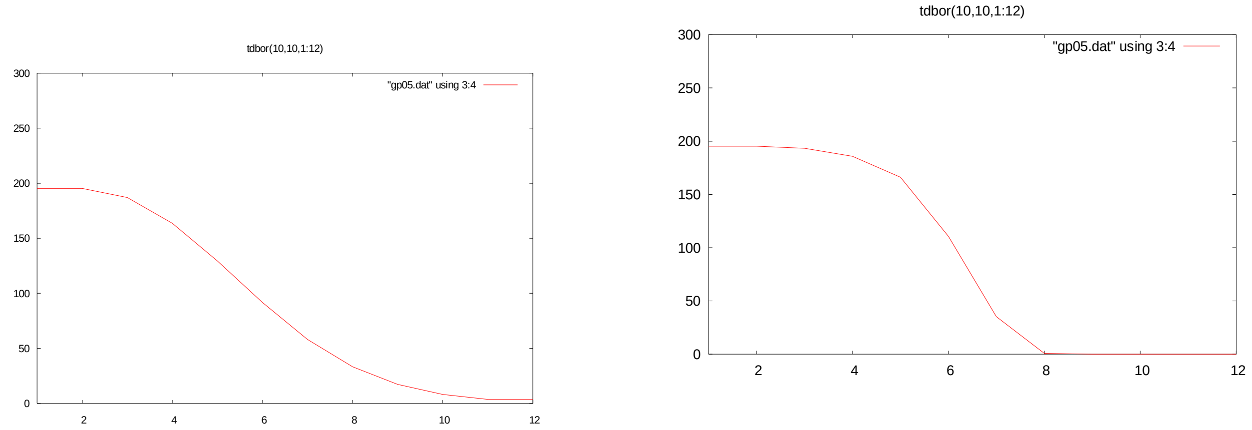

Figure 10. Axial propagation of boron front in core with the first (left) and second order (right) discretisation.

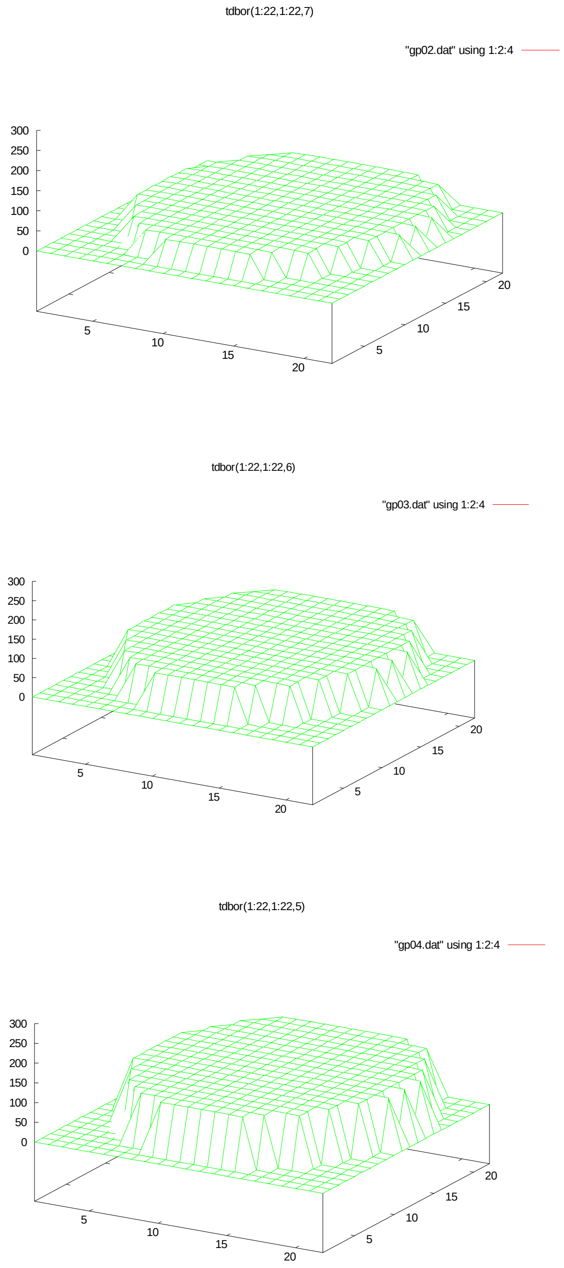

Figure 11. Boron concentration in three successive axial nodes in first-order discretisation.

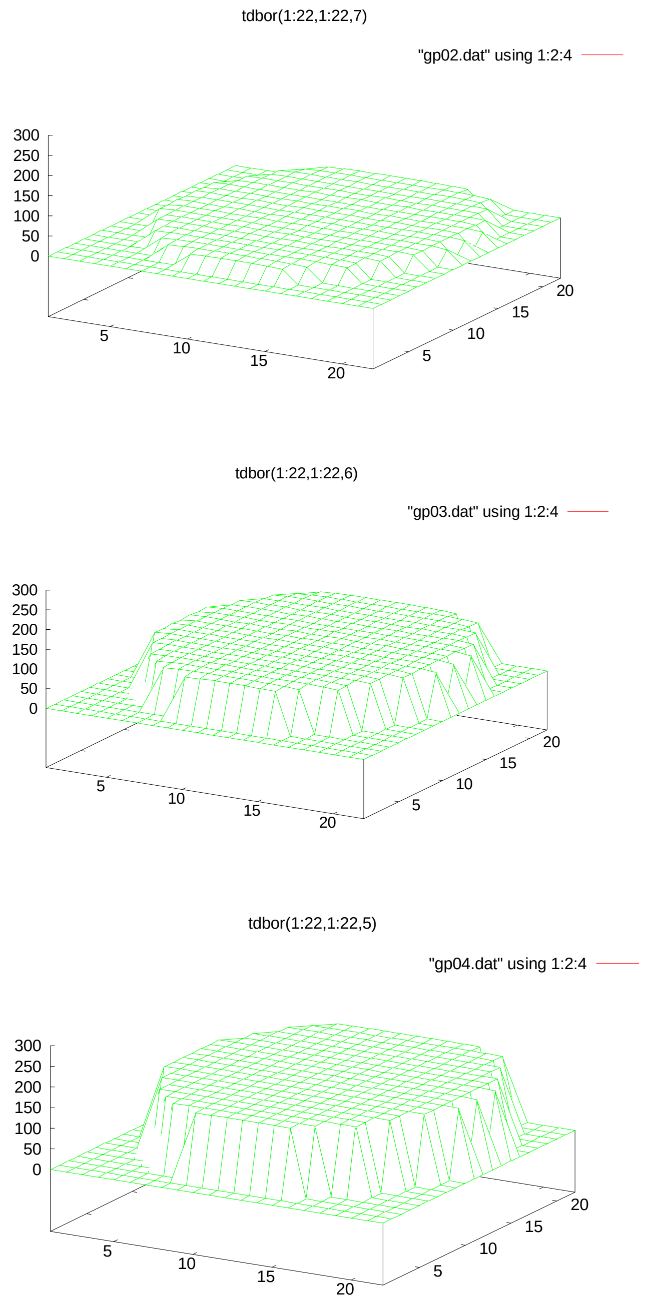

Figure 12. Boron concentration in three successive axial nodes in second-order discretisation.

A more pronounced improvement can be achieved in cases, where dense nodalisation is used with the six-equation model, as indicated in the basic test in Figure 13, where a simple model consisting of one pipe (length = 600 m and flow area = 0.01 m2) is divided into 100 calculation nodes of equal length. The pipe contains water with the pressure 1 MPa and temperature 100 °C. The mass flow in the pipe is constant (about 17 kg/s). In the beginning of the test the boron concentration inside the pipe is 1000 ppm. The boundary condition defining the incoming boron concentration is changed to 0 ppm and the simulation is continued for 500 seconds. After that the incoming concentration is changed back to 1000 ppm and the simulation continued for another 500 seconds.

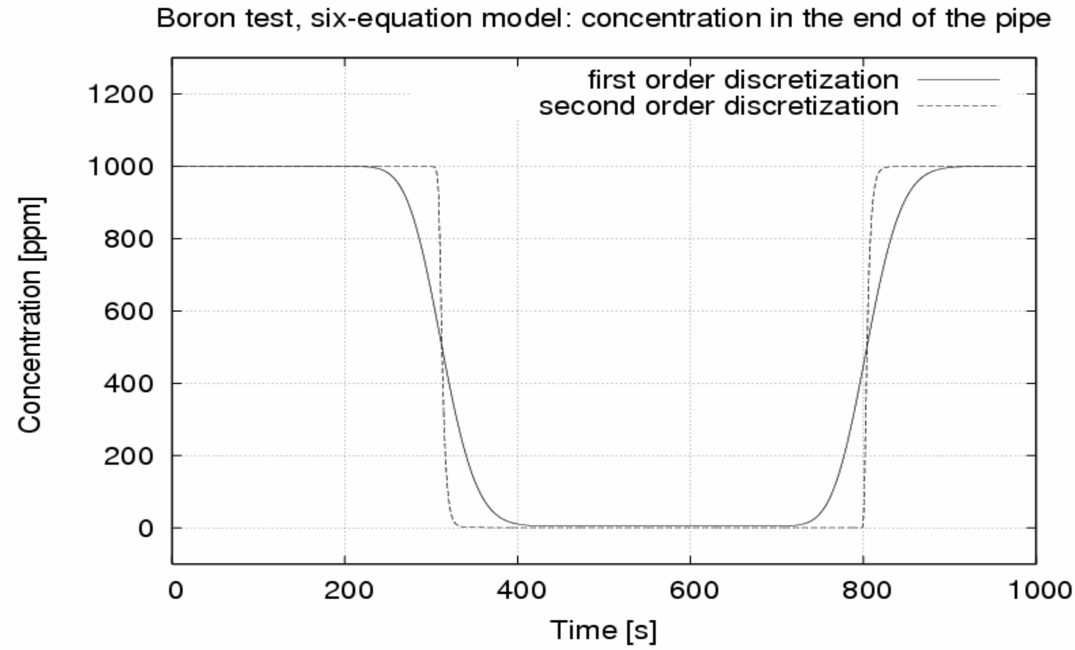

Figure 13. Improvement in boron propagation front end of a pipe divided into 100 axial nodes.

4. FURTHER DEVELOPMENTS

Development of APROS simulation environment is continuing constantly is various application areas. In the nuclear area a further coupling with more accurate fuel behaviour calculation model of VTT is foreseen. Further improvements are also foreseen in the 3-D core model both with improved accuracy of the present finite-difference based solution and with eventual inclusion of a nodal solution method, as well as studies on the possibility of coupling APROS plant models with external core physics and dynamics calculation packages.

5. CONCLUDING REMARKS

APROS simulation environment is able to describe the1-D and 3-D neutronics of the reactor core. It is also able to describe the thermal hydraulics of the core and circuits either with 5-equation or 6-equation thermal hydraulics. It can also describe the plant automation and electrical systems, as well as the behaviour of the containment. The peculiar feature of APROS in comparison to other coupled systems is that all parts in the coupled system are described with the same code.

The most recent possibility is the coupled calculation of the process and the containment. The calculation examples presented indicated the functionality this newest coupling. The results obtained were in good agreement with those obtained with reference codes.

A second-order upwind discretisation scheme applied for the boron concentration solution improved the accuracy of the description of boron front propagation ion core and in the circuit.

ACKNOWLEDGEMENT

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