Preliminary validation of the APROS 3-D core model of the new Loviisa NPP training simulator

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Abstract

Loviisa NPP has experienced in the past several modernization phases. The two VVER-440 units started operation in 1977 and 1981, respectively. The power of each unit is now 510 MWe and their present operation licenses cover the planned 50 years operation lifetime. A new training simulator is being built as a part of the extensive plant automatisation renewal that is scheduled to be finalised in 2014. The 3-D core model of the new training simulator has been built using the APROS software. APROS is also the software for the rest of the training simulator. Prior to building of the simulator core model, an extensive comparison was carried out between APROS and VTT's in-house reactor analysis code HEXTRAN that has been widely used in Loviisa licensing calculations by the Finnish safety authority STUK. The agreement between APROS and HEXTRAN was generally acceptable. The largest differences were related to the effect of control rods and the radial flux shapes especially near the core boundary. It was concluded that APROS core model was suitable for modelling the training simulator core. On the basis of previous experience on the speed of various APROS core models a model with approximately 100 thermal hydraulic flow channels divided into 10 axial sections was assumed to be realistic for real time performance. Various alternatives were studied resulting into a model with 110 channels. The simulator core model has been tested with comprehensive set of test cases against data from current Loviisa training simulator LOKS, data from some plant transients and calculations carried out with other models. The results indicate that the new 3-D simulator model is suitable for application in the training simulator. At the moment the simulator core and process model can be run in real time in parallel combination either with two separate computers or using a dual core computer. Work is still going on to refine the process and automation models to solve the bottlenecks found in particular in the calculation of the LOCA cases.

Keywords

Training simulators, core modelling, neutronics, thermal hydraulics

1. INTRODUCTION

Loviisa NPP has experienced in the past several modernization phases. The two VVER-440 units started operation in 1977 and 1981, respectively. The power of each unit is now 510 MWe and their present operation licenses cover the planned 50 years operation lifetime. A new training simulator is being built as a part of the extensive plant automatisation renewal that is scheduled to be finalised in 2014.

The 3-D core model of the new training simulator has been built using the APROS software. APROS is also the software for the rest of the training simulator. APROS Simulation Environment has been co-developed and is co-owned by Fortum Nuclear Services and VTT Technical Research Centre of Finland. The simulation environment is described in references [1,2].

In addition to Loviisa NPP applications APROS has been used in many applications. Currently APROS software is used by VTT as TSO for the Finnish Radiation and Nuclear Safety Authority STUK for Olkiluoto 3 EPR plant safety studies. Simultaneously Fortum Nuclear Services has been building an independent model of Olkiluoto 3 for the plant owner Teollisuuden Voima Oyj (TVO).

This paper describes the new Loviisa VVER-440 training simulator 3-D core model and its performance in the comparisons with VTT in-house codes and in test cases versus real plant data and transients run with the current Loviisa training simulator LOKS.

2. TESTING OF APROS-3D CORE MODEL AGAINST REFERENCE HEXTRAN CORE MODEL FOR LOVIISA VVER-440

APROS 3-D core model is a two-energy group, six delayed neutron group finite difference type model that is able to describe both hexagonal and quadratic lattice types [3]. The core model of HEXTRAN is a two-energy group, six delayed neutron group nodal model for hexagonal lattices [4].

The APROS 3-D core model is able to use the same cross-section data as the HEXTRAN code. Besides the different solution method the largest differences in neutronics solution between these two codes are the description of control rods and the description of core boundaries. Control rods are described with control element two-group constants (cross sections) in APROS, whereas albedoes are utilised for control rod description in HEXTRAN. In core boundary description APROS utilises extrapolation lengths whereas albedoes are utilised in HEXTRAN. The two codes utilise different thermal-hydraulic models, but the effects resulting from that difference were minimised to as small as possible in these code to code comparisons.

For fuel assemblies both APROS and HEXTRAN are able to use the same cross-section data files that had been generated at the plant using VTT’s in-house code HEXBU-3D [5]. Before the creation of the simulator core model, proper cross section data files had to be created for the control rod description in APROS [6].

The APROS-HEXTRAN comparisons were carried out with detailed core models, where each assembly was divided axially into 20 nodes, and each assembly was placed in its own thermal hydraulic flow channel in both codes. Thus, there were 313 fuel assemblies, 37 control rods, 313 one-dimensional flow channels. This APROS core model with 6260 neutronics nodes and 6230 thermal hydraulic six-equation model calculation nodes represents typically the nodalisation schemes in safety analysis applications.

In steady state detailed comparisons of flux, temperature etc. on node by node basis between the two codes was carried out. At steady state the largest differences between the two codes in the node wise fast and thermal flux values were found at the core boundaries, as is illustrated in Figure 1. This difference is due to the more refined handling of core boundaries. There was also some difference in the effect of control rods on axial flux. The cases studied in the extensive comparison are given in Table 1. The results of the comparison have been reported in detail in reference [7].

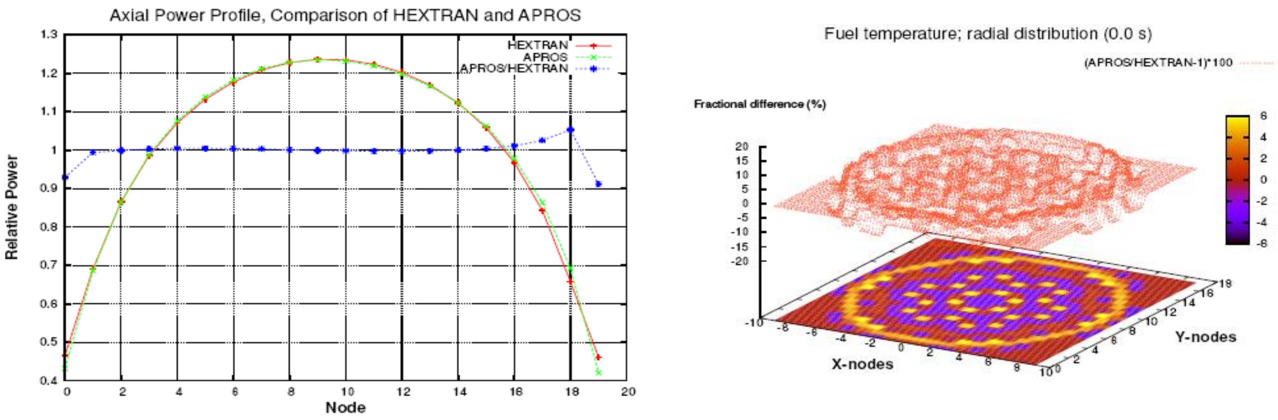

Figure 1. APROS-HEXTRAN COMPARISON: Axial power profiles (left) and radial fuel temperature distribution (right) at steady state.

Table 1. APROS-HEXTRAN comparison cases.

Plant state	**Comparison case**
Steady state	Detailed comparisons of flux, temperature etc. on node by node basis
Transient	SCRAM - insertion of all control assemblies with 0.2 m/s,
Transient	Insertion of group 6 (control assemblies 1, 7 and symmetric positions) with 0.02 m/s
Transient	Insertion of control assembly 7 with 0.02 m/s
Transient	Reduction of coolant inlet flow to 90 % in 5 s
Transient	Reduction of coolant inlet flow to 80 % in 5 s
Transient	Reduction of coolant inlet flow to 50 % in 10s

In Figures 2 and 3 two examples of the transient tests are given. In both cases the core average power behaviour agrees quite well and in the node wise comparisons the largest differences are at core boundaries. In the coolant transient in Figure 3 the difference of the different thermal hydraulics models of the two codes is probably contributing to the small difference in power behaviour during the transient. At steady state the core average fuel temperatures were set to equal value via tuning of the fuel cladding gap conductance in the models.

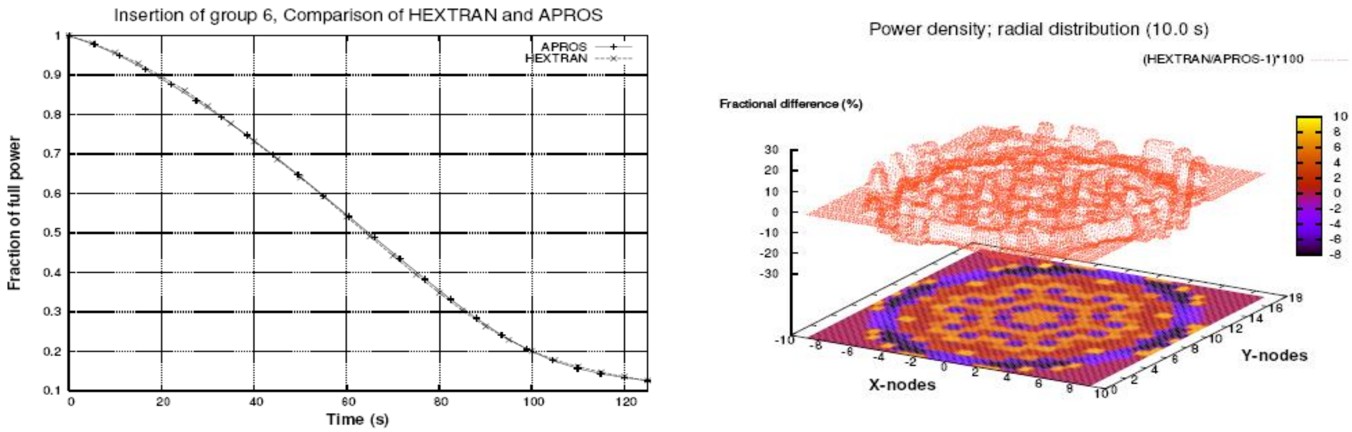

Figure 2. APROS-HEXTRAN COMPARISON: Reactor power vs. time and fractional difference in radial power distribution at time 10 seconds during control rod group 6 insertion.

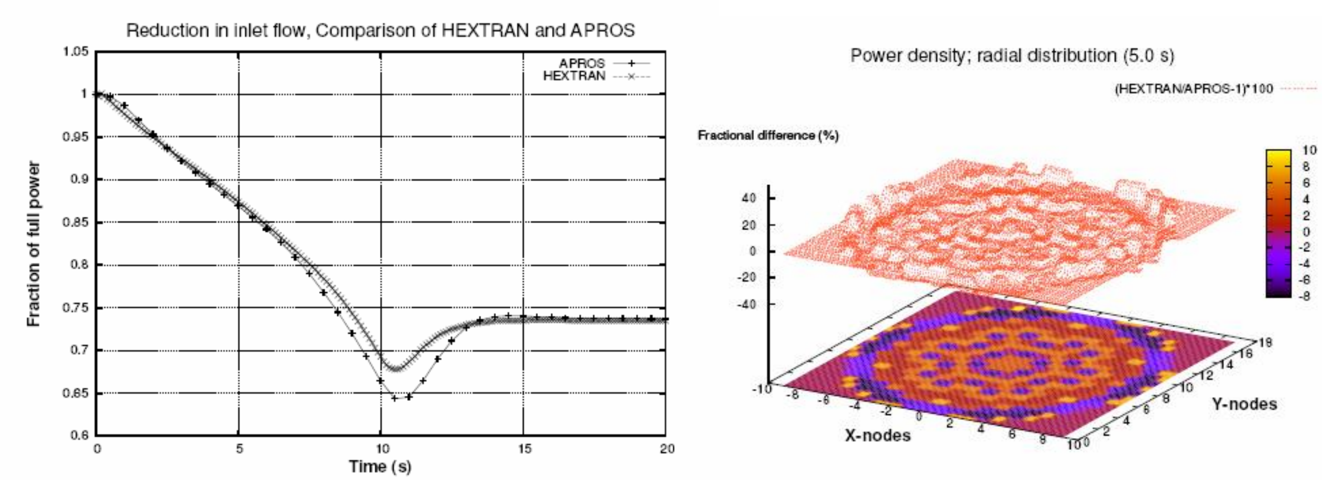

Figure 3. APROS-HEXTRAN COMPARISON: Reactor power vs. time and fractional difference in radial power distribution at time 5 seconds during the reduction of coolant inlet flow from 100 % to 50 % in 10 seconds.

In general the agreement between the two codes was found to be good, especially considering the core overall behaviour (power, fuel and coolant temperature, coolant density etc.). In node wise comparisons the largest differences were found at the core boundary nodes. The differences were due to the better accuracy of the nodal method used in the reference code HEXTRAN versus the finite difference method used in

APROS and due to the different description of core boundaries. However, it was concluded that these differences were not significant for training simulator purposes. Thus, APROS was found to be suitable for modelling the new Loviisa simulator core.

3. CREATION OF THE NEW SIMULATOR CORE MODEL

On the basis of previous experience on the speed of various APROS 3-D core models [3,9,10] a model with approximately 100 thermal hydraulic channels divided into 10 axial sections was assumed to be realistic for the required real time performance. Various alternatives to divide the fuel assemblies into thermal hydraulic channels to obtain the best agreement with the detailed APROS and HEXTRAN models were studied. The studies resulted in 3-D core model that consists of 313 fuel assemblies, 37 control rods and 110 one-dimensional thermal hydraulic flow channels. The fuel assemblies in the neutronics model as well as the thermal hydraulic channels have been divided into 10 axial nodes. In the test calculations the 3-D model has been directly connected with the plant process and automation model. In the APROS 3-D core model for Loviisa training simulator the 6-equation thermal hydraulics model is used in the core thermal hydraulic channels and in primary circuit nodes.

At present the current APROS plant model can be run both using the 3-D APROS core model and a with the very fast 1-D APROS core model, which is suitable for many such tests during the simulator development where the reactor core is playing a minor role. Table 2 gives information on extent of the current plant model and Table 3 gives information on the 3-D core model.

Table 2: Extent of the new Loviisa training simulator without the 3-D core model.

Component type	Number of components
Homogeneous thermal hydraulic nodes	2828
Six-equation thermal hydraulic nodes	943
Heat structure nodes	4650
Basic pumps	192
Motor pumps	6
Control valves	277
Shut off valves	1980
Common valves	16

Table 3: Extent of the 3-D core model in the new Loviisa simulator model.

Component type	Number of components
Fuel assemblies	313
Control rods	37
1-D Flow channels in core model	110
Neutronics nodes	3130
Six-equation thermal hydraulic nodes	1103

In APROS the number of six-equation thermal hydraulic nodes is the most decisive factor for calculation speed. Thus, the slowing down of the simulator speed from 1.5 faster than real time with the 1-D core model to some 70 % of real time with the 3-D was reasonable since inclusion of the 3-D core doubles the amount of six-equation nodes in the simulator model. Radial power distribution in the simulator 3-D core model is shown in Figure 4.

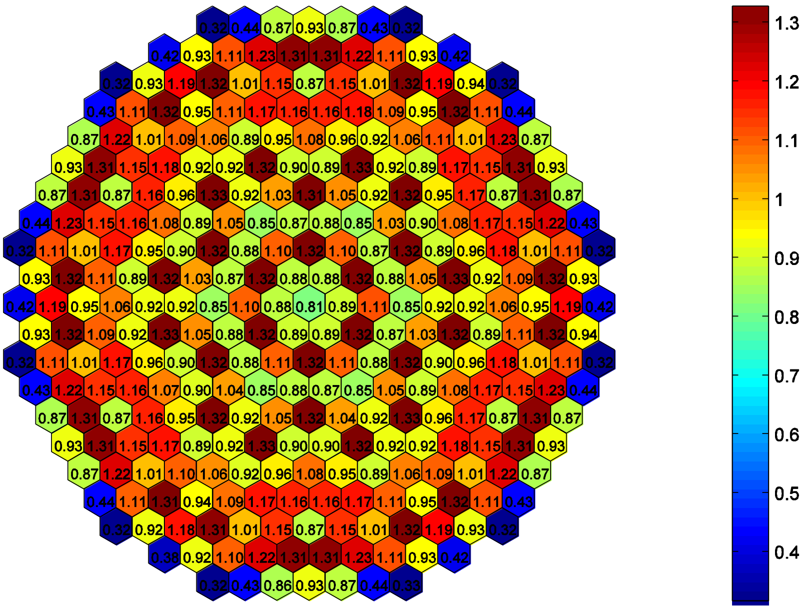

Figure 4. Radial power distribution at BOC.

4. PRELIMINARY VALIDATION OF THE NEW SIMULATOR CORE MODEL

The results obtained with the new simulator core model have been compared with data from current Loviisa training simulator LOKS, data from some plant transients and calculations carried out with other models. The cases of the preliminary validation are given in Table 4. The creation of the core model and the testing have been described in detail in [8].

Table 4. Test cases of the new simulator core model.

Test case
Steady state operation
Reactor scram

Fast shut-down
Slow shut-down
Dropping of one control rod group
Dropping of one control rod
Stopping and starting of one main circulation pump
Stopping of three main circulation pumps
Stopping of three main circulation pumps after turbine trip
200 cm2 LOCA
20 cm2 LOCA as ATWS

Some of the test results have been shown in Figures 5-14. In some cases, such as the control rod drop shown in Figure the behaviour of APROS was deemed to be more physical by the experts at the plant than that of the old simulator. In APROS reactor power stabilizes to the constant value whereas in old simulator LOKS power slowly creeps to a lower value. Similar power creeping in old simulator can be seen also in other test cases such as in the fast shut-down shown in Figure 10. The radial power distribution obtained with the new model is shown in Figure 6.

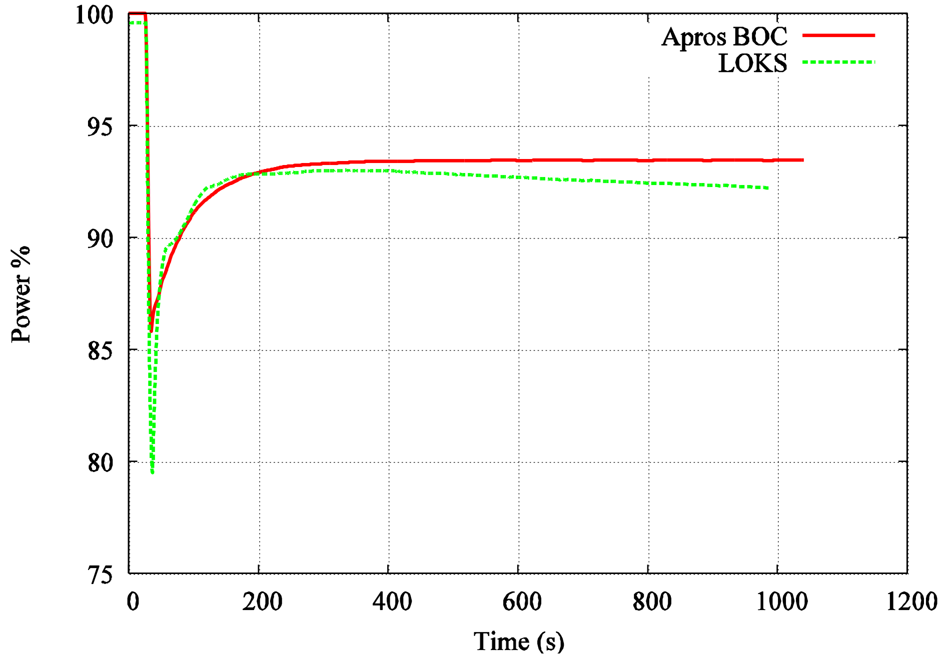

Figure 5. APROS vs. old simulator (LOKS): Total power vs. time, Control rod drop, rod NCL207, group 6, BOC.

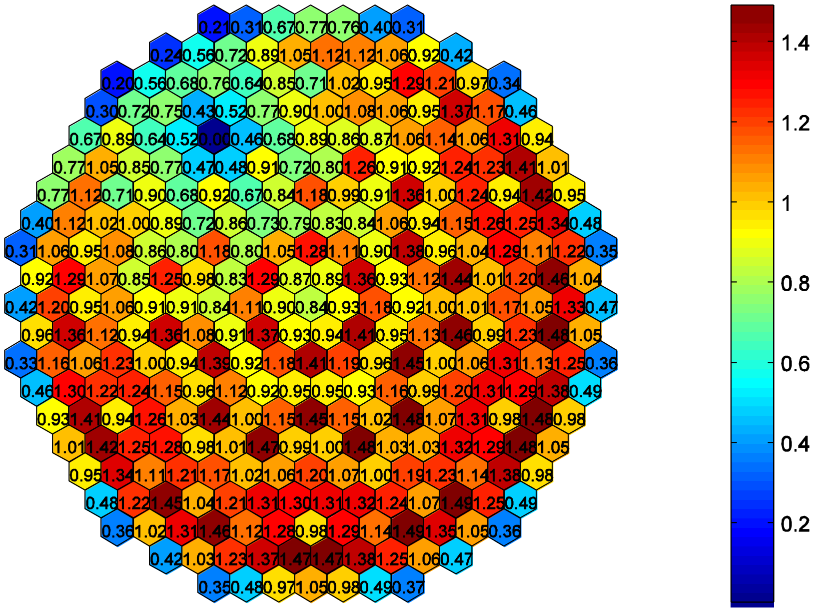

Figure 6. Radial power distribution 15 seconds after control rod drop, rod 207, group 6, calculated with APROS

In comparisons with existing real plant data from the Loviisa Units 1 (LO1) and 2 (LO2) the new model was able to describe the plant overall behaviour and trends well, but all details were not accurately simulated, as shown for example in Figure 7 and Figure 8, where deficiencies in modelling of steam generator level control lead to different behaviour of steam pressure. In Figure 9 where three main circulation pumps trip simultaneously 87 seconds after turbine trip, the behaviour of reactor power is very similar to measured plant data.

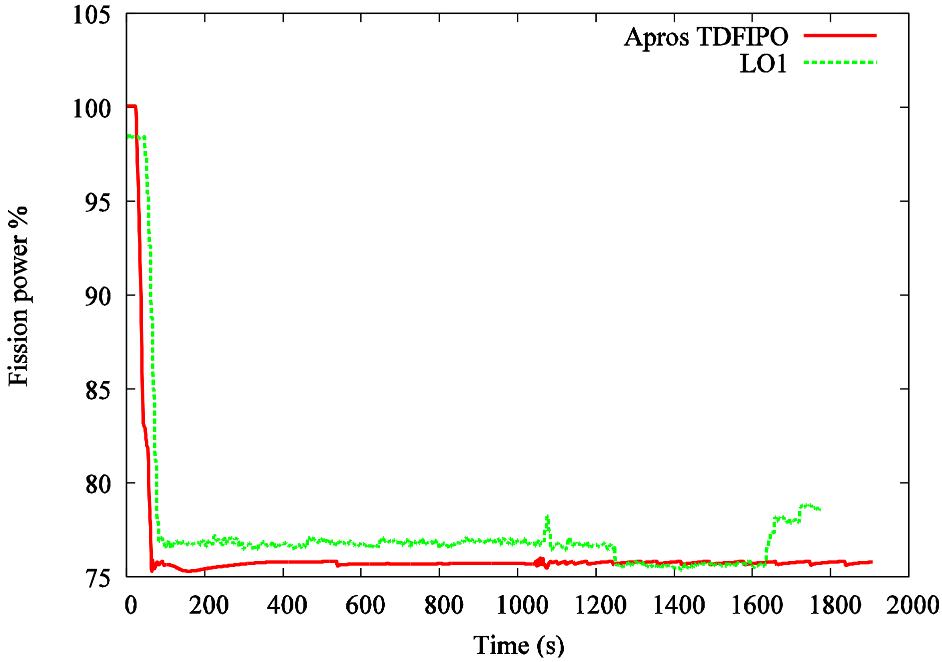

Figure7. APROS vs. plant data (LO1): Stopping and starting of main circulation pump YD11D001, Fission power vs. time.

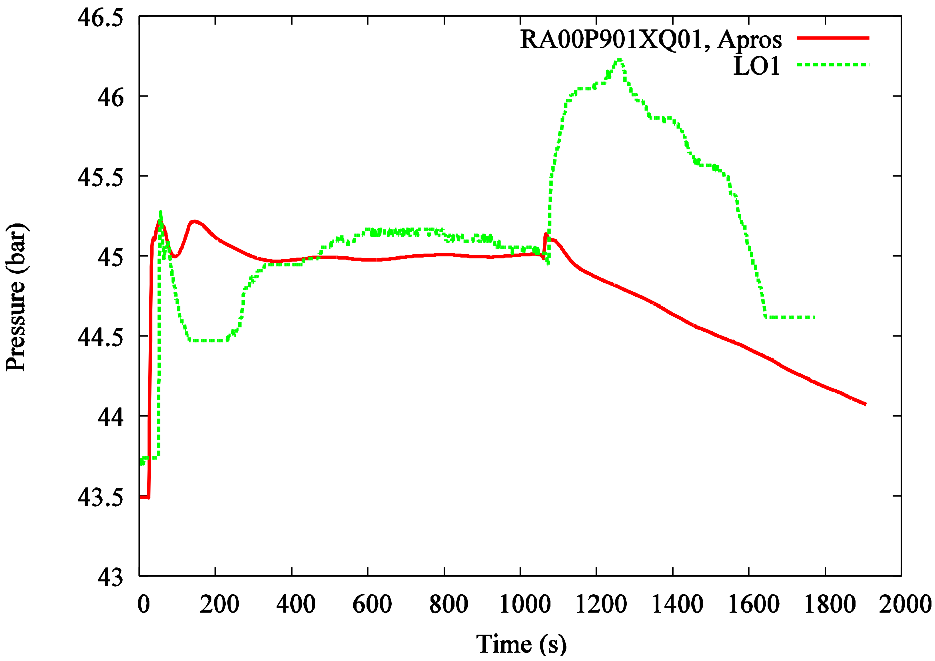

Figure 8. APROS vs. plant data (LO1): Stopping and starting of main circulation pump YD11D001, Steam pressure vs. time.

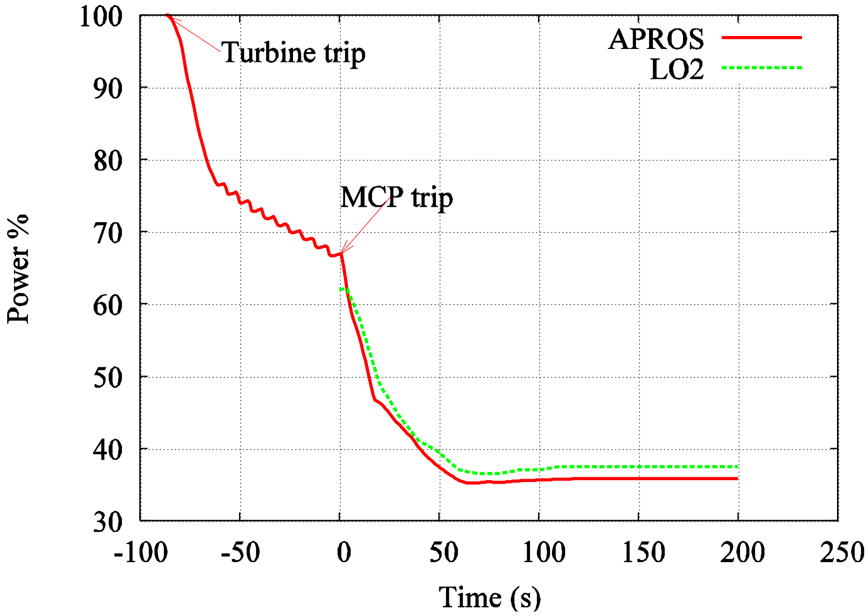

Figure 9. APROS vs. plant data (OL2): Turbine trip and stopping of three main circulation pumps, Reactor power vs. time.

In some cases there were also changes either in the plant modelling or in the control algorithms in the plant that resulted in some differences in the models. Such an example is shown in Figure 10 and Figure 11, where the power level in the successive trip of three main circulation pumps is in fairly good agreement in the old and in the new simulator, but the control rods remain at somewhat higher level in the old simulator at each step.

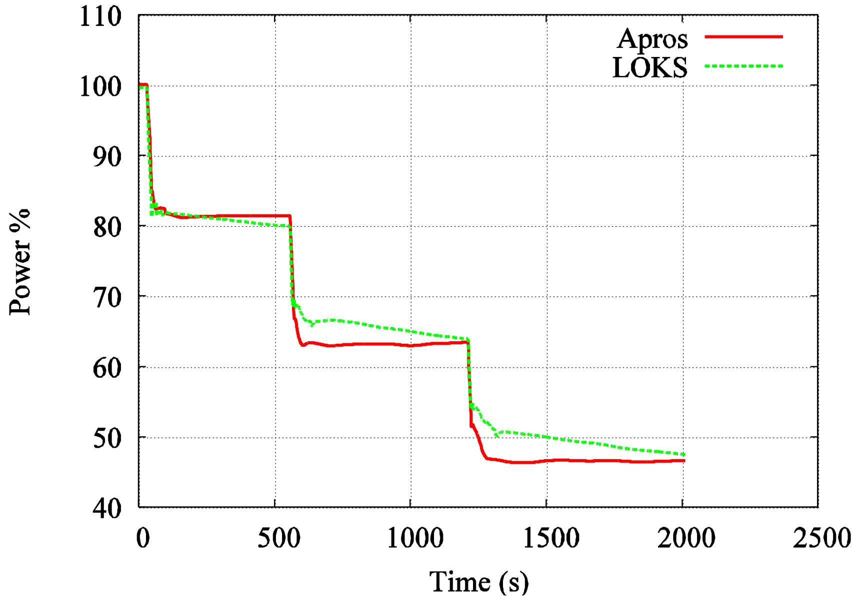

Figure 10. APROS vs. old simulator (LOKS): Successive stopping of three main circulation pumps, Fission power vs. time.

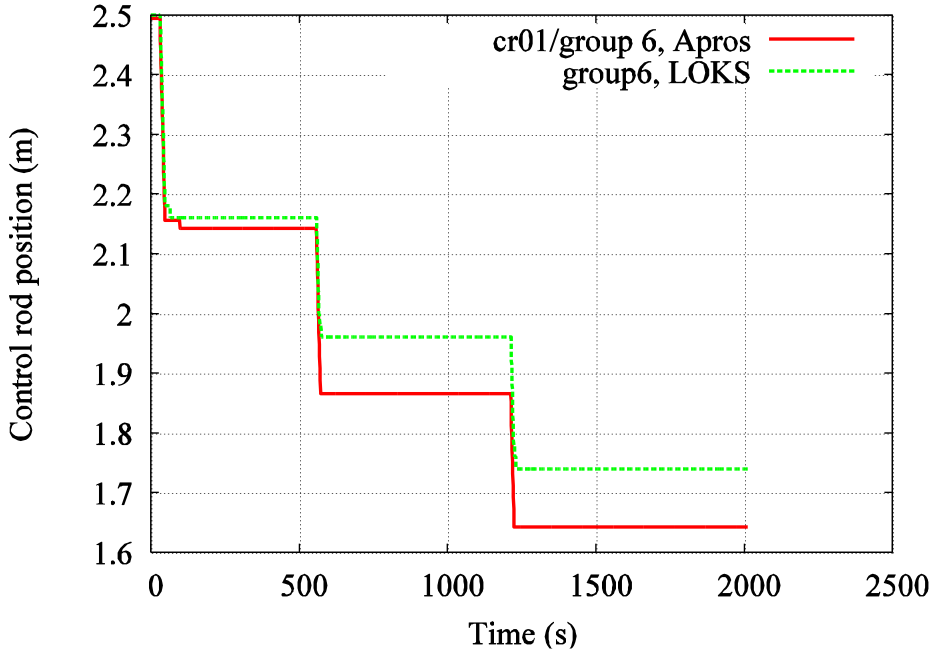

Figure11. APROS vs. old simulator (LOKS): Successive stopping of three main circulation pumps, Control rod position vs. time.

In order to test 3-D core response to the primary side leak a test case of 20 cm^2 LOCA as Anticipated Transient Without Scram (ATWS) was carried out and compared to the behaviour of the old training simulator. The reactor core behaves similarly to the old simulator as can be seen in Figure 12.

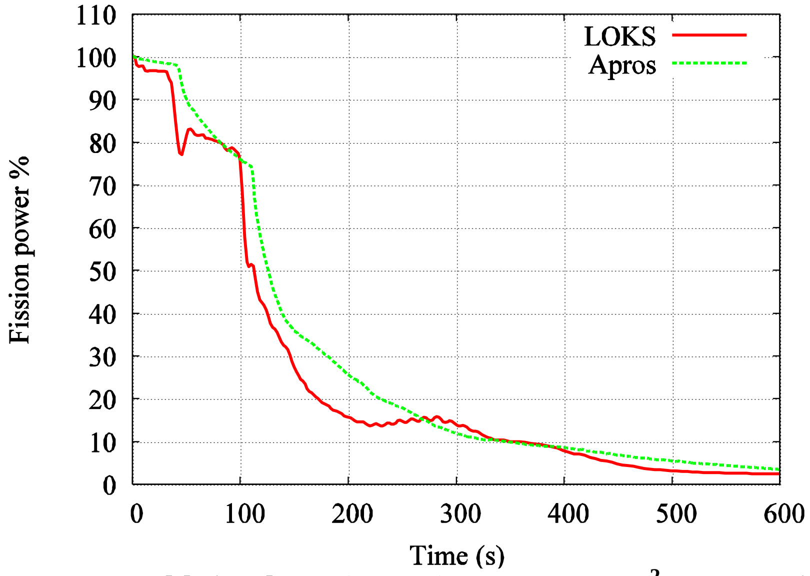

Figure12. APROS vs. old simulator (LOKS): LOCA 20 cm^2 ATWS, Fission power vs. time.

Some of the test carried out for the 3-D core model, such as the 200 cm^2 LOCA proved out to be very challenging for the entire simulator model. In the LOCA case scram takes place at the early stages of the transient as shown in Figure 13. The 3-D core model did not experience any problems in surviving the transient even if most of the reactor core is uncovered. Also behaviour of primary circuit conditions is similar with APROS than with the old simulator as shown in Figure 14. However, the calculation of the transient turned out to very effective in revealing several errors and bottlenecks in the circuit and in the plant automation model.

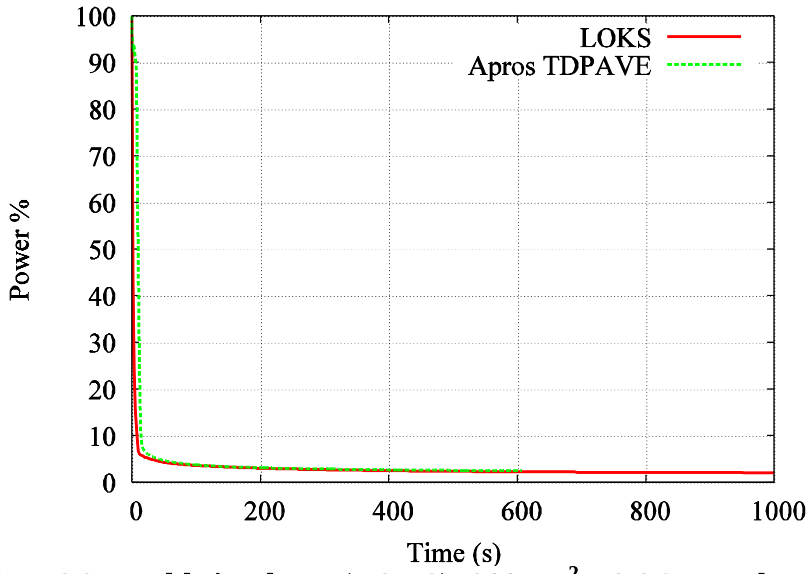

Figure 13. APROS vs. old simulator (LOKS): 200 cm^2 LOCA, Total power vs. time.

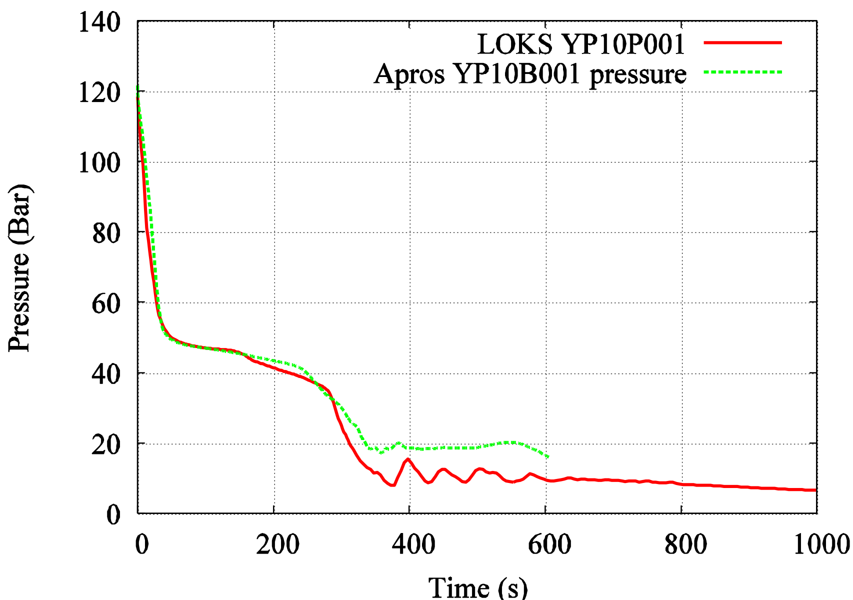

Figure 14. APROS vs. old simulator (LOKS): 200 cm^2 LOCA, Pressurizer pressure vs. time.

5. FURTHER DEVELOPMENTS

The new simulator core model created was tested in the mode where the 3-D core model and the plant process and automation model were all run on the same processor. In this combination the simulator was slower than real time. A separate project for the parallelisation of the 3-D core model and the process model has been carried out [11]. In that project the main purpose was to realise the parallelisation both using to separate computers and using a computer with dual core and to verify that the parallelised model behaved similarly with the original model. In that project calculation speed 1,22 times real time was obtained with an Intel Core 2 computer (2,40 GHz, 3,25 GB memory).

A separate project has also been carried out to increase the analysis capability of APROS by addition of a nodal hexagonal neutronics model into APROS [12]. This, however, is primarily for safety analysis purposes and is expected to be ready for daily use within 2-3 years after thorough testing.

At the moment the simulator core and process model can be run in real time in parallel combination either with two separate computers or using a dual core computer. Work is still going on to refine the process and automation models to solve the bottlenecks found in particular in the calculation of the LOCA cases and significant improvements have been achieved in comparison to results presented in [13].

6. CONCLUSIONS

A new training simulator is being built for the Loviisa NPP a part of an extensive plant automatisation renewal that is scheduled to be finalised in 2014. The simulator is realised using APROS software. In this paper the creation and testing of the 3-D core model of the simulator was described. The first step of development of new 3-D APROS core model was an extensive comparison between APROS and VTT's in-house nodal code HEXTRAN that has been widely used in Loviisa licensing calculations by Finnish Radiation and Nuclear Safety Authority STUK. In general the agreement between the two codes was found to be good and APROS was found to be suitable for modelling the simulator core.

The new simulator model created with APROS has been primarily validated using data from current Loviisa training simulator (LOKS) and plant data from some transients at the Loviisa NPP. The results of the comparisons with the current simulator and plant data indicate that the new APROS 3-D core model is suitable for application in the new training simulator.

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