TOPSAFE
Dubrovnik, Croatia, 30.09 - 3.10.2008

APROS Simulation Model for Olkiluoto-3 EPR Applications

Kari Porkholm, Harri Kontio, Herkko Plit
Fortum Nuclear Services Ltd
POB 100, 00048 FORTUM, Finland
Kari.Porkholm@fortum.com, Harri.Kontio@fortum.com, Herkko.Plit@fortum.com

Marjo Mustonen, Kristiina Söderholm
Teollisuuden Voima Oyj
27160 EURAJOKI, Finland
Marjo.Mustonen@tvo.fi, Kristiina.Soderholm@tvo.fi

ABSTRACT

On the assignment of the plant owner Teollisuuden Voima Oyj, Fortum Nuclear Services Ltd has developed an APROS simulation model for Olkiluoto 3 EPR type Nuclear Power Plant. The developed model is being used for independent engineering and safety analyses of Olkiluoto-3 EPR Nuclear Power Plant Unit. The simulation model contains a detailed description of the primary and secondary circuits, emergency systems, protection systems, main and some auxiliary control systems. The simulation model has been validated in steady state, transient and accident situations. The EPR simulation model has been used in the analyses of some transients such as a spurious closure of low pressure steam admission valves and reverse flow of the low pressure turbine extraction lines. The developed simulation model has been utilized also in the safety analyses e.g. in the analysis of the cold leg large break loss-of-coolant accident (LBLOCA). For this application, a new counter-current flow limitation (CCFL) correlations for the downcomer and the upper tie plate have been implemented in APROS. In the paper, a short overview of APROS Simulation Software and its utilization in different kinds of applications are given. The paper describes the extent of the developed EPR application model and some results of the validation of the model. The description of the new CCFL correlations and the results of the validation calculations are presented. Finally, some results of the analyses of the transients and LBLOCA accident are presented and the utilization of APROS in these applications is discussed.

1 INTRODUCTION

The electricity consumption is growing in Finland. At the same time, old fossil power plants are being decommissioned. The Olkiluoto 3 Nuclear Power Plant (OL3) which is now under construction will compensate for the increasing demand and will replace obsolete production capacity. The environmental factors are becoming more important in the power generation. The OL3 will also help Finland to attain the targets defined in the Kyoto Protocol.

The OL3 project is being implemented on a turnkey basis by a French-German Consortium formed by AREVA NP and Siemens. The OL3 is a pressurized water reactor, more specifically an EPR (European Pressurized Water Reactor).

The design of the process and automation systems as well as the production of the safety analyses are some of the numerous tasks of the Consortium in the project. The interest of the plant owner is to make sure in the early phase of the project that all the plans and analyses results correspond to the requirements which are conditions for the safe and economical operation of the plant.

A simulation is an effective and useful tool to understand more deeply the behaviour of the plant. By means of the simulation, the plant owner can check the process and automation plans as well as make comparison calculations with safety analyses delivered by the Consortium. Due to this, Teollisuuden Voima Oyj asked Fortum Nuclear Services Ltd to develop a basic APROS simulation model for OL3. The developed simulation model covers the main processes of the primary and secondary circuits, safety systems, main control and protection systems as well as electrical systems. The modelling work was started in March 2005 and the validated model was ready for the applications one year later. Thereafter, the model has been applied in many engineering and safety analyses.

2 APROS SIMULATION SOFTWARE

The development of an Advanced PROcess Simulation software (APROS) was initiated 1986 in co-operation with Fortum Nuclear Services Ltd and VTT Technical Research Centre of Finland. APROS is a multifunctional simulation tool, which is suitable for various tasks during a complete project cycle of a nuclear and thermal power plant from the plant design to operator training. It can be used e.g. in preliminary design, detailed process and automation design, testing, engineering and safety analysis as well as training simulator applications.

The power plant library consists of comprehensive simulation models. The thermal hydraulic library contains three-, five- and six-equation models for the calculation of one-dimensional two-phase flow. Fast access material property tables are used for the computation of the water and steam material properties. The component library includes an extensive set of ready-made unit operation or process component models for the simulation of different kinds of processes, such as nuclear reactor and boiler plants, including automation and electrical systems.

The applied modelling and simulation tool has many useful and also unique features:

- physical, accurate and dynamical models
- graphical, interactive modelling
- fast running simulator
- extensive validation
- computer independence
- the plant including the process, automation and electrical systems can be modelled
- open and easy connection for external routines as DLL-files or communicating interfaces (APROS Communication Library ACL, OPC, OPC-XML-DA).

The validity of power plant models ranges from cold start-up to normal operation modes, normal and emergency shutdown, and load rejections and to failures of any combination of process, automation or electrical components.

3 APROS APPLICATIONS

Today, APROS has users in 22 countries. Power plants, engineering offices, safety authorities, research organisations and universities are using APROS in the process and automation design, development of emergency operating procedures, testing of I&C systems, accident analyses and training simulator applications.

During the last ten years many large projects have been performed and started at Loviisa Nuclear Power Plant to continue and improve the safety and good availability of the plant [1]. The utilization of APROS to analyse and simulate the behaviour of the power plant in transient and accident situations has shown an important role in all these projects.

A modernization and power uprating program of Loviisa VVER-440 reactors was carried out in 1995-97. Among other things, Loviisa Final Safety Analysis Report (FSAR) was extensively revised as part of the licensing process for higher reactor thermal power. The major part of FSAR safety analyses were calculated by APROS using the uprated 1500 MWth as a nominal power.

The original design life time of Loviisa nuclear power plant is 30 years. The operating license would have expired at the end of 2007 and 2010 for the units 1 and 2, respectively. Fortum, the owner and the operator of the plant, applied an operating license extension of both units for 20 years starting from the beginning of 2008. For the application, a great number of different studies and analyses were performed by APROS to show to the authorities that the plant can be operated safely for another 20 years.

It is obvious that the lifetime of the original I&C systems is not sufficient to guarantee the safety and the good availability of the plant in the future. Due to this fact, a project for the renewal of the existing I&C systems has been started. In the project, the analogue I&C systems will be renewed by digital I&C systems in four phases during 2005...2014. APROS based simulators will be used extensively during the renewal project [2]:

- an engineering simulator for design and analysis of control and process changes
- a development simulator for design, testing and qualification of the human-machine interface (HMI)
- a testing simulator for testing of the I&C software and for retuning of the controllers
- a training simulator to familiarize the operators and other technical personnel to the operation of the new monitor-based control room facilities.

4 APROS MODEL FOR OLKILUOTO-3

The basic APROS model for OL3 includes a detailed description of the reactor coolant system with all four loops as well as reactor control and shutdown equipment. The pressurizer model includes 40 calculation nodes, 20 nodes in the outer layer and 20 nodes in the inner part. Residual heat removal systems for reactor coolant and coolant treatment system are modelled including water tanks, pipe lines, valves, heat exchangers and pumps. As an example a primary circuit model is shown in Figure 1.

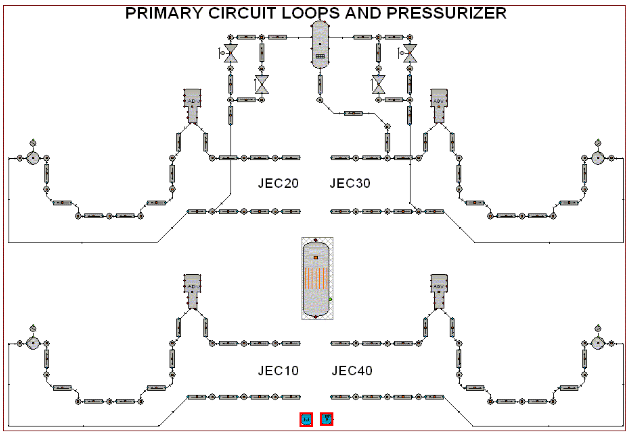

Figure 1**:** Part of the whole model simulating the primary circuit of the EPR power plant

The reactor core model consists of an average core divided into 20 vertical nodes having 1-D reactor kinetics calculation. The reactor by-pass flow channel is modelled with 6 nodes beside the core model. The upper plenum of the pressure vessel is divided into two parallel parts and the downcomer into four 90^{o} sectors. The lower plenum is divided into three layers in vertical direction and each sector of these layers consists of 2 nodes, one in the center part and one on the edge.

The secondary side is modelled as a closed circuit. All four steam generators are modeled by a ready-made APROS process component specifically developed for the EPR-type steam generator. The blowdown lines are connected to the steam generators. The steam lines and valves, high and low pressure turbines, moisture separators, reheaters, turbine by-pass valves, condensers, low pressure heaters, feed water and emergency feed water pumps, high pressure heaters and tanks as well as lines between different components are included in the secondary circuit model.

The following protection systems are modelled:

- reactor trip
- partial reactor trip
- plant protection
- turbine trip
- turbine protection

The control systems have an important role to the behaviour of the plant. The following control systems are included in the model:

- pressurizer level control
- primary pressure control
- reactor power control
- steam generator level control
- turbine control
- turbine by-pass control
- main steam release control
- feed water level control
- some other auxiliary control systems

The simulation model contains also the primary and secondary side electricity network as well as an external network, which has been modelled with one generator and one load module.

5 VALIDATION OF OLKILUOTO-3 MODEL

The heat balance tests as well as accidents and transients, e.g. SBLOCA (small break loss of coolant accident) and house load transient, were calculated with APROS. The results of the APROS calculations were compared to the results of the PSAR analyses.

The calculations results of the secondary side heat balance tests showed that the calculated steady state values of the APROS model are generally in very good agreement with the values calculated by the Consortium.

The calculation results of the transients and SBLOCA accident were essentially similar to the results of the PSAR analysis. The differences between APROS and PSAR calculations are in general easy to explain by the different initial assumptions.

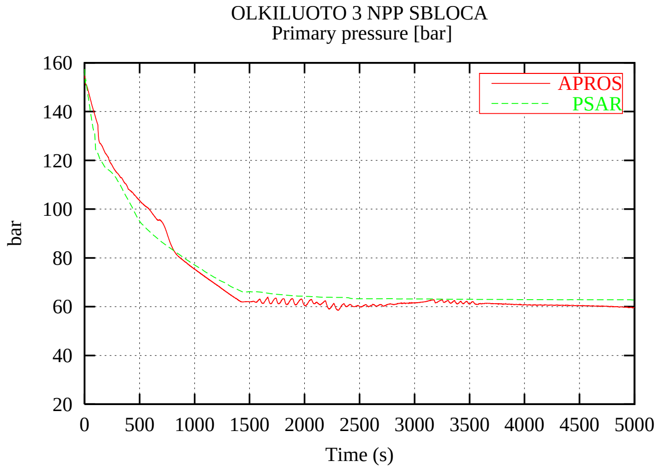

Figure 2: SBLOCA, primary pressure behaviour

6 OLKILUOTO-3 ENGINEERING APPLICATIONS

The developed OL3 simulation model has already been used to make comparison calculations with the engineering calculations delivered by the Consortium. The simulation model has also been used to understand more deeply the behaviour of the power plant in some transients. In the following, some results have been given as examples.

6.1 Spurious Closure of Low Pressure Steam Admission Valves

It is important to know the behaviour of the pressure of the moisture separator reheater (MSR) plant in case the low pressure admission valves close spuriously. The Consortium had earlier analyzed such kind of transient by own models. The plant owner wanted to make the comparison calculations and asked Fortum Nuclear Services Ltd to analyze the same transient by the developed OL3 simulation model.

Two different cases were analyzed. In the first case, the water amount stored in the moisture separator/reheaters was small (0.07 m^3) and in the second case about 4 m^3. At the beginning of the calculations, the plant was at full power. The closure of the low pressure steam valves caused the pressure increase in the MSR plant.

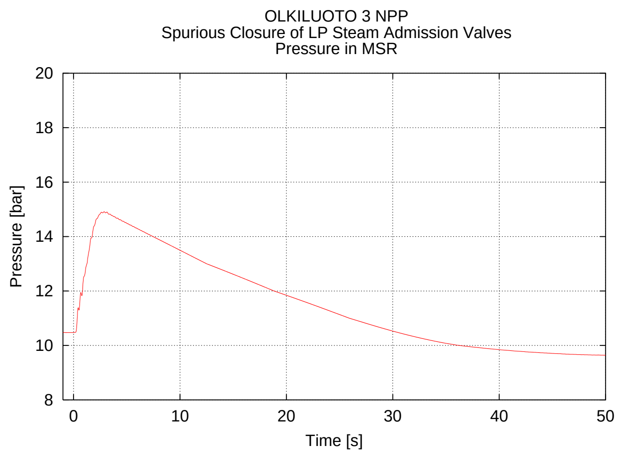

Figure 3: Spurious closure of steam admission valves, MSR pressure behaviour

The pressure level actuated the turbine trip in 0,755 second. The turbine trip signal closed the main steam line valves and turbine extraction lines valves and the MSR plant was isolated from the rest of the turbine plant excluding the extraction steam line from the MSR plant to the feed water tank. The maximum pressure of MSR plant was reached in both cases almost at the same time (about 2.9 second).

The simulation results calculated with APROS are very close to the results delivered by the Consortium.

6.2 Reverse flow of Low Pressure Turbine Extraction Lines

A rapid reverse steam flow in the extraction lines can cause problems with the blades in the low pressure turbines. Such kinds of problems have been taken place already in some large nuclear power plant units. Due to this, Teollisuuden Voima Oy asked to study these phenomena by the developed OL3 model. In the study, 12 transients were analyzed. The basic transient cases were the house load and the turbine trip. The varied parameters in the simulations were the reactor power and the cooling water temperature of the condenser.

Eight different kinds of house load transients were analyzed. The worst case was the transient where the reactor was at full power and the cooling water temperature of the condenser was 25 ^{o}C. The total integrated mass flow from three parallel low pressure preheaters to three low pressure turbines has been presented as an example in Figure 4.

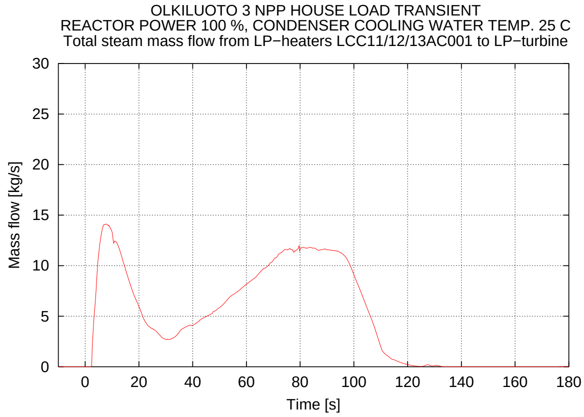

Figure 4**:** House load, total reverse mass flow of three parallel low pressure preheaters

Four different kinds of turbine trip transients were analyzed. The worst case was the transient where the reactor was at 105 % power and the cooling water temperature of the condenser 0 ^{o}C. The total integrated mass flow from three parallel low pressure preheaters to three low pressure turbines has been presented in Figure 5.

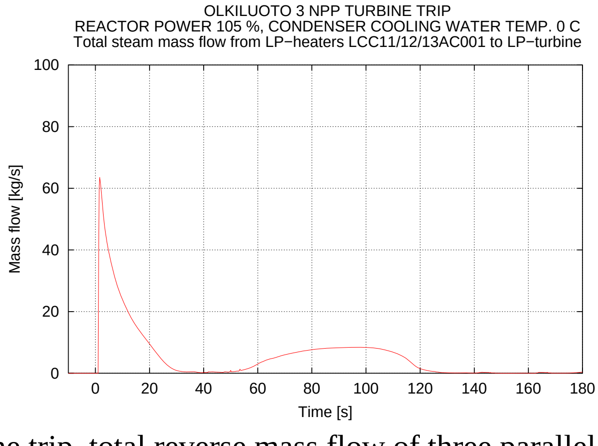

Figure 5**:** Turbine trip, total reverse mass flow of three parallel low pressure preheaters

In both transients, the reverse steam flow to the low pressure turbine took about 130 seconds. In the first transient, the integrated mass flow was 934 kg and in the second one 1139 kg. In both transients, less than 10 % of the total steam came from the hot water of the drain pipe lines. The most of the steam came from the condensate of the heat exchangers.

By means of the simulation model, the plant owner has the possibility to estimate the risk to the blade failure more extensively in different kinds of transients, if needed.

7 LOSS-OF-COOLANT ACCIDENT

7.1 New CCFL Correlation

APROS has a sophisticated thermal hydraulic library including the homogeneous three-equation model as well as separated phase flow five- and six-equation models. The existing six-equation model is based on one-dimensional conservation equations of mass, momentum and energy. The six-equation model contains also models for the simulation of non-condensable gases.

Due to layout of main coolant line in- and outlets to the reactor pressure vessel, special CCFL correlations for a downcomer and an upper tie plate are needed in the analyses of loss-of-coolant accidents of EPR-type reactor. In the development, work the Glaeser CCFL correlations were implemented in APROS [3].

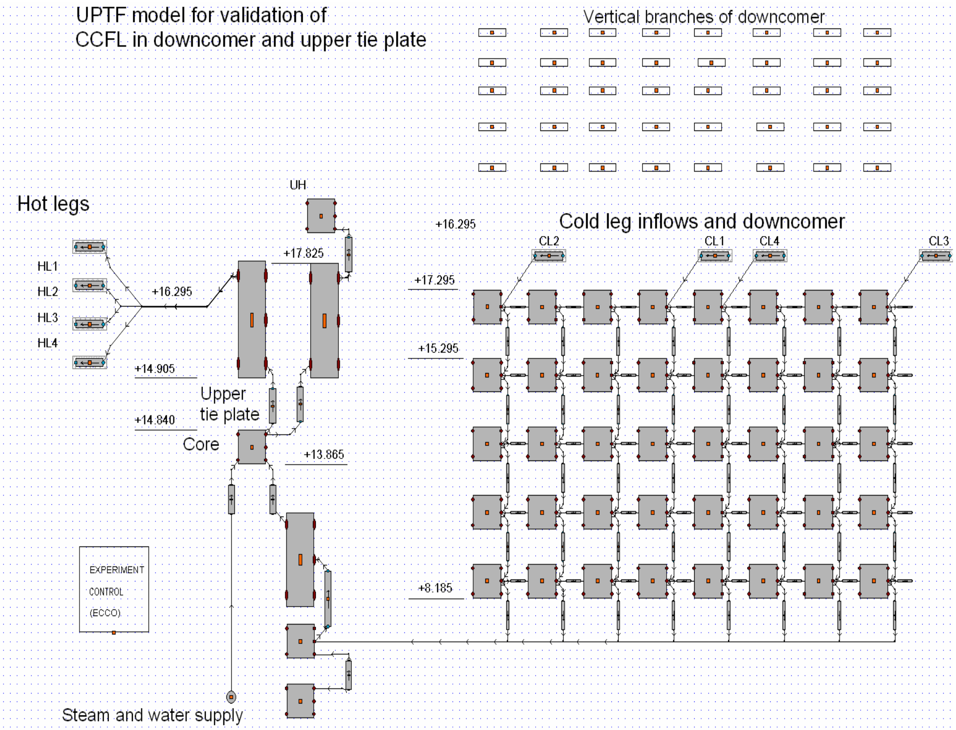

Figure 6: Simulation model of UPTF for validation CCFL correlations

The developed correlations were validated by calculating several downcomer and upper tie plate test cases of the Upper Plenum Test Facility (UPTF). The results of the downcomer and tie plate experiments show that the calculated values are close to the measurements. In the RUN 200/III, the relative difference is large but compared to the total injection mass flow the difference is not significant. In the validation of the tie plate experiment, the same water level 15 cm above the tie plate has been used.

Table 1: Data of the calculated downcomer experiments

Run No.	Steam into DC (kg/s)	ECC flow into DC (kg/s)	Down flow calculated (kg/s)	Down flow experiment (kg/s)	ECC water subcooling ΔT (°C)	Pressure (kPa)
200/I	104	494	**3.0**	**5**	22	451
200/II	54	736	**222**	**351**	9	330
200/III	102	735	**57**	**6**	23	498
201/I	102	CL2:487 CL3: 490	**845**	**861**	CL2: 10 CL3: 11	330
202/II	128	CL2.486 CL3.491	**512**	**714**	CL2: 13 CL3: 14	416
201III	102	CL1: 493 CL2. 487 CL3. 489	**737**	**942**	CL1:14 CL2:14 CL3:15	414
203IV	51	CL1:493 CL2:485 CL3:487	**1017**	**1031**	CL1:3 CL2:3 CL3:6	337

Table 2: Data of the calculated tie plate experiments

Run No.	Steam flow through upper tie plate (kg/s)	ECC flow into upper plenum (kg/s)	Down flow calculated (kg/s)	Down flow experiment (kg/s)	ΔT (°C)	Pressure (kPa)
Part1: 1	172.98	2 x 100	**65**	**76**	29	603/600
Part 1:2	151.48	2 x 100	**83**	**87**	28	585/588
Part 1:3	127.46	2 x 100	**100**	**135**	24	542/539
Part 1:4	103.15	2 x 100	**124**	**142.8**	21	496/496
Part 1:5	76.54	2 x 100	**167**	**182**	19	464/463
Part 2:1	215.0	400	**96**	**109**	30	624/620
Part 2:2	198.33	400	**153**	**243**	35	704/704
Part 2:3	163.54	400	**202**	**243**	33	674/673
Part 2:4	130.83	400	**235**	**354**	32	650/652
Part 2:5	98.48	400	**336**	**324**	26	586/588
Part 2:6	68:25	400	**402**	**390**	24	520/527

7.2 Cold Leg Large Break Loss-of-Coolant Accident

The developed OL3 model has been used in the analysis of LBLOCA guillotine break (2ALOCA). For the analysis work some modifications were needed in the nodalizations of the pressure vessel and core model.

The following modifications were made to the downcomer, lower and upper plenum and reactor core:

- the downcomer and the first part of the lower plenum were divided into eight sectors
- in the rest of the lower plenum four sectors were used
- each downcomer sector was divided into 12 nodes in the axial direction
- all nodes of the sectors were connected to the neighbour nodes by the cross flow branches
- the upper plenum were divided into the centre flow channel and eight surrounding flow channels
- all the layers were divided into four nodes in the axial direction
- the centre and surrounding sector nodes were connected by the cross flow branches
- the reactor core was divided into eight channels based on the fuel power level
- the fuel rods were connected to the different fuel channels
- the hot fuel rod was included into the hot assembly fuel channel as one fuel rod
- the flow channels were divided into 40 thermal hydraulic volumes axially
- the nodes of the reactor core were connected by the cross flow branches
- each thermal hydraulic volume had 20 separate heat structures nodes

In the analysis of the break, the location of the leakage was in the cold leg of the loop one between the reactor coolant pump and the reactor pressure vessel.

At the initial condition of the accident case, the emergency core cooling system of the loop one injected the water directly into the break. A single failure was assumed to the check valve located in the loop three, which prevented the pump injection to that loop. Loss of offsite power was assumed and the diesel for the low and medium head safety injection pumps of the loop two was in addition assumed to be in the maintenance thus hindering water supply with these pumps. The accumulator connected to the loop two was able to supply water. The containment pressure was supplied to the model as a boundary condition value and the plant owner defined the function of the gap conductance used in the analysis. Based on the above assumptions, two accumulators connected to the loops two and four as well as one low head and one medium head safety injection pump connected to the loop four were available in the selected 2ALOCA case.

The results of the calculated accident showed that the acceptance criteria are fulfilled in the analyzed accident.

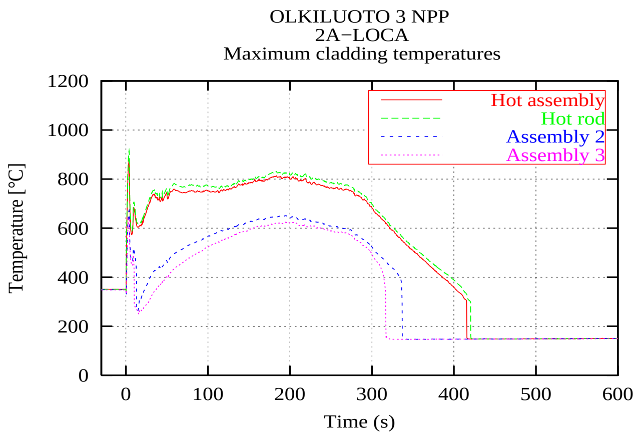

Figure 7: LBLOCA, maximum cladding temperatures

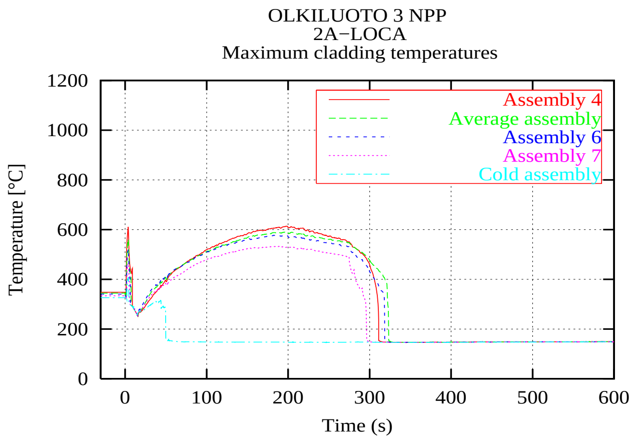

Figure 8: LBLOCA, maximum cladding temperatures

8 CONCLUSIONS

The developed OL3 simulation model includes the description of the primary and secondary circuits, electrical systems as well as automation and protection systems. This makes it possible to study the behaviour the whole power plant unit by one simulation model. The multifunctional simulator features of APROS e.g. to use the same software in engineering and safety analyses makes the utilization of the OL3 simulation model more effective and economical.

By means of APROS and the developed OL3 simulation model, the plant owner has an opportunity to make independent safety analyses. This increases the reliability of the simulation results of the complicated accident situations.

REFERENCES

[1] E. RAIKO, H. Kontio and K. Porkholm, “Capability of APROS in the Analyses of Diesel Loading Sequences,” The 5th International Conference "Safety Assurance of NPP with WWER" FSUE OKB "GIDROPRESS", Podolsk, Russia, 29 May - 1 June, 2007.

[2] K. PORKHOLM, A. Ahonen and O. Tiihonen, “Utilization of the simulators in I&C renewal project of Loviisa NPP,” Technical meeting to develop a technical report on upgrade and modernization of NPP training simulators, KSG, Essen, Germany, September 19-22, 2005.

[3] M. HÄNNINEN, “Implementation and Validation of Downcomer and Upper Tie Plate CCFL Correlations in a Two-Fluid Code,” Proceedings of the 16th International Conference on Nuclear Engineering, ICONE 16, Orlando, Florida, USA, May 11 - 15, 2008.