LBLOCA Analyses with APROS to Improve Safety and Performance of Loviisa NPP

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Summary

Thermal-hydraulic system and simulator code APROS has been successfully used in safety analyses. A proper validation process of the code is essential to guarantee reliable calculation results in accident analyses. LBLOCA analyses have indicated that safety and performance of a nuclear power plant can be improved with the help of such computer code. When the parallel processing is applied, the calculation time is reduced remarkably.

Introduction

The development of APROS started in 1986 as a joint effort of the Technical Research Centre of Finland (VTT) and Fortum Engineering Ltd. The aim was to create an Advanced Process Simulation (APROS) environment for the simulation of conventional and nuclear power plant processes [1]. APROS can be used for process and automation design, safety analyses and training simulator applications. It provides tools, solution algorithms and model libraries for full-scale modeling and simulation of power plant processes, including the process automation and electrical systems.

Analyzing LBLOCA sets high requirements for the analysis code. In general, many thermal hydraulic validation cases have to be done with the code and current model. However, the specified LBLOCA validation is essential for ensuring the reliability of calculations due to crucial importance of LBLOCA in the NPP safety strategy.

Loviisa NPP (VVER-440) modernization and power uprating project, which started in 1995, included a large variety of safety analyses. Especially in this project, the proper validation of the calculation model was needed for nuclear safety authority to accept the results. APROS LBLOCA calculations were validated against various separate effect tests and by comparison calculations to previous DRUFAN/FLUT analysis results.

There is also a project for Loviisa NPP safety parameter optimization, where LBLOCA accident analyses play an important role. The plan is to change accumulator and low pressure safety injection pump parameters. The accident analyses, which included LBLOCA, SBLOCA and primary to secondary leakage accident (PRISE) analyses, showed clear improvement in the plant performing with the new parameters. In the LBLOCA, the minimum mass inventory in the reflood phase increased and the peak cladding temperature (PCT) decreased remarkably. The main motivation in optimizing the emergency core cooling system (ECCS) parameters is to increase the flexibility in the fuel management in regard to the core loading patterns and thus to gain a significant saving in the fuel economy. The up-to-date and advanced analysis methodology shows that this goal can be achieved by improving the safety at the same time.

This paper presents various aspects of the APROS LBLOCA analyses, as well as the APROS simulation environment and the validation process of the LBLOCA model. The modeling principle and results of the LBLOCA analyses, including the modernization and power uprating as well as the safety injection parameter optimization analyses, are described. Finally, a short discussion of reducing of the calculation time takes place.

APROS Simulation Environment

APROS is a computer independent code that supports several operating systems. It provides physical models, solution algorithms and generic components for use in different simulation systems for design, analysis and training purposes. With these tools full-scale modeling and simulation of power plant processes are available, including control and electrical systems. The modular and hierarchical approach of APROS allows process analysis at various conceptual levels. The closely process-related input data are entered through a fully graphical user interface. The generation of model equations and choice of solution methods are automatically performed by APROS. Unique online features of APROS enable the user to make any parameter or model changes online and immediately to continue the simulation.

The thermal hydraulic models of APROS include one-dimensional three-, five- and six-equation flow models. The different thermal-hydraulic models can be used in the same simulation example. One-dimensional solution of the heat conduction in the heat structures can be used together with each of thermal-hydraulic models. The heat conduction between heat structures can also be applied to vertical direction, which enables the two-dimensional heat conduction in the core. All the thermal-hydraulic models are based on mass, energy and momentum conservation equations. In addition to conservation equations, for example in the six-equation model, the constitutive equations are needed for the friction between wall and both phases, for the interfacial friction, for the heat transfer between wall and both phases, and for the interfacial heat transfer. The quantities to be solved in the model are pressures together with phasic velocities, void fractions and phasic enthalpies.

APROS has traditionally been a code operating in different UNIX-systems. However, the newest version 5.0 of APROS operates also in PC workstation in Windows NT operation system. In the PC-version, the modeling is performed totally with the graphical user interface. In this way, the structure of the model can be presented with process and automation pictures. Also, all the simulations can be performed via the graphical user interface.

Simulation Model

A detailed model of the Loviisa NPP was developed during the plant modernization project and reported by Norrman et al. [2]. The model was used for majority of the modernization and power uprating accident analyses [3]. In the model, the primary circuit including steam generators has been described with the 6-equation model and the secondary circuit with threeequation model. The primary circuit modeling is very detail including all the main components and even the ECC system with pipelines. The model also includes all the main control systems, i.e. reactor control, primary circuit pressure and pressurizer level control, turbine power control, steam generator level control and turbine bypass control as well as several auxiliary control systems and the electrical system.

For LBLOCA analyses, the same model as used in other Loviisa NPP safety analyses was used, but the core region model was reconstructed. Because VVER-type reactors have separate core flow channels, the core was divided into seven flow channels. At first, fuel assemblies were divided into four different groups based on fuel burn-up. UO_2 thermal conductivity and gap conductance values, which originate from Loviisa NPP fuel statistical evaluation [4], were then calculated for each group taking into account the fuel assembly or fuel rod power levels. The less is the gap conductance, the more energy is conserved in the fuel. Three channels represented hot assemblies of the first, second and third cycle and the hot rod of each cycle was placed into the corresponding hot channel. Modeled channels and their peaking factors for the top skewed load profile in the beginning of cycle (BOC) situation are listed in Table 1.

Table 1. Typical core flow channel modeling used in APROS LBLOCA analyses

Name of fuel rod	Number of assemblies	Number of rods	Radial peaking factor	Gap conductance [W/m^{2}K]
First cycle hot assembly average rod	48	6047	1.33	3000
First cycle hot rod	-	1	1.54	3500
Second cycle hot assembly average rod	48	6047	1.15	3100
Second cycle hot rod	-	1	1.54	3600
Third cycle hot assembly average rod	12	1511	1.02	3500
Third cycle hot rod	-	1	1.40	4100
Average assembly average rod	126	15876	1.03	5000
Cold assembly average rod	42	5292	0.40	7000
Follower assembly average rod	36	4536	0.93	5400
Stuck follower assembly average rod	1	126	1.12	5400

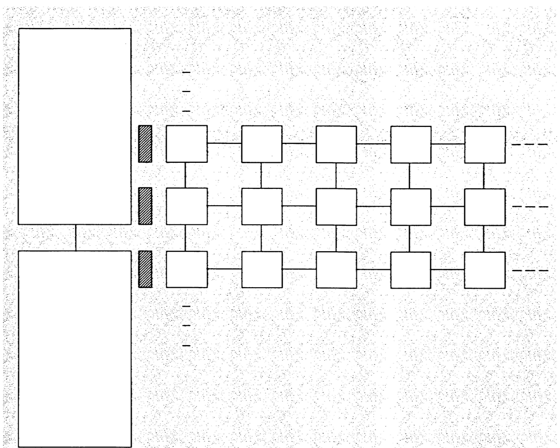

Figure 1. Heat structure nodalization. Orthogons are thermal-hydraulic nodes and squares are heat structure nodes.

Altogether, there were 40000 heat structures in the core. Each channel was divided in axial direction into 40 thermal-hydraulic nodes. Ten heat structures stacked one upon another were connected to one thermal-hydraulic node. In radial direction, there were also ten heat structures. The heat structure nodalization is illustrated in Figure 1. Hot rods did not have their own thermal-hydraulic nodes but they were placed in the respective hot assembly channel. Heat transfer and cladding temperature in hot rods were thus using corresponding hot assembly thermal-hydraulics.

LBLOCA Validation

LBLOCA is still considered one of the most difficult licensing cases for the simulation codes to analyze. This is due to fact that phenomena are mostly three-dimensional and the codes, like APROS, are usually designed for one-dimensional calculation. In the Loviisa case, the situation becomes even more difficult since the accumulators and low pressure safety injection pumps have combined injection configuration. Therefore, a thorough validation of the LBLOCA calculation model was essential to be able to achieve reliability and credibility of the licensing analyses.

CCFL Validation

The 6-equation interfacial friction model of APROS was validated against IVO stationary counter-current flow limitation (CCFL) experiment [5]. The test facility consisted of a vertical flow channel with different internal components, which described upper tie plate of the reactor, fuel rod bundle and grid spacers. During the tests, a stationary water and air flow rates were maintained and the flow rates were then measured for the entire fuel assembly.

APROS calculation was made for steam/water saturated system at 0.22 MPa pressure. At this pressure, the density of saturated steam equals that of air in atmospheric pressure at which the experiment was performed. The results were plotted using the Kutateladze number K^* for liquid and gas

$$K^*_{f,g} = j_{f,g}\left[\frac{\rho^2_{f,g}}{g\sigma\left(\rho_f-\rho_g\right)}\right]^{\frac{1}{4}}.$$

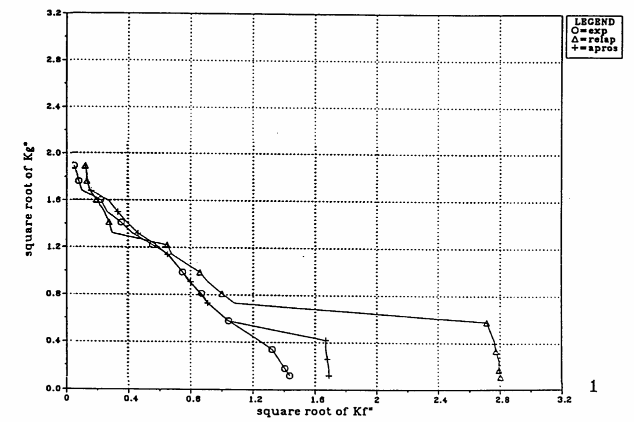

Figure 2. Comparison of RELAP5/MOD3 and APROS calculation results with the experimental data.

Calculated and experimental data is presented in Figure 2. Also, calculated RELAP5/MOD3 results are presented in the figure. With high steam velocities results agree well with measured data, but there is some discrepancy in the low steam velocity region. In general, the APROS results match well with the measured data.

Reflooding Validation

The quenching and reflooding phenomena were validated against reflooding experiments of the REWET-II facility [6]. REWET-II is a scaled model of the pressure vessel and primary loops of VVER-440 type reactor [7]. The flow areas and volumes are scaled to 1:2333 but the elevations correspond to actual reactor dimensions. A single assembly, consisting of 19 electrically heated rods with a chopped cosine shaped axial power distribution, simulates the reactor core.

In the experiment, the initial rod temperature was 600 °C and pressure 0.3 MPa. The lower plenum was full of water in the beginning of the experiment and the coolant temperature was 50 °C. The ECCS water was injected into the downcomer with the mass flow rate 69 g/s which corresponded to flow rate of 160 kg/s in the reference reactor.

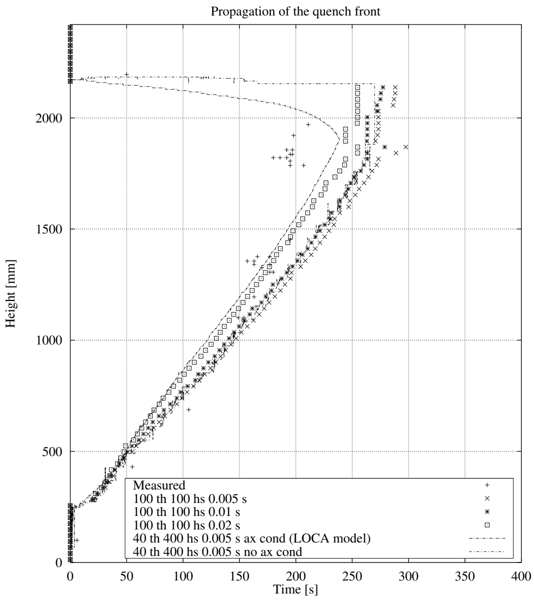

Figure 3. Propagation of quench fronts in different variations.

The assembly was modeled with two different nodalizations. In the first nodalization, the assembly was divided into 100 thermal-hydraulic nodes in the axial direction and the heat structures were divided equally. In the second nodalization, there were 40 thermal-hydraulic nodes in the assembly. One thermal-hydraulic node was then connected to ten stacked heat structures (Figure 1). So, the total number of heat structures in the fuel rod axial direction was 400. In both nodalizations, the heat structures were divided into 10 heat structure nodes in the radial direction. The axial heat conduction was neglected except in one variation case.

The calculations were performed with different time-steps and with the two nodalizations. Results are presented in Figure 3. The best result was obtained with the nodalization where 40 thermal-hydraulic and 400 heat structures were used together with axial conduction applied to the model. In this case, the quench front propagation and the height of the last hot piece agreed very well with the measured data. This nodalization scheme was also used in all the further LBLOCA analyses.

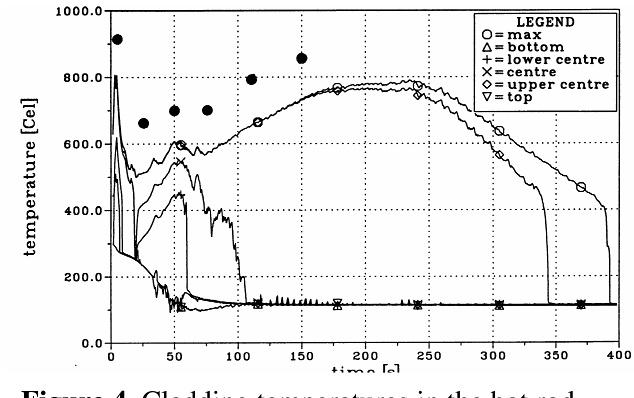

Figure 4. Cladding temperatures in the hot rod. DRUFAN/FLUT results are plotted with discrete points.

Comparison to GRS Results

Gesellschaft für Reaktor-sicherheit (GRS) made in the late 80's LBLOCA analysis for Loviisa with DRUFAN and FLUT computer codes [8]. In the calculations, the core was divided into six different flow channels, and also the hot channel was described (Table 2). The downcomer was modeled with two parallel nodalizations; the one connected to the broken loop and the other to the rest five loops. Loss-of-offsite power as well as limitation of the ECCS system function was assumed in the accident. The break size was 2x100%, and the break was located in the cold leg between the reactor coolant pump and the reactor pressure vessel. The GRS calculation time was 150 s.

Table 2. Core flow channels used in APROS GRS-validation analyses

Name of fuel rod	Number of assemblies	Radial peaking factor	Gap conductance [W/m^{2}K]
Hot assembly average rod	113	1.18	3450
Hot assembly hot rod	18	1.40	2000
Hot rod	-	1.70	2200
Average assembly average rod	97	1.00	3450
Cold assembly average rod	48	0.36	3450
Follower assembly average rod	36	1.00	3450
Stuck follower assembly average rod	1	1.40	2000

APROS modeling was done according to the basic Loviisa model [2]. However, some modifications, which described the reactor more like in DRUFAN/FLUT nodalization, were done to be able to validate results. On the other hand, for example all the six loops, modeled in original APROS Loviisa model, were maintained despite that in DRUFAN/FLUT only three different loops were modeled.

Cladding temperature of hot rod in both calculations is plotted in Figure 4. DRUFAN/FLUT temperatures, which were available only up to 150 s, were higher than respective APROS temperatures. In the APROS model, heat structures in the core were divided into 10 stacked nodes as in the GRS nodalization this was not done. Also, better internal flow circulation of APROS in the core region affected the cladding temperature behavior. In general, qualitatively results were equal, but quantitatively some deviations occurred. However, those differences mostly originated from the boundary conditions defined for both calculation models.

Accident Analyses

The assumptions in all the analyzed cases were similar. In the beginning, the initial power was 102 %. The break was located in the cold leg between the reactor pressure vessel and the reactor coolant pump. Only one low and high pressure safety injection pump and two accumulators, one injecting into downcomer and the other into upper plenum, were assumed to function from the ECCS. The loss-of-offsite power delays the starting of the ECCS and other emergency injections, and therefore it was assumed to coincide with the turbine trip.

Modernization and Power Uprating Project

In the Loviisa modernization and power uprating project, the thermal power was uprated from 1375 MW to 1500 MW. One of the crucial safety analyses in the Loviisa modernization and power uprating project was LBLOCA. The base case was selected and it was analyzed with several parameter variations to be able get better understanding of different phenomena. First, break size in the reactor pressure vessel side was varied from 60 % to 100 %. The blowdown period was analyzed with different break sizes. The most conservative case was

2x100 % cold leg break due to highest cladding temperatures in the end of blowdown phase. Thereafter, the gap conductance of the average powered fuel rods was varied from 4000 W/m^2K to 8000 W/m^2K. The blowdown period was investigated once again. The gap conductance of hot assembly average rod and hot assembly hot rod were 2000 W/m^2K and 2200 W/m^2K, respectively, and they were kept constant in all the variation cases. The most conservative case was the one with the highest gap conductance. A small gap conductance on average rods balanced the relative flows between different flow channels, and thus, hot rod maximum PCT was lower than with high gap conductance. In general, the effect of gap conductance was not dominant.

The maximum cladding temperature was reached during the first peak of the blowdown phase. In the reflood phase, the maximum temperature remained 20 °C lower than in the blowdown phase being for the hot rod 875 °C and 852 °C, as the acceptance criterion is 1200 °C. In about 400 s the whole core was quenched. Also, the oxidation thickness was calculated, which was, however, very far from allowed limits. So, the analysis results fulfilled all the acceptance criteria.

Effect of Power Uprating

A parameter variation, where the total thermal power was decreased down to the original level, was also calculated. All other assumptions and the calculation model were the same as in the 1500 MW licensing analysis. Core power was reduced so that the total thermal power at nominal stage was 1375 MW. However, the hot channel power together with the hot rod was maintained to be able keep the maximum linear power rate 325 W/m.

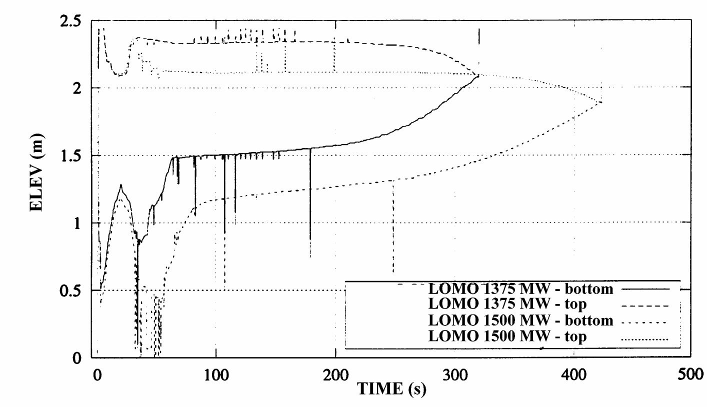

Figure 5. Propagation of quench fronts in the modernization analyses.

The blowdown phase was almost identical to the one with uprated power. Due to different power distribution, flow in different flow channels deviated slightly from 1500 MW case. In the low power fuel assemblies, no difference in the cladding temperatures was noticed. In the average and hot assemblies, the difference in the cladding temperature was distinct. The maximum cladding temperature in the reflood phase was 150 °C lower than in the uprated power calculation. Main reason was a larger amount of low power assemblies, which quenched faster and thus the internal flow in the core strengthened. The quench front propagation took mainly place from the bottom (Figure 5) and only minor top down quenching was predicted. Conclusion from this variation was that the initial thermal power has a distinct effect on the peak cladding temperature.

Effect of Assembly Power

LBLOCA was also analyzed with respect to the whole refueling cycle. Beginning of cycle (BOC), middle of cycle (MOC) and end of cycle (EOC) situations were inspected. The flow channels were modeled according to Table 1. The most crucial one was the BOC-situation. In all analyzed cases, the nominal power was 1500 MW. The BOC-situation was then compared to a low-leakage loading pattern where the maximum assembly power peaking factor was raised from 1.28 to 1.33. The reason for that change was the fuel economy. The change of load would enable to put the third cycle assemblies to the edges of the core, so that around the core there would be a "low power zone". The low-leakage load has also an advantage of reducing the neutron fluence on the pressure vessel wall.

During the blowdown period the results were very similar to the base case results. Because the linear power was the same in the hot assemblies and in the hot rod, also the maximum temperatures in the blowdown period were the same. During the reflood period, the primary mass inventory decreased below 40 ton, while in the base case this did not occur. The limit of the mass inventory, which still is able to quench from the bottom, was passed, and thus higher cladding temperatures were reached. The maximum temperatures were about 150 °C higher than in the comparative case.

Maximum PCT varied from 700 °C to 850 °C depending on assumption of the core loading pattern. It is believed that PCT is closely linked to the reactor vessel coolant inventory and to the internal flow in the core during the accident. Also, the loop seals have an influence on the pressure difference, and thus on the water level in the core.

ECCS Parameter Optimization

Based on assembly power variation, it was noticed that the primary coolant mass inventory has a significant effect on the PCT of the hot rod. The nominal primary mass inventory of Loviisa reactor is about 165 tons. The minimum mass inventory during the reflood phase depends quite much on the ECCS accumulator parameters. The accumulator injection is able to increase the primary circuit coolant mass up to 60 tons by the end of the injection. Thereafter the coolant mass inventory decreases until the low pressure safety injection exceeds the break mass flow rate.

The current ECCS parameters are following: accumulator pressure 5.4 MPa and water volume 40 m^3, and the low pressure safety injection (LPSI) pump shut-off head 0.8 MPa. In a case of a LBLOCA, it means that accumulator injection starts in an early phase when the break mass flow rate is still large due to high primary pressure. Therefore a large amount of accumulator water is lost via break. Based on this argument, the idea of improving the ECCS performance by changing the accumulator parameters was examined. At the same time also the effect of higher LPSI pumps shut-off head was studied.

Low Pressure Safety Injection Pump Shut-off Head

There have been considerations that the LPSI pump shut-off head could be increased in order to be able to start low pressure safety injection earlier which would be beneficial especially during SBLOCA. This idea was also supported by the medium-size PRISE analysis which clearly indicated that the higher head of the LPSI pump made it possible to stop high pressure safety injection (HPSI) much earlier than in case with the current pumps. However, concerning the LBLOCA, higher shut-off head was not expected to have any major influence on the results. Due to practical limitations in the plant, it was decided to increase the maximum head to 1.0 MPa.

Reduction of Accumulator Pressure

In this variation, the influence of accumulator pressure reduction on LBLOCA was inspected. As mentioned earlier, the accumulator injection starts at high pressure. When reducing the accumulator pressure, the injection starts later, and thus the amount of water that is spilled out of the primary circuit through the break is reduced and the coolant mass inventory during the reflood phase increases. However, it must be noticed that the accumulator injection may not start too late to prevent the whole primary circuit from emptying.

A LBLOCA analysis where the accumulator pressure was decreased to 3.5 MPa was carried out. The influence was that during the reflood phase the cladding temperatures did not begin to rise but stayed at 550 °C level until the fuel rods finally quenched at 200 s. The final quenching was almost 200 s earlier than with the current accumulators (Figure 6). So, the better timing of accumulator injection increased mass inventory minimum during the reflood phase so much that temperature rise could be prevented.

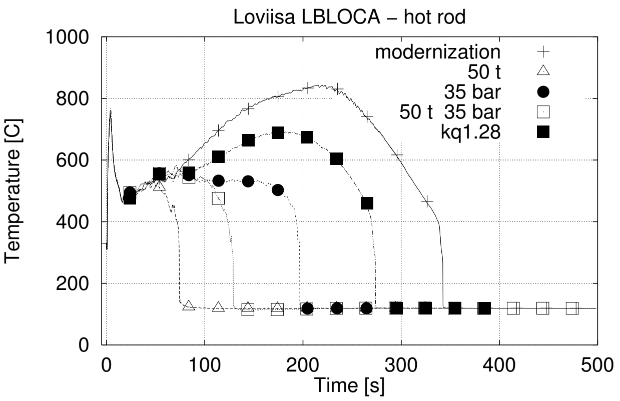

Figure 6. Cladding temperatures of hot rod in various LBLOCA analyses.

Increasing of Accumulator Water Volume

Another variation, where the water volume in the accumulator was increased, was also calculated. The injection would start at the same moment as with the current accumulators, but it would last longer. The limitations in the accumulator itself were inspected and it was noticed that it was possible to increase the water volume by 10 m^3.

The prolonged accumulator injection period could quench all the fuel in 75 s. When the accumulators were empty, the whole core was quenched and because the coolant mass inventory was high enough, no temperature rerise occurred any more.

R*eduction of Pressure and Increasing of Water Volume in the Accumulator*

A combination of two previous changes was also examined by increasing water volume and reducing pressure in the accumulators. The aim of this was to increase the minimum coolant mass inventory during the reflood phase, and thus to reduce the maximum cladding temperature and the time of the core quenching.

The LBLOCA analysis results showed that the minimum primary coolant mass inventory during the reflood phase was 47 tons (Figure 7). In the blowdown phase, the coolant mass inventory decreased down to 15 tons before accumulators started to inject. The injection raised the inventory up to 60 tons. By the end of the calculation, the inventory balanced to about 50 tons level. Due to improved accumulator injection, the core quenched at 130 s and the maximum cladding temperature during the reflood phase was only 580 °C.

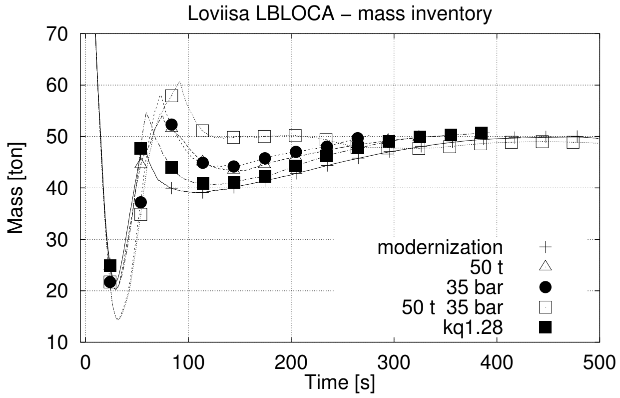

Figure 7. Primary mass inventory in various LBLOCA analyses.

All the ECCS parameter variations showed that the maximum PCT in LBLOCA is reached during the blowdown phase. Unfortunately PCT during blowdown phase depends on stored energy and cannot be influenced by the ECCS system. However, the situation during the reflood phase can be improved. Not only the cladding temperature rise can be prevented, but also the coolant mass inventory minimum during the reflood phase can be increased. In respect to the cladding temperatures and core quenching, keeping the current accumulator pressure and increasing water volume would be the best solution for LBLOCA. However, when considering the coolant mass inventory, pressure decrease together with the water volume increase is the best solution. Even then the quenching takes place much earlier than with current parameters.

Besides LBLOCA, SBLOCA and PRISE were analyzed assuming the new accumulator parameters (pressure 3.5 MPa, water volume 50 m^3) together with the new low pressure safety injection pump parameter (shut-off head 1.0 MPa). Those analyses showed clear safety improvement, too. Based on these APROS analyses, Loviisa NPP will apply for the ECCS parameter change from the Finnish nuclear safety authority.

Discussion

APROS simulator has been extensively used in Finland for safety analyses, including licensing analyses. A thorough validation process has been performed, and it is still continued to increase the code reliability in the accident analyses. APROS provides both 5- and 6-equation models for simulation purposes, which on the other hand means more validation work. However, the advantage, which can be obtained from this feature is so evident that it is worth preserving these both code versions. The 5-equation model is best suited for training simulator and fast running purposes, as the 6-equation model is meant for very accurate analyzing needed in licensing cases.

The 5-equation model can already now calculate transients and accidents faster than real time. This feature is very useful when planning plant modifications or making sensitive analyses how the results would “approximately” look like. Of course, this does not mean one cannot rely on results, but when a very high accuracy is needed, the 6-equation model is then preferred. For example in case of plant modifications, preliminary analyses can be done with the 5-equation model and then the actual licensing analyses with the respective 6-equation model. In this way, a lot calculation time is saved.

LBLOCA, which was presented in this paper, is the most time consuming case. Nowadays, it takes about 100 h to calculate 500 s of LBLOCA (Alpha DEC processor: SPEC fp 18.7). It should also be noticed that the most time consumption originates from the heavy modeling. Alone in the core, there are 40000 heat structures.

Parallel processing has been used to reduce the calculation time. The Parallel Design and Analysis Software (PARAS) has recently been developed for APROS. In the PARAS, the user divides the simulation model into independent subdomains. This is possible via shared library, interface functions that provide information of other processes and connection modules. The subdomain separation itself is achieved by external boundary conditions which are updated every time step during the simulation. Actually, one of the advantages when using PARAS in APROS is that different subdomains may have different time step size. Thus, the user is able to optimize the total time consumption. For example, the user can divide the original model into a small subdomain and into a larger one, where the small subdomain requires very small time step size as the rest of the model does not. So, the both subdomains require the same calculation time and total time consumption is reduced. So far, PARAS has been tested with three parallel processors and the calculation time has been 2.3 times faster than with one respective processor.

Conclusions

The APROS code system was validated and applied to the LBLOCA analyses for the Loviisa VVER-440 plant during the plant upgrading programme. The validation employed comparison calculations against REWET experiments carried out for the Loviisa reactor and benchmark type calculations to compare with previous analysis with the DRUFAN/FLUT code system (predecessor of the ATHLET code).

The main method for uncertainty evaluation was to carry out a large number of runs with different parameter values. The procedure helped in creating understanding of the sensitivity to parameter changes. Based on the work, it was concluded that the performed power uprating of the plant does not increase the fuel peak cladding temperature. The results indicate that the PCT remains below 800ºC and the creep of the Zr-1%Nb cladding material can be avoided.

The results also indicated that a key parameter is the minimum primary coolant mass inventory during the reflood phase. The inventory can be improved by optimising the ECCS accumulator parameters in order to avoid excessive spilling of the accumulator injection during blowdown. The change of the accumulator parameters would allow higher power peaking factors at the same time when the PCT still remains below 800ºC.

The work demonstrates how the use of advanced methodology can help the utility both by improving the performance of the plant and by maintaining at the same time the high level of safety. In fact, the results of accident analyses ensure even higher safety margins than previously expected.

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