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ADVANCED PROCESS SIMULATION WITH APROS FOR VVER-91, THE NEXT GENERATION REACTOR DESIGN FOR VVER-1000

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ABSTRACT

The paper describes the capabilities of APROS code in the simulation of the VVER-91 concept. The VVER-91 models realized with APROS are described and a short overview of the various types of analysis performed is given. Particular emphasis is paid on the ATWS analyses performed with APROS. The results of APROS in a steam line break ATWS analysis are reported in detail and compared to the results of the HEXTRAN code, that has been used extensively in the ATWS and other accident analyses of VVER-91.

I. INTRODUCTION

APROS simulation software can be used for the simulation of fossil and nuclear power plant processes and chemical plant process dynamics[1]. APROS has been developed by the Technical Research Centre of Finland (VTT) and IVO Power Engineering Ltd (IVO PE). The key features are grouping of the physical models into general and application specific packages, on-line simulation, inter-activity with possibility to make modifications in physical parameters and in model structure, and use of the model with graphical user interface. Real-time or faster than real time calculation can also be reached in most applications. The APROS concept allows building of detailed models of various types of plants for design, analysis and training purposes. In nuclear engineering APROS can be used in the feasibility studies, in plant design and licensing, as well as in the design of the operational and emergency procedures during plant commissioning and during plant operation.

VVER-1000/model 91 reactor, also known as VVER-91 is a four loop plant with horizontal steam generators. A special feature of the VVER-91 reactor is the increased number of control rods compared with the standard reactor design having 61 clusters. In the computer code models discussed in this paper 97 control rod clusters have been assumed according to the design originally proposed for Finland (V413).

The use of APROS in context of the VVER-91 concept was started with process and automation studies. Thereafter several ATWS analyses for VVER-91 with APROS have been performed. In the ATWS analyses it has been possible to compare the results obtained with APROS to those obtained with other codes.

II. APROS MODEL OVERVIEW

APROS has one- and three-dimensional neutronics models. Both models are based on the two energy group, six delayed neutron group diffusion equations. In both models the basic equations are discretized versus time. The 3-D core models of APROS are able to describe the full cores of BWR- and PWR-type reactors with quadratic fuel assemblies and VVER-type reactors with hexagonal fuel assemblies. Reactor core description in the 3-D model includes thermal hydraulic channels, fuel assemblies, reflector assemblies and control assemblies[2]. Reactivity feedback effects due to fuel temperature, coolant density and temperature, coolant void fraction, coolant boron content, and control and scram rods are taken into account in the model. The feedback correlations depend on the application.

For the one- and three-dimensional core models the user can select either homogeneous, 5- or 6-equation thermal hydraulic model[3]. The homogeneous two-phase flow model is based on the mass, momentum and energy conservation equations of the mixture. The five-equation model is based on the conservation equations of mass and energy for liquid and gas phases and the momentum equation for mixture of gas and liquid. The gas and liquid interface friction is not calculated, but the differential phasial velocities are obtained through the drift flux correlations. A separate drift flux model calculates the mass flow rates of the phases. No iteration is needed in this model.

The six-equation model describes the behavior of one-dimensional two-phase flow. The model is based on the conservation equations of mass, momentum and energy for the gas and liquid phases. The equations are coupled with empirical correlations describing various two-phase phenomena. The pressures and the velocities, volume fractions and enthalpies of each phase are solved from the discretized equations using an iterative procedure. Special correlations are provided for the reflooding phenomena.

Heat transfer modules connect all three models with their own heat conduction solutions. Calculation of fuel rod temperatures, coolant conditions and boron concentration is performed within the thermal hydraulic models of APROS.

Hot channel calculations can be performed in APROS either simultaneously with the calculation of the average core or afterwards on the basis of the data stored. Several hot channels can be calculated simultaneously with different critical heat flux correlations, fuel, gas gap and cladding material properties and connections to different fuel assemblies of the average core. Fuel enthalpy, oxide layer thickness on cladding surface and power production by cladding oxidation according to the Baker-Just model are calculated in the hot channels.

The user creates the plant circuit model with the process components (pressurizer, steam generators, pumps, valves, pipes, accumulators) of APROS. The process components require design-oriented input data. In addition, the user has to select the thermal hydraulic model. In the circuit all the same thermal hydraulic model alternatives are available as in the core. The process components then create the calculational level description consisting of nodes and branches. Creation of the process model is usually done with the graphical user interface of APROS. With the graphical user interface the user has always up-to-date presentation of the actual model used in calculation. The user can make changes to the process via the graphical user interface and continue simulation immediately with the modified model.

The control and protection systems can be described and modified with the automation system components of APROS in the same manner as the process components using the graphical user interface.

III. VVER-91 MODELS REALIZED WITH APROS

IVO Power Engineering Ltd has studied main control system design, feedwater pump cavitation and process and control system of condenser with APROS VVER-91 model[4]. In these studies one-dimensional core model and homogeneous thermal hydraulics model were used. Typical features of the analysis were detailed description of the subsystem studied and real-time or faster than real time calculations. In these applications the secondary circuit was described extensively.

At IVO Power Engineering Ltd ATWS analyses for the VVER-91 with the APROS model include boron dilution in small break LOCA cases[5], and de-pressurization of primary circuit with pressurizer relief valves. In these studies one-dimensional core model has been used. Both 5-equation and 6-equation thermal hydraulic models have been used.

The ATWS analyses for VVER-91 at VTT Energy with APROS 3-D core model include the analysis of steam line break (basic case and two variations), steam header break and erroneous connection of a reactor coolant pump. The steam header break resulted in symmetric behavior in core whereas the other cases resulted in asymmetric behavior in the core. In these analysis the 5-equation thermal hydraulic model has been used both in the core and in the circuit in order to obtain reasonable calculation time. The primary and secondary circuits have been described in the extent required in the analysis. The control system description has been limited to the systems involved in the transient.

IV. ATWS ANALYSES FOR VVER-91

A. General

ATWS analyses for the VVER-91 concept have been previously performed at VTT and IVO PE with other codes, such as successive versions of the well-known RELAP-5 code and with the combination of the Finnish reactor dynamics codes HEXTRAN[6] and SMATRA[7,8] developed at VTT. In order to measure the capabilities of the Finnish APROS code with three-dimensional core model in ATWS cases, the analysis of steam line break was carried out simultaneously with the APROS and HEXTRAN codes. Both codes had three-dimensional core model with two energy groups and six delayed neutron groups. The main difference was that in APROS the core was described with a finite-difference type model and in HEXTRAN with a more accurate nodal model. In both codes the circuit thermal hydraulics was based on the 5-

equation concept.

B. The APROS VVER-91 Model for the ATWS Analysis

In the APROS model the core is described with 163 one-dimensional thermal-hydraulic channels. Neutronics description includes 163 hexagonal fuel assemblies. Both in neutronics and in thermal hydraulics the core is divided axially into ten sections.

The nodalization of the circuits is based on the models used in previous analyses with other codes. The nodalization describes the main fluid volumes and solid structures of the primary side and the secondary side up to the steam header. All four loops are modelled separately. Figure 1 shows the presentation of APROS VVER-91 primary circuit model on the workstation screen. In the 3-D VVER-91 APROS model for ATWS analyses the process description on workstation screen consists of 23 process figures and 28 control and protection system figures.

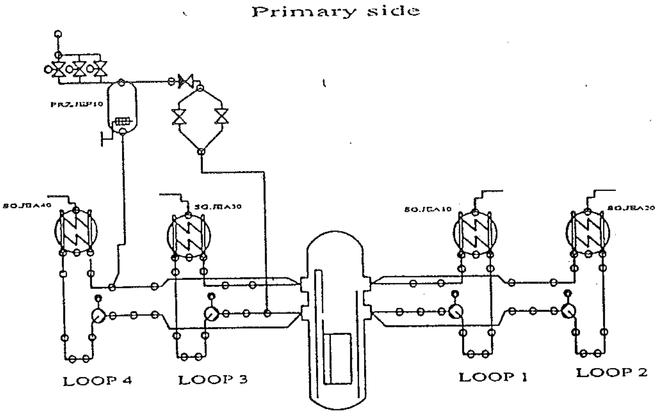

Figure 1. APROS VVER-91 primary circuit on workstation screen.

In order to be able to calculate transients with an asymmetric response in a three-dimensional core model the downcomer, lower plenum and upper plenum are divided into four parallel sectors according to the four loops. Horizontal cross-flow junctions between the parallel nodes allow mixing of the liquid between the sectors.

In the model any size of break can be placed in any position. In the steam line break ATWS case the break is located before the main steam isolation valve. The break is double ended and modelled with three valves, two valves opening with a break area equal to the steam line cross section area and one valve which closes the flow path across the break.

The steam generators are described with a quite detailed five-layer model. The steam header is modelled with one node. The turbine is modelled as a pressure boundary. Between the steam header and the turbine there is a fast acting turbine trip valve and a turbine control valve. The control valve regulates the pressure in the secondary side.

Table 1. Extent of the APROS VVER-91 model

Component type	Max. numb. of comp.
Neutronics nodes	1630
Thermal hydraulic nodes	2040
Thermal hydraulic branches	2377
Heat structure nodes	17794
Basic valves	3
Shut-off valves	22
Common valves	34
Control valves	14
Basic pumps	12
Motor pumps	4
Analog signals (in use)	290
Binary signals (in use)	507
PI controllers	5

Heat structures describing pipes, vessel walls and internal structures are connected to the primary side nodes and to the steam generator nodes. No heat structures are modelled in the steam lines. Typical extent of APROS model with three-dimensional core for the ATWS analyses has been given in Table 1.

All safety and protection systems that have any effect on the calculated cases are described with the available modeling methods of APROS. The main emphasis is on the correct simulation of the thermohydraulic parameters. Most of the plant systems are expected to operate as designed. Some special assumptions are made due to conservative reasons or due to a special character of the event.

C. Steam line break ATWS

In the steam line break ATWS case it was assumed that the break takes place at full power (104 %). The break is located in a steam line in front of the steam line isolation valve. The isolation valve is assumed to fail to close. After the break the following key assumptions are made:

-failure of reactor trip signal (ATWS)

-mixing factor between sector flows at core inlet 10 %

-two emergency boration pumps (JDH) are available 50 s after activation signal
-make-up water injection system (KBA) is not operating
-four emergency feed water pumps are available
-feed water tank has capacity 250 m^3 after turbine trip.

The calculations were performed independently with the APROS and HEXTRAN codes. Both used three-dimensional core description and similar circuit and automation and control system description. For both codes hot channel analysis using two sets of fuel gas gap conductance values were performed. In the analysis the Smolin and Gidropress correlations for critical heat flux were used. In APROS 20 axial nodes were used in the hot channels. The hot channel analysis for HEXTRAN was performed with 40 axial nodes per fuel assembly.

The basic neutronic characteristics of materials are described in APROS for VVER-reactor by standard two-group diffusion theory parameters in the same way as in HEXBU-3D[9]. The parameters for VVER-1000 fuel were calculated with the CASMO-HEX code[10]. The reactor core was assumed to be in the end of the equilibrium cycle state with zero boron concentration. The end of cycle burnup state created by the HEXBU-3D code was used in the APROS assemblies.

Due to conservative assumptions in neutronics the fuel temperature reactivity feedback was adjusted to -2.5 E-5/°C, and the coolant temperature reactivity feedback to -64 E-5/°C. The boric acid concentration was 0 g/kg. The axial profile was adjusted into cosine shape with power peaking factor 1.49.

At steady state the relative powers of the highest power assemblies in APROS were 1.35 versus the value of 1.24 in HEXBU-3D or HEXTRAN. This is due to the fact that the finite difference type models, like APROS, tend to overestimate the power of the high power nodes. Since the node size in VVER-1000 core model is larger than in VVER-440 the overestimation is more pronounced than that observed in the comparison of APROS results and core measurement data or HEXBU-3 D results for VVER-440 core[11].

The pressure decreases in the secondary side and especially in steam generator in the affected loop when the break takes place. The pressure decrease results in an increased heat transfer rate from the primary to the secondary side and hence the cold leg and the core inlet temperatures start to fall.

The power behavior calculated by APROS and HEXTRAN is presented in Figure 2. The major features predicted by both codes are the initial power peak due to cold water inlet into the core, the power decrease due to decrease in the core flow rate as the pump in the affected loop stops and due to increase in the core coolant inlet temperature, local maximum of reactor power resulting from inlet of cold water plug into core due to flow reversal in the affected loop, power reduction due to boric acid injection, and a drastic reduction in power resulting from the stopping of the still operating three reactor coolant pumps in the intact loops.

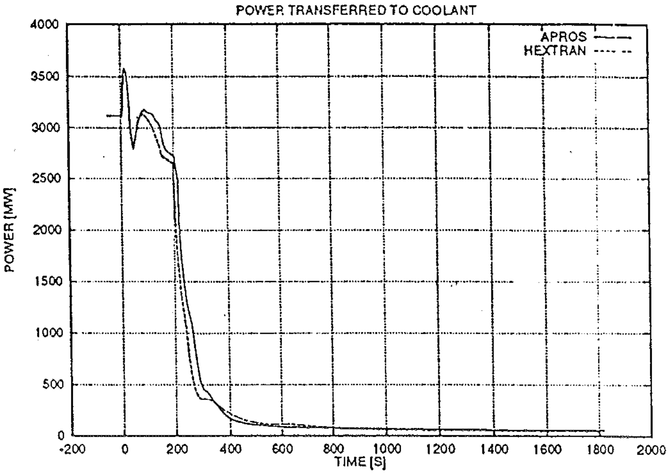

Figure 2. Power transferred to coolant in steam line break ATWS for VVER-91. APROS and HEXTRAN results.

Figure 3 shows the primary side pressure calculated with the APROS and HEXTRAN codes. The calculated secondary side pressure in the steam generator 1 in the affected loop and in the steam generator 2 in one of the intact loops are presented in Figure 4. Both codes predict similar pressure behavior pattern although there are small numerical differences between the results.

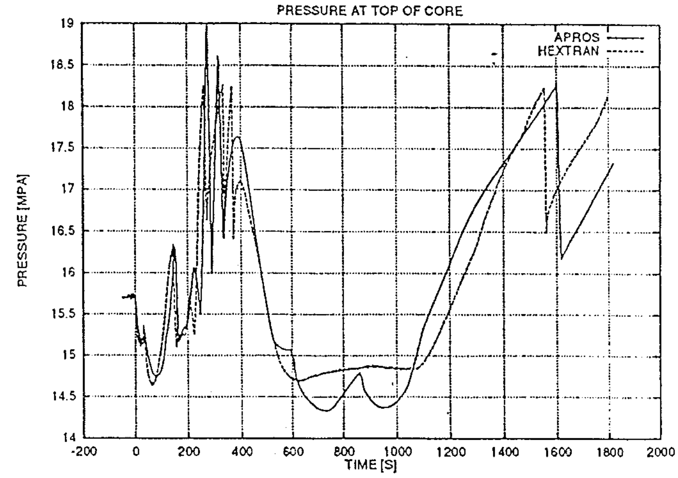

Figure 3. Pressure at top of core in steam line break transient for VVER-91. APROS and HEXTRAN results.

The core flow rate is decreased first after some 10 seconds of the transient when the reactor coolant pump in the affected loop stops. The flow reverses in the affected loop at about 35 s. The reversed cold water flow in the affected loop is mixed in the upper plenum with the reactor water flow, and the water going to the intact loops is then being cooled down. When the cold water plug reaches the reactor the power increases again. The power is reaching a local maximum at about 100 s. The subsequent power reduction thereafter is caused by boric acid, which is injected into the cold legs of two intact loops by the JDH pumps. At time 194 s the feed water tanks are empty, i.e 250 m^3 of water has been consumed after the turbine trip. The main feed water injection stops and the level in steam generators in the intact loops start to fall. When the level decreases 0.5 m below the nominal level the reactor coolant pumps in the intact loops stop. Stopping of the reactor coolant pumps in the intact loops reduces quickly the flow rate through the reactor and as a consequence the core power drops dramatically. The power decreases further due to the increase of boric acid content in the circuit.

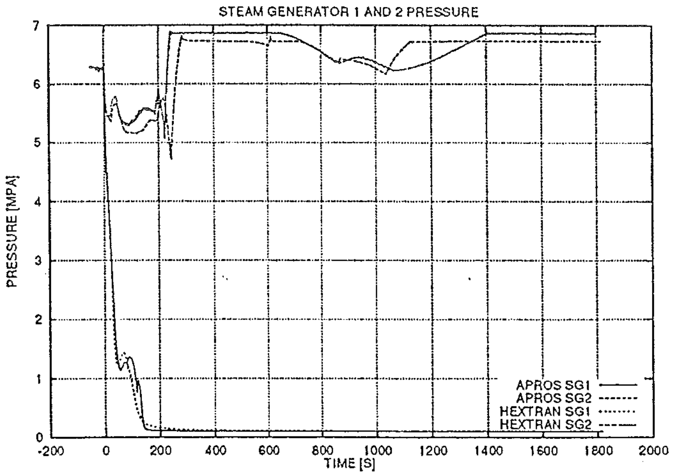

Figure 4. Steam generator pressure in steam line break transient for VVER-91. APROS and HEXTRAN results.

Emergency feed water pumps start injection to steam generators in the intact loops when the level decreases 0.9 m below the nominal level. The transient has been calculated until 1800 s. By this time the reactor has been shut down to a safe state.

Figure 5 shows the core coolant inlet temperature behavior calculated with APROS and HEXTRAN in sector 1 which obtains most of the inlet water from the affected loop 1 and in sector 2 which obtains most of the inlet water from the intact loop 2, when 10 % mixing between the sectors at inlet has been assumed. The initial coolant temperature decrease predicted by APROS for sector 1 is 14°C and 12°C by HEXTRAN. In sector 2 the corresponding decreases are about 7°C and 5°C, respectively.

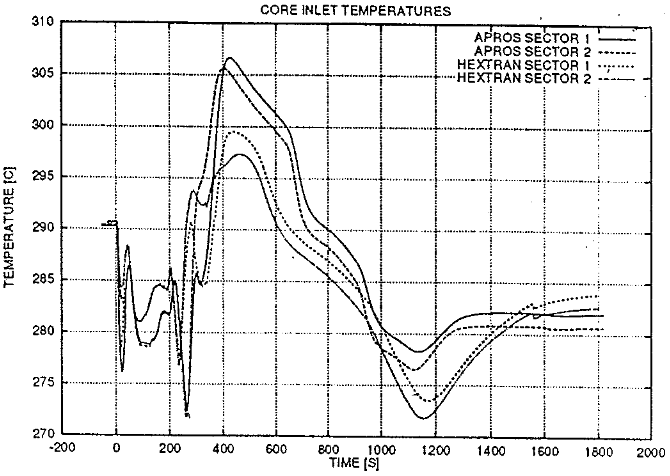

Figure 5. Core coolant inlet temperature in steam line break transient for VVER-91. APROS and HEXTRAN results.

The core average boron concentration calculated with the APROS and HEXTRAN codes is shown in Figure 6. Both codes predict quite similar increase in the concentration.

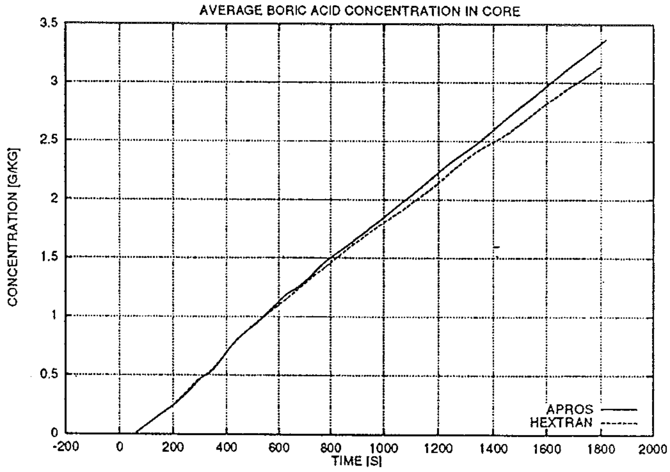

Figure 6. Boron concentration in steam line break transient for VVER-91. APROS and HEXTRAN results.

Figure 7 shows the behavior of the core reactivity calculated with the APROS and HEXTRAN codes. The initial peak is due to core inlet coolant temperature decrease. A substantial decrease in reactivity takes place when the reactor coolant pumps stop and consequently the core coolant temperature increases. There is a rather large difference in the calculated reactivity value calculated by APROS and HEXTRAN from about 300 to 700 s. This is due to the difference in core inlet temperatures. During the interval from about 400 s to 1000 s the average liquid temperature in core is decreasing. Simultaneously the core boron concentration is increasing steadily. These two effects largely compensate each other in the reactivity behavior. After the time 1000 s the core coolant temperature stabilizes and the reactivity decreases due to the increase of the boron concentration in core.

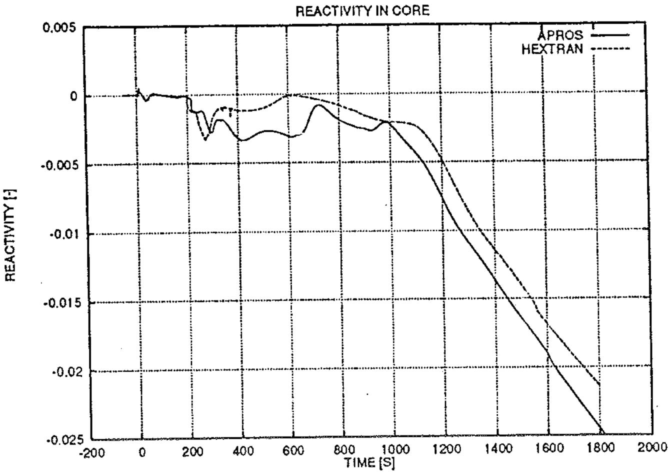

Figure 7. Reactivity behavior in steam line break transient for VVER-91. APROS and HEXTRAN results.

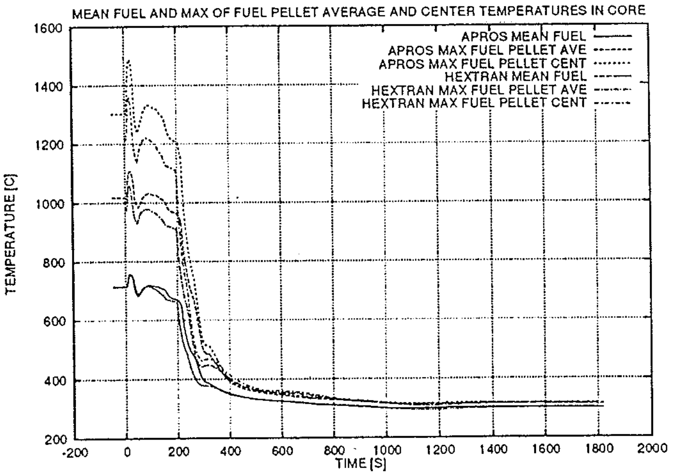

Figure 8. Fuel temperatures in the average core in steam line break transient for VVER-91. APROS and HEXTRAN results.

Maximum fuel pellet centerline temperature, maximum of pellet average temperature and mean fuel temperature in the 3-D core calculated with APROS and HEXTRAN are shown in Figure 8. Due to the fact that APROS tends to overestimate the power of the highest power assemblies, the maximum pellet center temperatures calculated by APROS are higher than those calculated by HEXTRAN already at steady state.

Four different hot channels have been calculated. Either Gidropress or Smolin bundle critical heat flux correlations were used, and the conductivity value of the gas gap was varied from the nominal value to the minimum value. Figure 9 shows the calculated DNB-margins according to the Gidropress correlation. The minimum values are calculated shortly after the time of the power peak. They were 1.55 and 1.43 with APROS and HEXTRAN, respectively. Thus DNB crisis was avoided according to both codes.

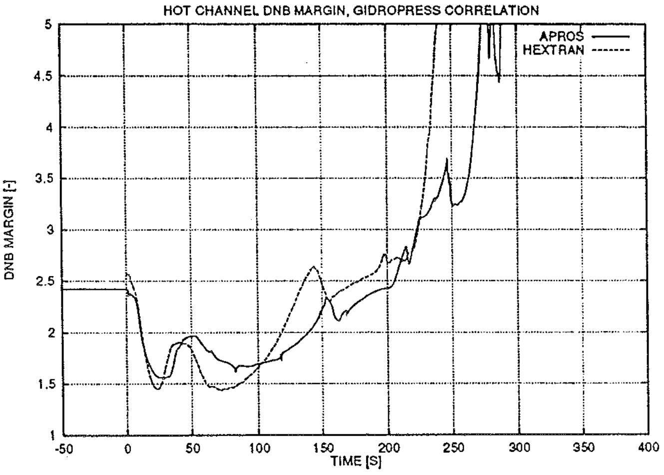

Figure 9. DNB-margins in steam line break transient for VVER-91. APROS and HEXTRAN results.

Figure 10 shows the fuel centerline, fuel average and cladding temperatures with APROS and HEXTRAN in the hot channel with nominal gas gap conductance. The maximum fuel centerline temperatures predicted with APROS and HEXTRAN were 1890°C and 1852°C, respectively. The maximum cladding surface temperatures reached with APROS and HEXTRAN were 368°C and 359°C, respectively. Using the minimum gas gap conductance in the hot channel analysis the fuel centerline maximum temperature values calculated with APROS and HEXTRAN were 2202°C and 2137°C, respectively. With APROS somewhat higher maximum linear power in the hot channel was calculated than with HEXTRAN, as can be seen in Figure 11.

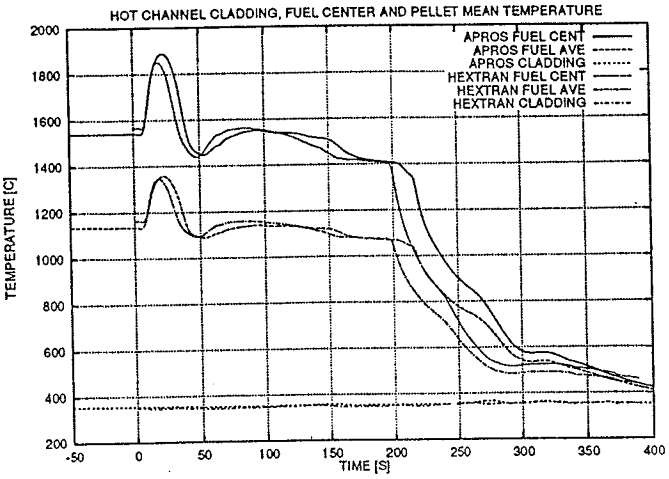

Figure 10. Hot channel fuel rod temperatures in steam line break transient for VVER-91. APROS and HEXTRAN results.

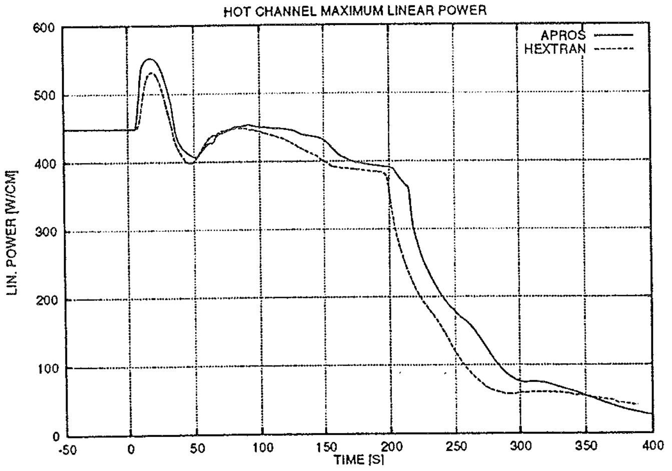

Figure 11. Hot channel max. lin. power in steam line break transient for VVER-91. APROS and HEXTRAN results.

The asymmetric nature of the transient in the core is clearly seen in the HEXTRAN representation in Figure 12 which shows the radial distribution of the ratios of the assembly average fission powers at the time of the maximum power peak to the values in the initial full power steady state.

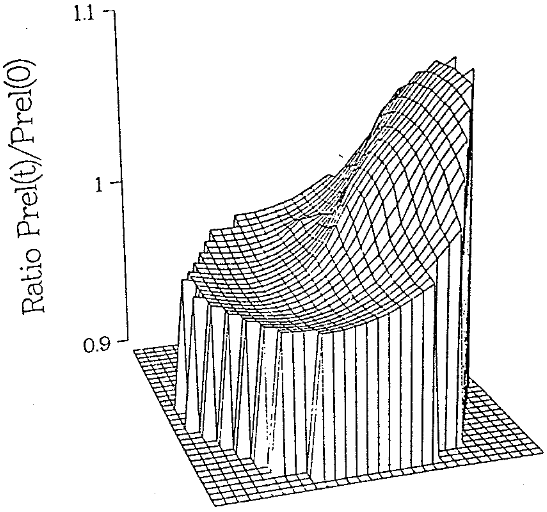

Figure 12. Relative power distribution change at the time of maximum power peak. HEXTRAN result.

As a summary it can be concluded that the results obtained with both codes for the average core and for hot channels were qualitatively consistent and the quantitative differences in the various parameters were quite small. Regarding the safety aspects both codes resulted in the same conclusions and indicated the fulfillment of the ATWS safety criteria. The small numerical differences between the results of the two codes were consistent and can be explained on the basis of the different models of the two codes.

D. Further VVER-91 ATWS analyses with APROS

The ATWS analyses for VVER-91 at VTT Energy with APROS 3-D core model were continued with calculation of two variations of the steam line break case. In the first variation it was assumed that the steam line isolation valve is operating normally, and in the second variation steam line break at low power (3 %) was analyzed. The results of these analyses were less severe than those of the basic case both considering the behavior of the average core and the hot channels.

Analysis work with APROS has continued with calculation of main steam header break, and analysis of erroneous connection of a reactor coolant pump. Also in these cases the analyses indicated the fulfillment of the ATWS safety criteria. As an example of the results obtained in these analysis the asymmetric coolant temperature distribution at the core inlet and the resulting asymmetric core power distribution at middle axial core level at the time of peak power have been shown in Figures 13 and 14, respectively for the erroneous connection of the reactor coolant pump (RCP) transient.

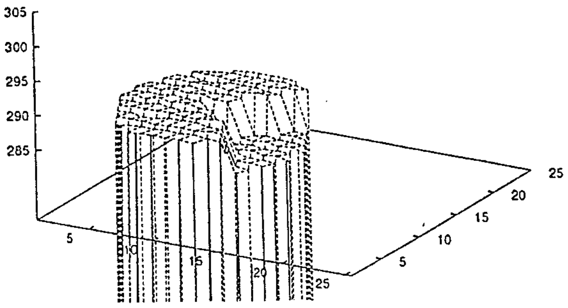

Figure 13. Core inlet coolant temperature in erroneous connection of RCP pump ATWS for VVER-91 . APROS result.

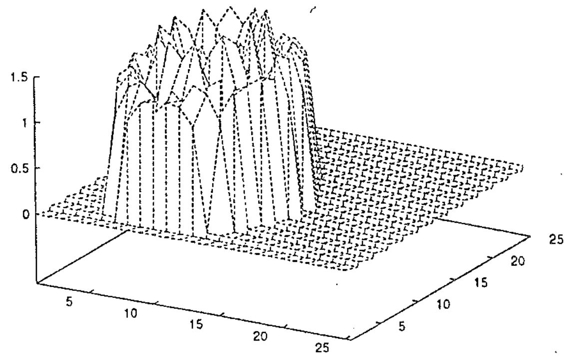

Figure 14. Core power response in connection of RCP pump ATWS for VVER-91. APROS result.

The most demanding core transient analyses for VVER-91, like control rod ejections or boron dilution with 3-D core model have been previously performed with HEXTRAN. Since HEXTRAN has more sophisticated core neutronics model, it is assumed that such analyses will be performed with HEXTRAN also in the future. However, APROS is capable for such analyses, too, and thus it would be possible to compare how well APROS could meet the standard set by HEXTRAN.

V CONCLUSIONS

Various APROS models with one- and three-dimensional neutronics and 5- or 6-equation thermal hydraulics have been created and used both for design studies and safety analyses at VTT Energy and IVO Power Engineering Ltd for the VVER-91 concept.

The comparison of the APROS results with the results of the HEXTRAN code in the steam line break ATWS case for VVER-91 concept indicated that APROS is capable for such type of ATWS analyses. The results obtained with both codes for the average core and for the hot channels were qualitatively consistent and the quantitative differences in the various parameters were quite small. Regarding the safety aspects both codes resulted in the same conclusions and indicated the fulfillment of the ATWS safety criteria. The small numerical differences between the results of the two codes were consistent and can be explained on the basis of the different models of the two codes. The comparison indicated the capability of APROS for such analyses.

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