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THREE-DIMENSIONAL CORE MODELS IN RESEARCH SIMULATORS

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ABSTRACT

The emphasis of the paper is in the description of the real time three-dimensional reactor core model of the OECD Halden reactor Project BWR research simulator HAMBO. The model performance is compared with the performance of the standard one-dimensional core model of the simulator in feedwater line break ATWS transient. The paper includes also a short overview of the entire simulator scope, testing and status. The alternative core models created during the search of a suitable real time three-dimensional core model and their further prospects in the research simulator environment are also presented. The requirements set to a research simulator are quite demanding. On the other hand it is used as the tool in the human factors reseach with crews consisting of plant operators, and in order to produce realistic results the tool, the simulator, must fullfill the requirements set for a full scope simulator. The requirements of detailed modelling, plant fidelity, flexible modification capabilities and capability of communication with the rest of the research environment are also essential when studing new technical solutions for operator aids in the control room. Traditionally, training simulators have been using one-dimensional core models and various kinds of methods to produce three-dimensional displays of core status within the real-time requirement. The paper indicates, that with the current capabilities of workstations and NT's a research simulator with the plant model on one computer and a real time three-dimensional core model in another is already realism and can bring further benefits also into this research area in near future.

1. INTRODUCTION

HAMBO is the new BWR research simulator of the OECD Halden Reactor Project Man-Machine laboratory HAMMLAB 2000 (Kvalem, 2001). The simulator describes the Forsmark-3 3300 MWth BWR plant situated in Sweden. In the simulator development project VTT Energy was responsible for the simulator models, using the APROS tool with GRADES graphical user interface, while the Halden Project designed and implemented the human machine interface, using Picasso-3 tool. The simulator has gone through extensive Factory and Site Acceptance tests with the participation of professional operators of the Forsmark-3 plant, and the simulator is currently in use at HAMMLAB (Karlsson et al., 2001).

The process models of HAMBO have been created with the Advanced PROcess Simulation Software, APROS (Silvennoinen et al., 1989), developed by the Technical Research Centre of Finland in close co-operation with Fortum Engineering Ltd. APROS provides tools, solution algorithms and model libraries for full-scale modelling and simulation of nuclear and fossil power plant processes, including the process automation and electrical systems. It has been developed for design, analysis and training simulator applications. It is a flexible modelling tool, which contains a real time database, a graphical user interface for model configuration and model execution, and has local area network connections for high performance data transfer to other software and hardware components of the simulator.

The requirements set to a research simulator are quite demanding. On the other hand it is used as the tool in the human factors reseach with crews consisting of plant operators, and in order to produce realistic results the tool, the simulator, must fullfill the requirements set for a full scope simulator. The requirements of detailed modelling, plant fidelity, flexible modification capabilities and capability of communication with the rest of the research environment are also essential when studing new technical solutions for operator aids in the control room.

The emphasis of the paper is in the description of the real time three-dimensional reactor core model. The paper includes also a short overview of the entire simulator scope, testing and status. The alternative core models created during the search of a suitable real time three-dimensional core model and their further prospects in the research simulator environment are also presented.

2. HAMBO RESEARCH SIMULATOR OVERVIEW

The HAMBO research simulator has been presented in detail in (Karlsson et al., 2001), and shall be the subject of separate papers to be published in international journals/meetings. In this context only an overview of the simulator is given on the basis of (Karlsson et al., 2001).

2.1 Research Simulator Requirements

The HAMBO research simulator has to fulfil the same general requirements as full-scope training simulators concerning the operational scope and dynamic behaviour. A further requirement is that software architecture must allow flexibile experimental set-up concerning both process models and control system models. The flexibility is particurlarly important for the research made with new systems in plant control and surveillance.

An essential prerequisite when specifying the extent of the model was that every measurement and alarm and everything operable in the main control room of the reference plant had to be modelled to work in a similar manner as in the real plant.

The acceptance requirements of the simulator included running of the simulator from full power to cold shutdown and back to full power using the real plant procedures. The acceptance requirements covered also running of 19 specified transients in real time.

2.2 Research Simulator Realisation

For the HAMBO simulator, APROS provided 1-D and 3-D reactor core models comparable to the codes used for core supervision at the plant, non-homogeneous, non-equilibrium thermal hydraulic model for the primary part of the model, and homogeneous two-phase model for Balance of Plant systems and for auxiliary plant systems. The containment was simulated by using a special thermal hydraulic model in APROS. The APROS automation system was used for modelling the full plant automation and control system. The APROS electrical system provided the components for calculating the electrical power consumption in the network and a possibility to simulate different loss-of-electrical-power situations.

The whole simulator model has been modelled using standard APROS components. The model is based on the plant drawings, operating instructions and training material. Plant measurements and reference simulator (GSIM) transient runs have been available for HAMBO tuning. Most of the systems and components have been modelled physically. In cases where features of APROS do not admit physical modelling a workaround has been done in order to make e.g. measurements behave correctly. The extent of the process and automation description has been presented in Table 1. The extent of the three dimensional core model has been indicated in Table 3.

Table 1. The comprehensiveness of the HAMBO model process & automation

Component or issue	Number
Grades nets (graphical user interface pictures)	1200
Process thermal hydraulics, 3-equation nodes	1683
Process thermal hydraulics, 5-equation nodes	215
Containment nodes	5
Heat structure nodes	1833
Process components, valves	1682
Process components, Pumps and fans	153
Process components, turbine sections	15
Process components, heat exhangers	77
Electrical system, Electrical nodes	410

Electrical system, Electrical switches	314
Automation and control system, controllers	171
Automation and control system, Analogue signals	12960
Automation and control system, Binary signals	52210
Input/output, Analogue signals to Picasso	2160
Input/output, Binary signals to Picasso	7278
Input/output, Binary signals from Picasso	2604

Detailed description of the systems modelleled have been given in (Karlsson et al., 2001). The user interfaces, that are a key feature in the actual simulator, as well as the simulator architecture, have been described in detail in (Karlsson et al., 2001).

2.3 Currents status

A set of 19 predefined transients have been calculated and the behaviour of main parameters of different systems have been compared to reference training simulator results and where applicable the plant instructions for disturbances have been checked. During the FAT and SAT the transients were calculated for 30 minutes or more. A requirement was that it had to be possible to reset system according to the plant instructions. In addition to the transients the acceptance testing included several steady state tests and the running of the simulator from full power down to cold shutdown, and back up again. No major discrepancies were noted during the SAT, and the BWR simulator was accepted by the Swedish and Finnish utilities in June 2000.

The calculated transients included electric load rejection, turbine trip, turbine trip with turbine bypass failing, main steam isolation valve (MSIV) closure, loss of normal condenser vacuum, pressure regulator failure closing turbine valve, re-circulation control failure with increasing flow, trip of one re-circulation pump, trip of all re-circulation pumps, start of one idle re-circulation pump, loss of feedwater heater, loss of all feedwater flow, control rod withdrawal at power, loss of offsite power, loss of auxiliary power, feedwater line break as ATWS, steam line break before main steam isolation valve (MSIV), manual reactor scram and maximum power ramp from the normal operation at 109.3 % to 75 % and back to 109.3% power .

2.4 On-going activities with HAMBO

The simulator is on warranty period until end of June 2001. The simulator is being used in and for four particular development projects: 1) development of an advanced alarm system for the simulator, 2) development of an experimenter system, 3) integration of the Halden Project computerised procedures system COPMA III into the simulator, and

4) Integration of the Halden tools PEANO (Process Evaluation and Analysis by Neural Operators) and COAST (Computerised Alarm System Toolbox) to the simulator.

3. REACTOR CORE MODELS IN THE HAMBO SIMULATOR

The HAMBO research simulator contains one- and three-dimensional nuclear reactor core models. Both models fulfill the real time requirement. In the present configuration the one-dimensional model calculations take part in the same computer as the plant calculations and the three-dimensional core model calculations are performed in another computer.

3.1 Reactor core neutronics and thermal hydraulic models

APROS software has one-dimensional and three-dimensional core neutronics models (Puska, 1999). Both models have two energy groups and six delayed neutron groups. In the models the basic equations are first discretized. In the three-dimensional model the neutron flux equations are integrated over the node volumes, a few approximations are made and the fast and thermal equations are solved using Gauss-Seidel iteration process. The finite-difference type three-dimensional neutronics model is able to describe hexagonal and quadrilateral fuel assembly geometries. The concentrations of six delayed neutron precursor groups are calculated. Iodine, xenon, samarium and promethium calculations are included, too, with user-selected speedup factor. 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 models.

The one- and three-dimensional core neutronics models can be connected with the homogeneous, the five-equation or the six-equation thermal hydraulic model of APROS. At present either the five-equation thermal hydraulic model or the six-equation thermal hydraulic model is used with the one- and three-dimensional neutronics models. The five-equation model is considerably faster in calculation speed (Puska, 1999), and has thus been selected as the natural alternative for the research simulator that has to fullfil the real time calculation requirement.

The five-equation model is based on the conservation equations of mass and energy for liquid and gas phases and momentum equation for mixture of gas and liquid. In the five-equation model the gas and liquid interface friction is not calculated, but the differential phase velocities are obtained through the drift flux correlations. A separate drift flux model calculates the mass flow rates of the phases. The quantities to be solved in the model are pressures, volumetric flows, void fractions and phasial enthalpies. No iteration is needed in the model.

3.2 One-dimensional model realisation

The one-dimensional core model of HAMBO is on the physical basis a two-energy group, six delayed neutron precursor group model. In the neutronics model the core is divided axially in 25 sections of equal length. The thermal hydraulics and the fuel rod consisting of fuel, gap and cladding is described using the reactor process component.

In thermal hydraulics the core is also divided axially into 25 nodes of equal length. Heat conductance in the fuel rod is described in the standard manner of APROS with 10 radial nodes in the fuel rod model. Core thermal hydraulics is described with the 5-equation thermal hydraulic model of APROS.

In one-dimensional model the APROS option of individually moving control rods is used. Thus, the movement of each of the 169 control rods can be taken into account also in the 1-D model and the rods have been connected to the automation driving the rods.

The one-dimensional model uses neutronics cross-section data that was condensed from the original full 700 fuel assembly 3D core cross section data. Both the original and condensed data sets were created at VTT Energy. The cross sections describe the Middle of Cycle (MOC) core status of cycle 7 of Forsmark 3.

In the one-dimensional model the user can observe the flux, power, fuel temperature, coolant density, coolant temperature, void fraction and boron concentration in each axial node, the core average values of these variables, the core axial power profile, and the position of each individual control rod. The one-dimensional core neutronics model is very fast, less than 2 % of simulator calculation time, and has no significant effect on the simulator speed performance.

3.3 Three-dimensional model realisation

The three-dimensional model is a two-energy group, six delayed neutron precursor group model. The neutron fluxes are solved according to the finite difference method. The three-dimensional core model includes 169 macro fuel assemblies divided into 25 axial sections of equal length. The macro fuel assemblies are placed into 29 thermal hydraulic flow channels that are also divided into 25 axial nodes of equal height. The macro fuel assemblies have been created principally by combining the four assemblies surrounding one control rod. The model describes all the 169 control rods existing in the core. Fuel rod heat conductance calculation in the three-dimensional model is identical with the fuel rod calculation method in the one-dimensional model. For each fuel assembly a separate fuel rod calculation is performed. Core thermal hydraulics is described with the 5-equation thermal hydraulic model of APROS. The 29 thermal hydraulic flow channels were created by combining principally 6-8 macro fuel assemblies into the same thermal hydraulic channel. However, one of the macro channels was replaced with 9 individual thermal hydraulic channels in order to allow the description of single control rod movements in a realistic manner. The construction of the reactor core model is presented in Figure 1.

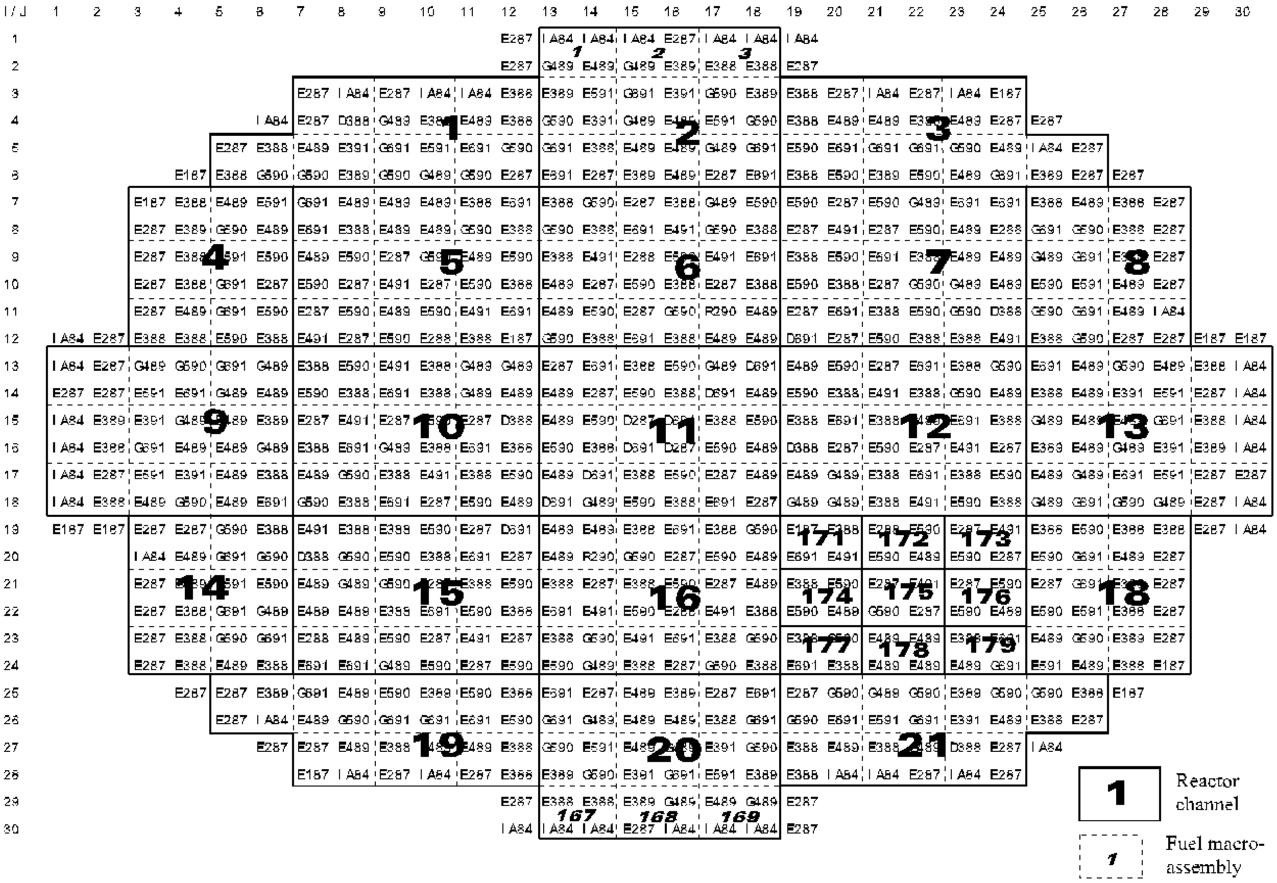

Figure 1. Real-time HAMBO simulator three-dimensional core model layout.

The three-dimensional model uses condensed neutronics cross-section set that was created from the full 3D cross section set at VTT Energy. The cross sections describe the Middle of Cycle (MOC) core status.

The number of thermal hydraulic channels and fuel assemblies had to be optimised in order to fulfill the real-time requirement set to the simulator core model. In neutronics the most reasonable alternative is the combination of the four assemblies surrounding each control rod. The thermal hydraulic calculation has more degrees of freedom when trying to optimise the calculation speed than the core neutronics. The channel division selected fulfills the real time requirements and gives reasonably good spatial description in the core.

The three-dimensional model in the present configuration has been tested both separately and together with the total plant simulation model at VTT Energy. In the test cases the plant model was run on one processor and the 3D core model on another processor. In the present configuration the 3D core model is connected to the plant analyser process via thermal hydraulic boundary conditions and the control rod position signals are transmitted to the 3-D core model control rods. The speeds of the plant model and the real time 3D core model have been indicated in Table 2.

Table 2. Execution speed of the simulator model on two HP 9000 workstations (C3600 and C3000), 2-processor Compaq AlphaServer ES40, and a PC with single / two 1.2 GHz AMD CPUs.

Case	**Simulation time / real time**		
	HP	**Compaq**	**PC**
Single processor			
1D steady state 100 s	1.14	1.58	1.31
1D turbine trip, first 500 s	0.89	1.20	1.36
1D steam line break, first 500 s	0.84	1.14	0.95
3D core alone, steady state 100 s	1.82	2.31	1.48
2 parallel processors, process with 1D running on the first processor, 3D core model on the second			
1D + 3D, steady state 100 s	1.12	1.54	1.24
1D + 3D, turbine trip, first 500 s	0.88	1.14	0.59
1D + 3D, steam line break, first 500s	0.83	1.14	0.57

With the three-dimensional model the user can observe nodewise all calculated variables from each axial level of the reactor core. The most interesting parameters include power level, fast and thermal neutron flux, fuel temperature, coolant density, coolant temperature, void fraction and boric acid concentration. The core average values as well as axial power profile are provided, too.

3.4 ATWS transient example

The validation of the research simulator model included calculation of 19 specified transients. The ATWS feedwater line break is presented here as an example. The transient tests the reactor plant system, emergency systems and interface to the containment systems.

This particular transient has the following course of events: A 200 % guillotine break inside the containment is opened and the hydraulic scram system fails to operate. The reactor protection system closes the steam line isolation valves and containment isolation valves. The reactor pressure increases and the relief valves in system 314 are opened and steam is blowed to the condensation pool 316. The pressure oscillates for a while until the control rod operation system (532) has inserted the rods through screw shutdown. The water level in the reactor vessel drops since no feed water is available. When the control rods have shut down the reactor the pressure decreases continuously. Forced blowdown is initiated in order to faster lower the pressure to a level where the low-pressure emergency feed water pumps are able to start to inject water to the reactor vessel. When the water level reaches the steam lines it starts to flow back to the condensation pool through valves open in the relief system. 30 minutes after the accident valves belonging to system 363 open and fill the lower drywell bottom with water. The transient tests the reactor plant system, emergency systems and interface to the containment systems.

The main parameters were found to be in accordance with the reference full-scope simulator (GSIM) results. Figures 2 and 3 show comparisons of the HAMBO 1-D core results and the corresponding reference simulator results for neutron flux measurement and reactor pressure measurement.

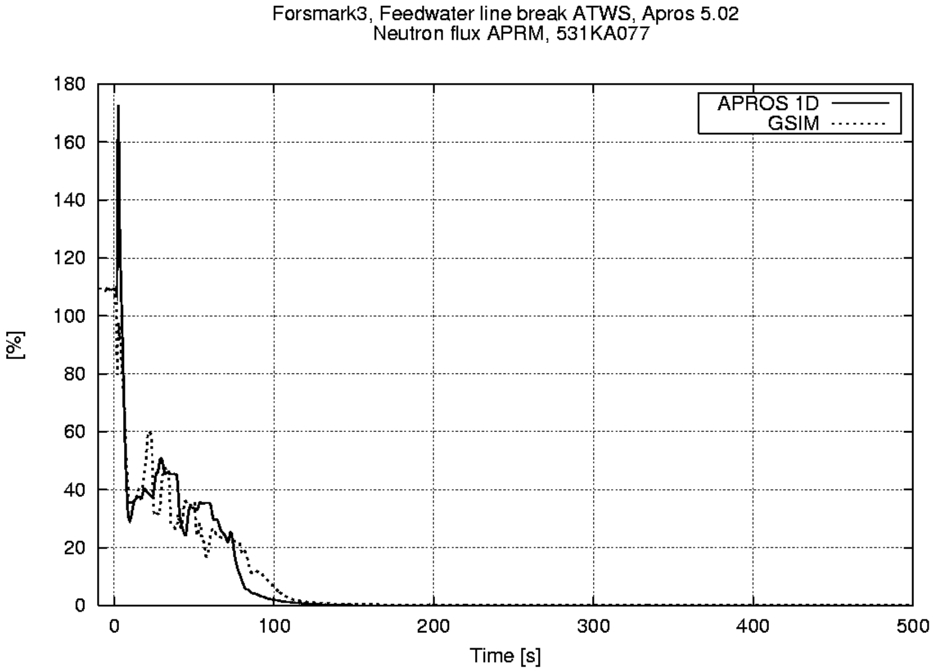

Figure 2. Neutron flux behaviour in HAMBO and in reference simulator.

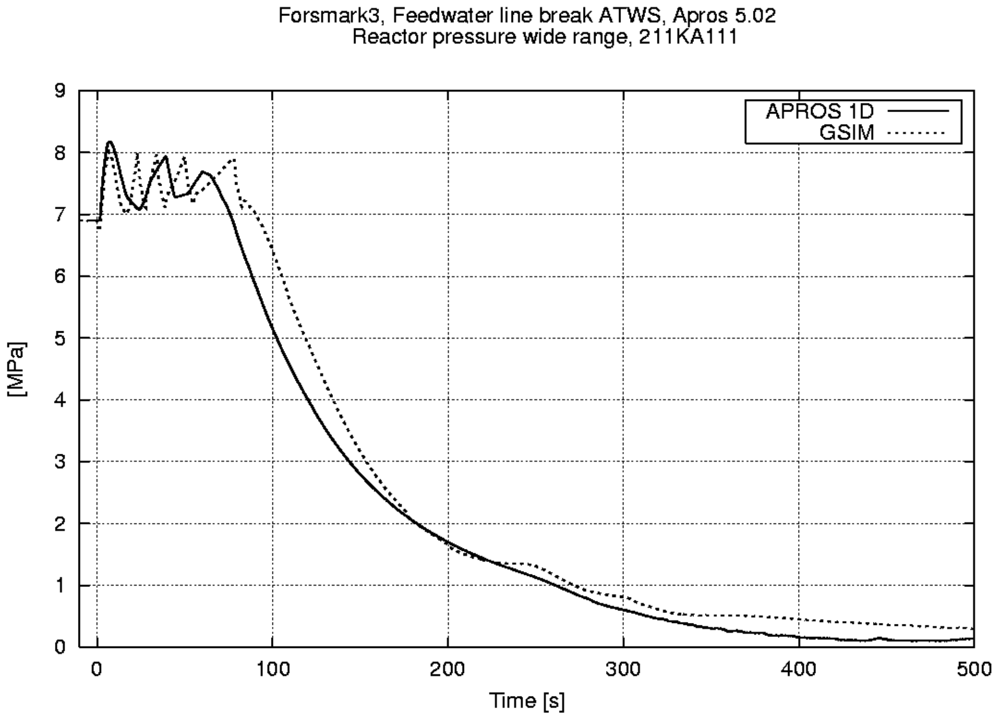

Figure 3. Reactor pressure behaviour in HAMBO and in reference simulator.

As examples of comparisons between the 1-D and 3-D core model performance the core average values for relative fission power, fuel temperature, coolant temperature and void fraction have been presented in Figures 4-7. The performance of the 3-D core model was found to be in agreement with the performance of the 1-D core model and the performance of the reference model, and was estimated to fulfill the current requirements set for the 3-D core model for the research simulator.

Figures 8 and 9 indicate the presentation capability and additional information that can be obtained with the real time three-dimensional core model. In Figure 8 the fast neutron flux, nodal fuel temperature and the void fraction distribution from middle of core level (node 10/25) and the current positions of the control rods have been presented for the transient power peak at 3.8 seconds. Figure 9 gives the corresponding information during the transient at time 50 seconds from the start of the transient.

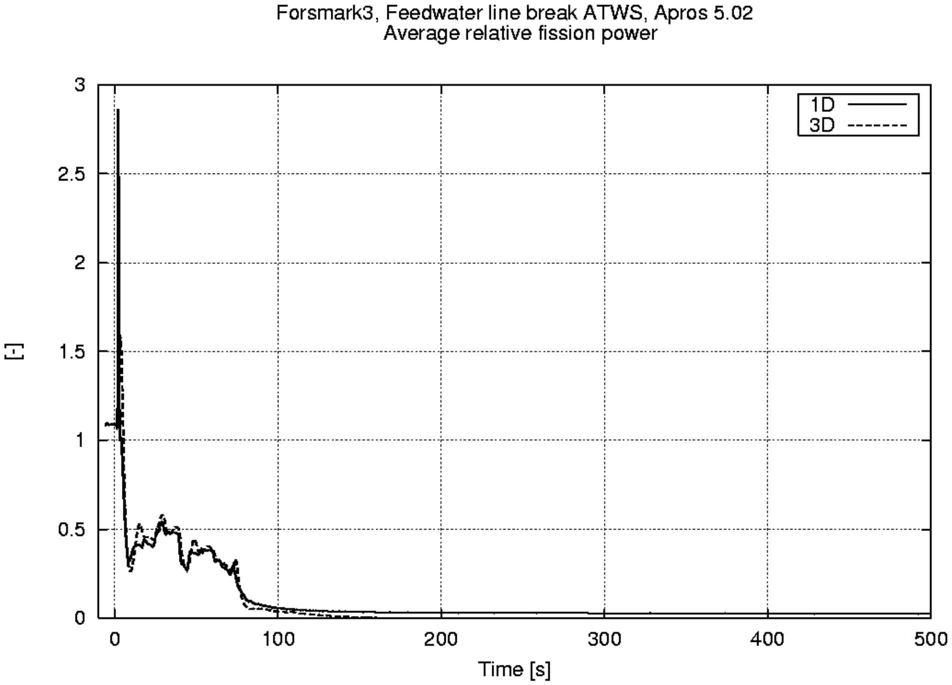

Figure 4. Fission power behaviour in the 1-D and 3-D core models of HAMBO.

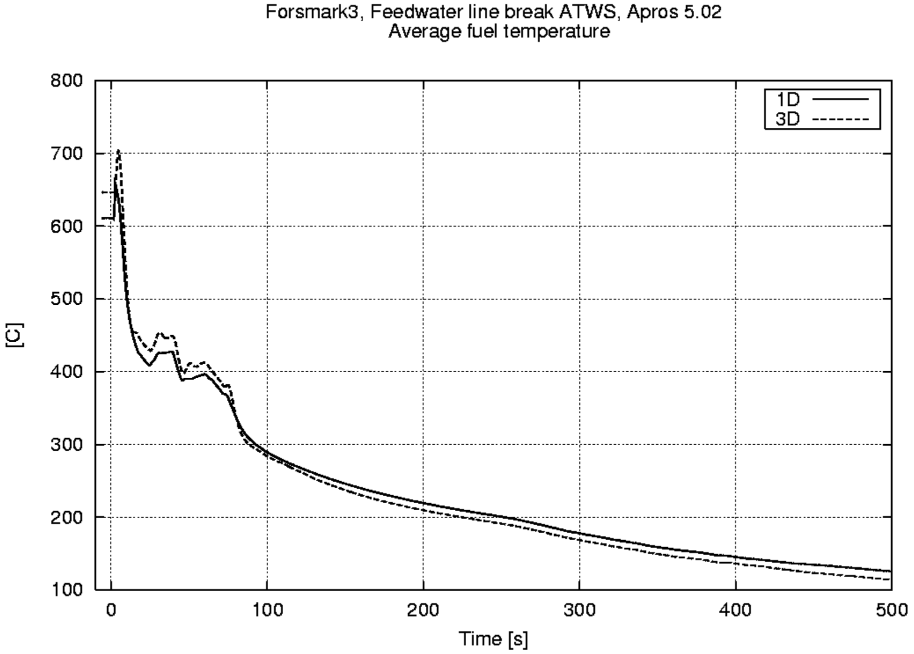

Figure 5. Fuel temperature behaviour in the 1-D and 3-D core models of HAMBO.

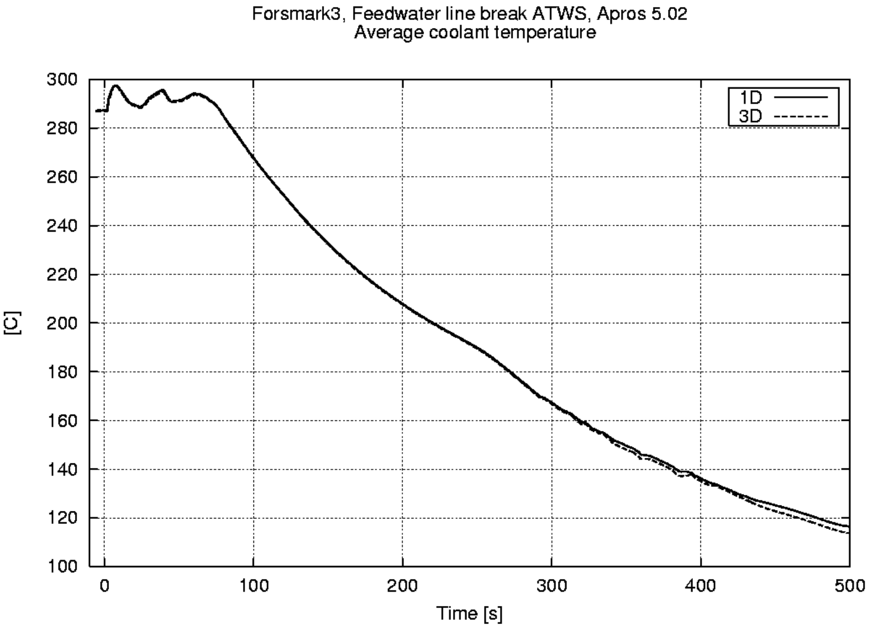

Figure 6. Coolant temperature behaviour in the 1-D and 3-D core models of HAMBO.

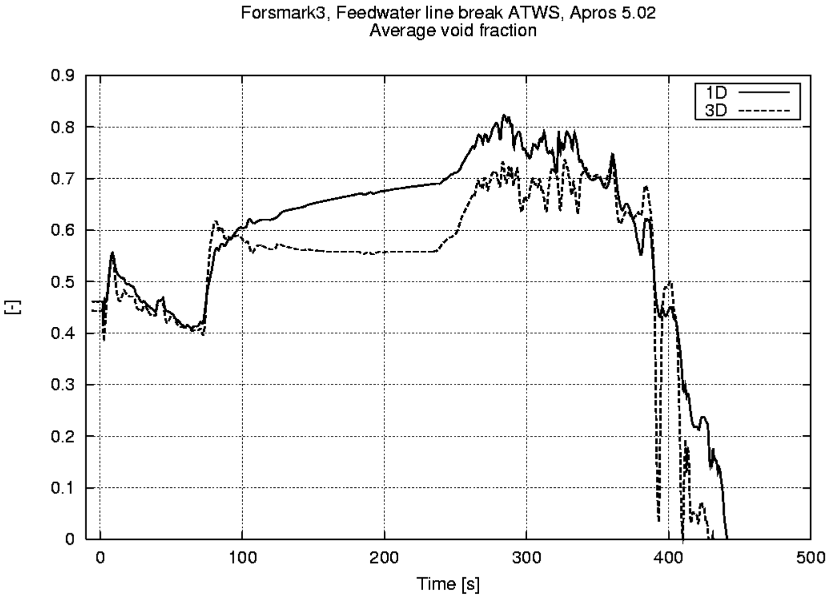

Figure 7. Coolant void fraction behaviour in the 1-D and 3-D core models of HAMBO.

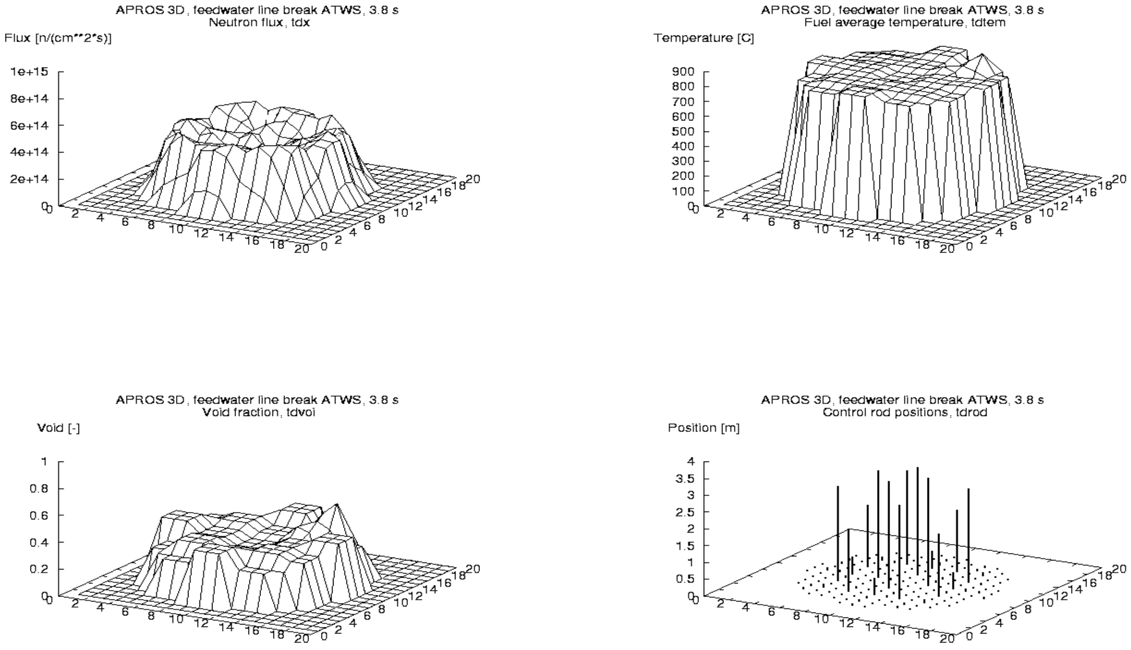

Figure 8. Fast neutron flux, fuel temperature and void fraction at middle core (10/25) at transient power peak.

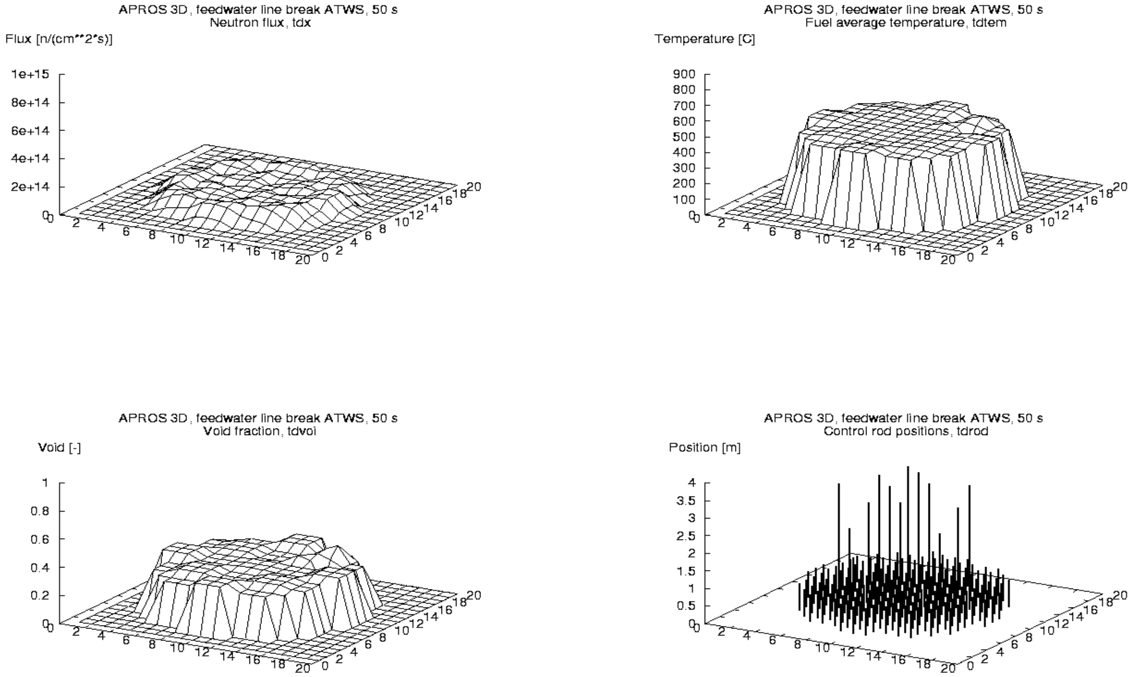

Figure 9. Fast neutron flux, fuel temperature and void fraction at middle core (10/25) at time 50 seconds from the start of the transient.

4. FURTHER PROSPECTS FOR THREE-DIMENSIONAL CORE MODELS

The speeds of several alternative core models were studied when searching a reasonable combination for the real time three-dimensional core model. The models looked at and their calculational performances have been described below.

4.1 Core model alternatives

In the construction of possible three-dimensional real time core models two basic boundary conditions were used. In neutronics the alternatives were either to use the original core description with 700 assemblies divided into 25 axial sections or use a condensed core with macro assemblies. The macro most reasinable macro assembly division was, naturally consired to be condensation of four assemblies surrounding a control rod into a macro assembly a omitting the corner assemblies with control rods. The division of core into 25 axial sections was kept in all alternatives considered due to requirements set by the rest of the simulator.

Thermal hydraulics calculations were known to be quite time-consuming in comparison to neutronics in APROS 3-D cores (Puska, 1999). Thus, the alternative of having 700 thermal hydraulic channels divided into 25 axial sections was ruled out from the study. The reasonable presentation for such a core for the viewpoint of best possible physical results would be the presentation of the 700 core assemblies in 185 macro channels in thermal hydraulics (consisting of 1-4 assemblies each). This alternative, however, was found to be all to slow, as indicated in Table 3. The altenative with 169 macro fuel assemblies in 169 thermal hydraulic channels is considered as the next promising alternative for the simulator real time core model with the present performance of approximately 50 % of real time. Table 3 indicates further that placing the 700 assemblies of the original core into one thermal hydraulic channel would meet the real time requirement. However, the requirement of plausible physical results is not met with such a construction.

Table 3. Performance of selected 3-D core models in ‘core alone’ mode with Compaq AlphaServer ES40.

Model	Assemblies	Neutronics nodes	Thermal hydraulic channels	Thermal hydraulic nodes	speed vs. real time
HAMBO real-time 3-D core model, 169 assemblies, 29 thermal hydraulic channels	169	4225	29	725	2.31
Prospects for next real-time model, 169 assemblies and 169 thermal hydraulic channels	169	4225	169	4225	0.51
Full 700 assembly 3D model with 1 thermal hydraulic channel	700	17500	1	25	1.28
Full 700 assembly 3D model with 185 thermal hydraulic channels	700	17500	185	4625	0.38

4.2 Further prospects with three-dimensional core models

The principal function of the present real time three-dimensional core model in the HAMBO simulator is to produce the data being used in the 3-D core displays in the simulator. For this purpose, the accuracy of the present real time core model has been assumed to be adequate. However, the core with the macro assemblies is not intended for safety studies due to the questionable accuracy of the finite-difference solution for such a large mesh size. The accuracy of the APROS finite-difference solution versus fuel management code for normal BWR mesh size has been studied in (Puska, 1999).

The development of computer technology since first three-dimensional APROS core models with a few thermal hydraulic channels and far from real time performance were presented in M&C in 1993 (Puska et al., 1993) has been so immense, that there is a good motivation to suggest the improvement of the accuracy in the simulator as well as in other applications via more detailed core models. One possible application area is the use of an entire simulator for safety analysis purposes, where the real time requirement is not crucial, as suggested by Puska and Tiihonen (2000). Another possible need of a more detailed core model would be in context of testing new core-specific operator aids in the simulator.

5. CONCLUSIONS

The paper presented the real time three-dimensional core model created with the APROS software for the OECD Halden Reactor Project HAMBO research simulator. The physical performance of the three-dimensional core model was found to be in agreement with the performance of the one-dimensional core model of the simulator, and to fulfill the requirements set by the three-dimensional core model in this application.

The results obtained indicate, that with the current capabilities of workstations and NT's a research simulator with the plant model on one computer and a real time three-dimensional core model in another is already realism and can bring further benefits also into this research area in near future, and extent the scope of the three-dimensional core models from the traditional neutronics – thermal hydraulics coupling into the real time simulator realm.

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