HEXTRAN-SMABRE CALCULATION OF THE 6TH AER BENCHMARK, MAIN STEAM LINE BREAK IN A VVER440 NPP

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ABSTRACT

The sixth AER benchmark is the second AER benchmark for couplings of the thermal hydraulic codes and three dimensional neutron kinetic core models. It concerns a double end break of one main steam line in a VVER 440 plant. The core is at the end of its first cycle in full power conditions. In VTT HEXTRAN2.9 is used for the core kinetics and dynamics and SMABRE4.8 as a thermal hydraulic model for the primary and secondary loop. The plant model for SMABRE consists mainly of two input models, Loviisa model and a standard VVER440/213 plant model. The primary loop includes six separate loops, the pressure vessel is divided into six parallel channels in SMABRE and the whole core calculation is performed in the core with HEXTRAN. The horizontal steam generators are modelled with heat transfer tubes in five levels and vertically with two parts, riser and downcomer. With this kind of detailed modelling of steam generators there occurs strong flashing after break opening.

As a sequence of the main steam line break at nominal power level, the reactor trip is followed quite soon. The liquid temperature continues to decrease in one core inlet sector which may lead to recriticality and neutron power increase. The situation is very sensitive to small changes in the steam generator and break flow modelling and therefore several sensitivity calculations have been done. Also two stucked control rods have been assumed. Due to boric acid concentration in the high pressure safety injection subcriticality is finally guaranteed in the transient.

1. PLANT MODELS FOR CODES

The sixth AER dynamic benchmark is the second AER dynamic benchmark for couplings of the thermal hydraulic codes and three-dimensional reactor dynamic core models. The previous fifth AER benchmark (AER 5th BM) /ref. 1/ was a steam header break and now the sixth is the Main Steam Line Break (MSLB), which leads to asymmetrical behaviour in the core and in the circulation loops. In VTT, HEXTRAN /ref. 2/ version 2.9 is used for the core dynamics and SMABRE /refs. 3, 4/ version 4.8 as a thermal hydraulic model for the primary and secondary circuits. Both codes need own input models because they can also be used separately.

All specifications of the benchmark /ref. 5/ are not repeated in the description of the input models. They have been followed as strictly as possible, the minor exceptions are reported here.

1.1 SMABRE model

The plant model for SMABRE is based mainly on two input models, the model for the Finnish Loviisa plant and the model of the standard VVER-440/213, which has been used in AER 5th BM /ref. 6/ and in several EU-projects. The geometrical differences between these plants consist mainly of three facts: reduction in the number of actual fuel assemblies in the core in Loviisa; different loop geometry due to different suction direction of the main circulation pumps; and different number and geometry of the pressurizer surge lines.

The Loviisa model without feed water and steam lines is the basis for SMABRE input for this benchmark. The primary loop piping geometry and steam line geometry are modified according to the benchmark specifications. Also, the core and core bypass flow area are modified according to the standard plant version.

The primary loop (Fig. 1) includes six separate loops. The pressure vessel is divided into six parallel channels except the upper head. The total number of nodes and junctions is 516 and 663, respectively. By the nodalization and the turbulent mixing model, 30 % mixing is provided in the pressure vessel before the core and 10 % after the core. The mixing degree is check in a artificial transient by stable boron content of 100 g/kg in loop 1. After stabilization the content of boron in the other loops are summarized in Table 1.

Table 1. Setup of mixing for AER 6th BM using flow with stable boron content in loop 1.

Loop/sector	1	2 and 6	3 and 5	6
Boron content in cold leg (g/kg)	100.	0.0	0.0	0.0
Boron content in core inlet (g/kg)	70.1	13.2	1.64	0.33
Boron content in hot leg (g/kg)	63.1	15.2	2.65	0.98

As the primary side related operational systems, the high pressure safety injection, pressurizer heaters and make-up water as a volume control system are described.

Loviisa steam generator model, used in the analyses, is shown in Fig. 2. The steam generator nodes are in five levels up to the upper level of tubes. The edge zone is described as a separate downcomer. The riser part includes the heat transfer tubes. A detailed simulation of water level measurements, narrow and large scale, are modelled. Feed water is described as a separate injection into each steam generator. The injection point is on the fourth level of the secondary side. Starting and stopping slopes of feed water are taken into account for intact steam generators. The regulating level is the narrow scale water level on the downcomer side similarly as it is measured in a real plant. For the broken steam generator, the time function is given fo feed water mass flow. Just after the break, feed water flow to broken steam generator i: increased to 300 kg/s until the steam generator isolation. During this time no level control i: used.

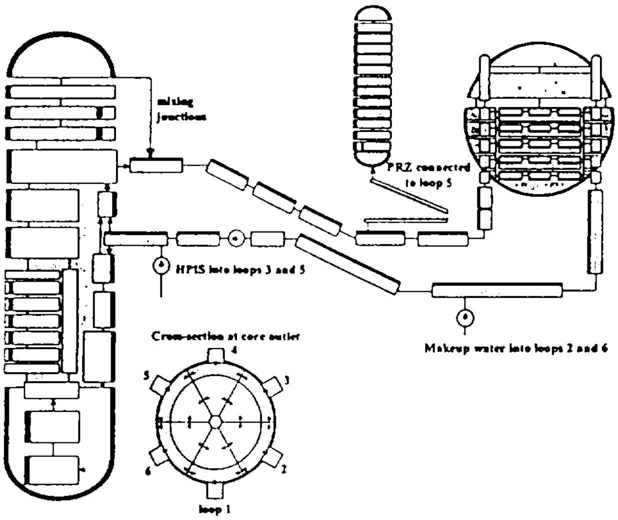

Figure 1. Nodalization of VVER-440 primary side for SMABRE code

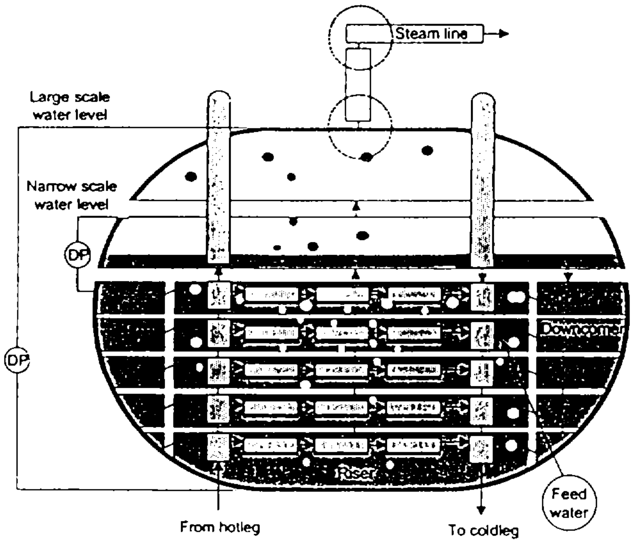

Figure 2. Nodalization of VVER-440 steam generator for SMABRE code

The steam lines are modelled up to the turbine valves (Fig. 3). In normal use positions of turbine valves are controlled with PID controllers, but due to the specification of the 6th benchmark possibility to model stable steam out through turbine valves was created. The steam header is divided into eight nodes, about 10 meters each. The double ended break is situated in steam line 1, diameter 0.425 m, near the main steam isolation valve (MSIV) depicted in Fig. 3.

The core has been divided into 5 axial nodes in SMABRE, and into 20 nodes in HEXTRAN. Below and above the core, there are quite short lower and upper plenum nodes. The core bypass is described with one node.

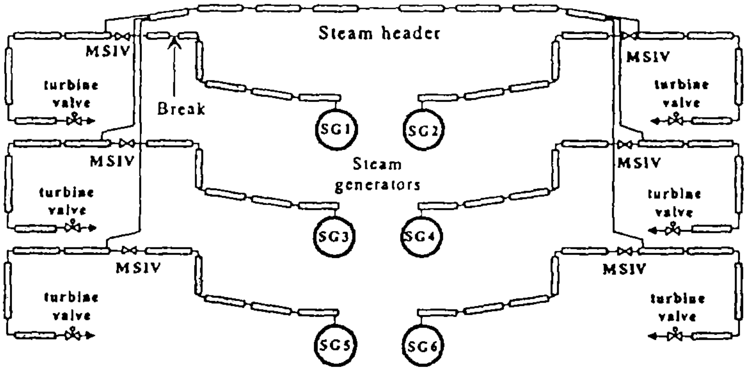

Figure 3. Nodalization of VVER-440 steam lines for SMABRE code

1.2 HEXTRAN core model

The input used for HEXTRAN is based mainly on the input of the fourth and fifth AER benchmark, but now the whole core is described, each fuel assembly with individual neutronics and heat transfer modelling as well as own thermal hydraulic channel divided into 20 axial nodes.

In the initial state the core is at the end of its first cycle in full power conditions. The nuclear data used in the calculations is based on the ENDF/B-IV library and it has been evaluated with the CASMO-HEX /ref. 7/ code for the three different fuel enrichments: 1.6, 2.4 and 3.6 %. The burnup state of the core was calculated with the HEXBU-3D /ref. 8 code. The burnup calculation of the first cycle was carried out at nominal power, all control rods withdrawn. 20 axial nodes of equal height were used. The calculated critical boron concentration at BOC was 1011 ppm and the calculated cycle length was 327.8 EFPD with 0 ppm at EOC.

For HEXTRAN calculations, the nuclear data developed similarly for wide temperature area was available. Also the albedos for the control rods were available for the different temperatures. The high isothermal re-criticality temperature of 210 °C, given in the specification, was produced by tuning the reactivity worth of the reactor trip (all control rods except the stuck rods) from 5.61 % to 3.15 %. The exponential tuning model of HEXTRAN $(a_{ij}^{*} = (a_{ij})^{0,535})$ was used for the albedos for the boron steel absorbers. The initial state of the reactivity worth calculation was at low power (1 kW), with full power xenon, working control rod group at height 1.75 m, core inlet temperature 260 °C and pressure 12.25 MPa. The resulting isothermal temperature coefficient at 210 °C was -24.4 pcm/K with all control rods except the two stuck rods fully inserted.

The core and fuel geometry and the power release values given in the benchmark specification are used. The fuel and cladding conductivity and capacity are modelled as temperature dependent and best estimate values for the decay heat are used as well. However, according to specification, constant value for gas gap heat transfer coefficient has been used, 3000 W/m^2K.

1.3 Initial state

The initial steady state conditions are listed in Table 2. The reactor is assumed to be at the end of the first cycle (EOC, 327.8 D) in nominal state. All control rods are out of core, except group 6 at position 175 cm. Xenon and samarium are in equilibrium state and there is no boron in water.

Critical flow in the breaks and valves in SMABRE is based on the separate break flow model by Moody combined with contraction coefficients of the break geometry. The best estimates for the contraction coefficients have been recommended in the literature and different values for subcooled liquid and two-phase mixture can be used in SMABRE. Normally in SMABRE for steam line breaks, the contraction coefficient 0.7 for saturated flow is used. This value was increased to 0.72 in order to get exactly the requested initial break flow rate in AER 5th BM. The same value was used here, too, and the traditionally used 1 s opening time for a break was decreased to 0.2 s.

For this benchmark calculation, the application of the Moody model was further developed. This was done by creating the dependency of quality to contraction coefficients. With the new model validated by comparisons with RELAP5, the break flow increases slightly.

Table 2. Initial state

PARAMETER	SPECIF.	CALCULATED
Total core power (MW)	1375.	1377.
Upper plenum pressure (MPa)	12.25	12.33
Core inlet temperature (°C)	267.4	267.2
Total core mass flow rate (kg/s)	9300.	9292.
Core bypass (%)	3.00	2.95
Pressurizer collapsed level (m)	5.97	5.92
Pressure at SG outlet (Mpa)	4.63	4.63
SG collapsed level (m)	2.015	2.004
SG narrow scale level (m)	-	0.125
Break opening time (s)	0.1	0.2
Contraction coefficient in Moody model for saturated flow, for subcooled flow	-	0.72 1.0
Feedwater starting/stopping level (m)	± 0.10	0.125 / 0.225 narrow level

2. CALCULATION RESULTS

The main events during the transient in the base case 1 are listed in Table 3. The break flows from the secondary system during the transient are shown in Fig. 4 with CASE 1. In figures results from the two extra variations (CASE 2 and 3) are also seen. The break opens at 0.0 s and the maximum total break flow is about 1357 kg/s during the first second. At first, after some water pulses through the break, the flow stabilizes for a while before at turbine valve closures at 11.6 s and total break flow increases due to the flow coming from the intact steam generators. Finally the break flow collapses down at main isolation valve closures.

Table 3. Sequence of events in base case 1

TIME	EVENT	CAUSE
-20.0	Steady state calculation with SMABRE	
-2.0	Calculation with HEXTRAN-SMABRE	
0.0	Double ended break opens SG1 feed water increases to 300 kg/s in 20 s	
3.1	Makeup water to loop 2	Pressurizer level < -0.10 m
5.8	PRZ heater group 1 on	Pressurizer pressure < 12.0 MPa
7.3	PRZ heater group 2 on	Pressurizer pressure < 11.9 MPa
8.8	PRZ heater group 3 on	Pressurizer pressure < 11.8 MPa
11.1	SCRAM signal	Reactor power > 110 %
11.6	Reactor trip, control rod speed 25.5 cm/s, Turbine trip; turbine valve closure in 0.5 s, Feed water temperature starts decreasing to 160 °C in 50 s.	0.5 s delay after SCRAM signal
14.0	PRZ heater group 4 on	Pressurizer pressure < 11.5 MPa
42.9	First HPIS signal no valid	Temperature in 2 hot legs no more > 255 °C
43.2	Makeup water to loop 6	40 s after makeup injection to loop 2
52.7	PRZ heater groups 1- 4 off	Pressurizer level < 2.56 m
55.9	Steam line MSIV 1-6 closure in 2.5 s, Feed water 1-6 off during 30 s	Steam header pressure < 3.0 MPa.
55.9	Second HPIS starting signal	Pressurizer level < 2.41 m and temperature in 2 hot legs > 150 °C
235.9	HPIS flow starts into loops 3 and 5	180 sec delay after signal
253.0	Second power maximum 58.3 MW	
398.0	End of calculation	

The lowering secondary pressure leads to a water temperature decrease in the primary side, especially in the broken loop 1. At maximum the temperature difference between the broken loop 1 and the loop 4, at the opposite site of the loop 1 in the pressure vessel, is 56 °C. At the same time at the core inlet after 30 % mixing in the downcomer and lower plenum, the temperature difference between corresponding sectors 1 and 4 is still 43 °C, shown in in Fig.

5. Further, in spite of clearly higher power level in sector 1 and 10 % mixing in upper plenum, the temperature difference between hot legs 1 and 4 is still 33 °C (Fig. 6).

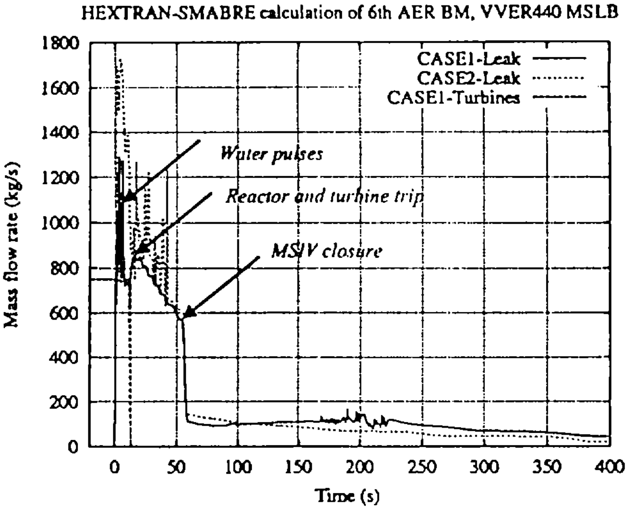

Figure 4. Total break mass flow from the steam generator 1 and the steam header direction and total flow to turbines.

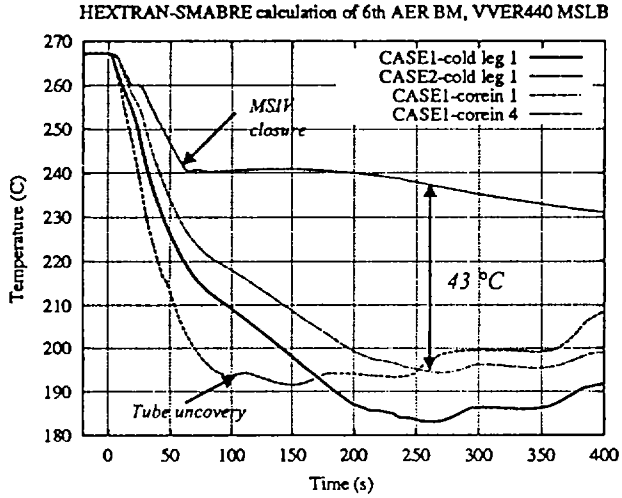

Figure 5. Cold leg and core inlet temperature in the broken loop 1 and sector 1

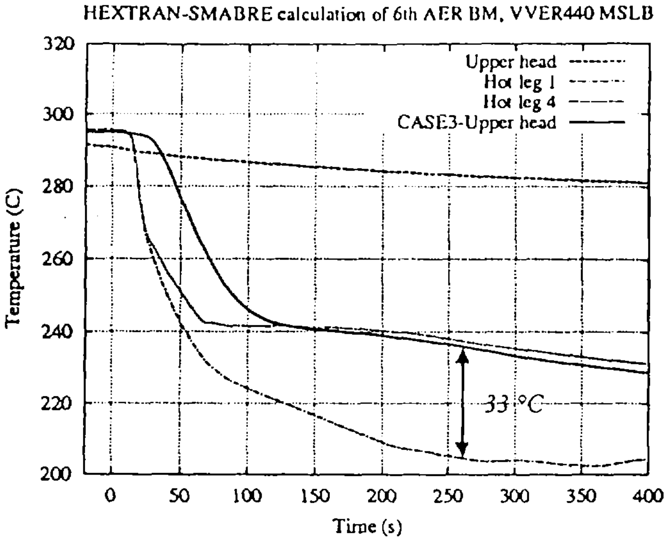

Figure 6. Hot leg and upper head temperatures

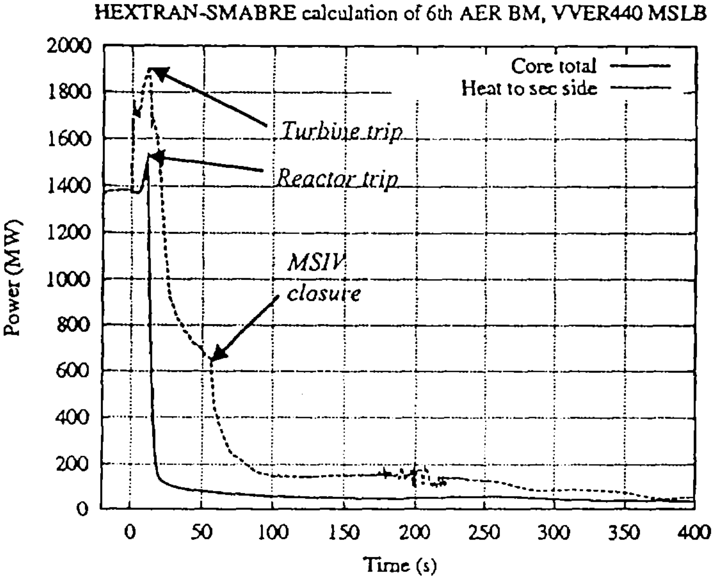

Figure 7. Total core power and heat removed to secondary side

At the beginning, the colder water at the core inlet results the core power to increase up to the SCRAM signal set point, 110 % of nominal power. Reactor trip starts half a second later at 11.6 s, shown in Fig. 7. In spite of the continuos core inlet cooling in sector 1, two stuck control rods in the corresponding sector, and the used high recriticality temperature, no actual recriticality after reactor trip was observed but only mild power increase instead, 58 MW in maximum at 253 s (Fig.7). The subcriticality is illustrated in Fig. 8 with negative reactivity values.

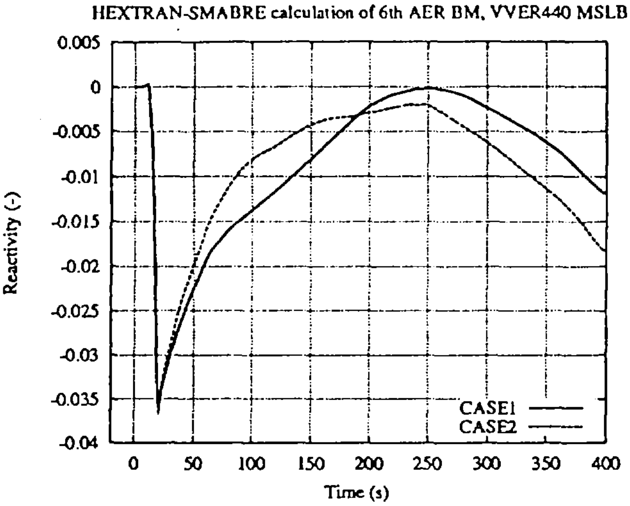

Figure 8. Reactivity

Two specified HPIS signals are modelled. The first starting signal for HPIS, upper plenum pressure lower than 9.3 MPa and the temperatures at least in two hot legs more than 255 °C, is not valid after 42.9 s due to too low temperatures in all the loops. The second HPIS starting set point, pressurizer level less than 2.41 m and temperature at least in two hot legs still above 150 °C, is fulfilled at 55.9 s. The injection is started to loops 3 and 5 after a delay of 180 s, describing the water coming from all the pipelines without boron. Highly borated (40 g/kg) water injection leads to a rapid power decrease. The maximum core power at that time is 58.3 MW. At the end of the calculation boric acid concentration in average in the primary loop and at the core inlet is above 0.5 g/kg. As a non-conservative feature, the pressure vessel head as well as the dead ends in the steam headers remain without boron when using one dimensional thermal hydraulic code.

1.1 Steam generator behaviour

The steam generator behaviour has a lot of meaning in transients with secondary breaks. When the break opens, pressure in the steam generator and in the steam lines drops rapidly. Due to flashing, there is water nearly to the top of the steam generators, shown in shortly increased swell level in Fig. 9. Also, the collapsed water level in the downcomer and riser part of the steam generator are shown in the figure. In SMABRE a void fraction of 0.80 is considered to be the limit for swell level. This kind of definition for the level where no flow is considered describes the swell level well in normal power situations, but in the case of zero power it gives an upper limit for water droplets content. This is one reason why there is a difference between the swell and collapsed levels in the end of the benchmark calculation when the power level is low and there is no much steam below the water level. Another reason is that the collapsed level simulates the real water level measurement in the plant when the characteristics of the measuring equipment in interpreting pressure difference into water level are considered. In this kind of transients with large pressure changes it means taking care of density differences in the measuring system.

The narrow scale water level is also modelled. This level is used to control feed water as it is used in real plants. Narrow and large scale model is validated to plant measurements at nominal state in Loviisa NPP.

The behaviour of heat removal to the secondary side, shown in Fig. 7, needs more attention; especially when in these calculations the response of the secondary heat transfer was very fast between the break opening and the turbine trip. When the break opens, a lot of energy is removed suddenly from the secondary circuit and the secondary side cools down the primary side. The heat removal to the secondary side follows practically the secondary pressure behaviour and the pressure behaviour is the result of the total mass flow out. In the beginning, the flow to the turbines is about half of the total steam outflow, (Fig.4). As a result of the constant turbine flow specified in the benchmark specification, the heat removal to the secondary side is about the same as the one calculated in 200 % MSLB for Loviisa with real turbine valve controls and response.

During flashing the whole water volume is boiling when the circulation in steam generators is modelled also at the bottom of the steam generator. Feed water is injected to the fourth level in the steam generators and practically there is no subcooling in the steam generator due to circulation. This may partly explain the fast response in the results of secondary parameters to the break opening.

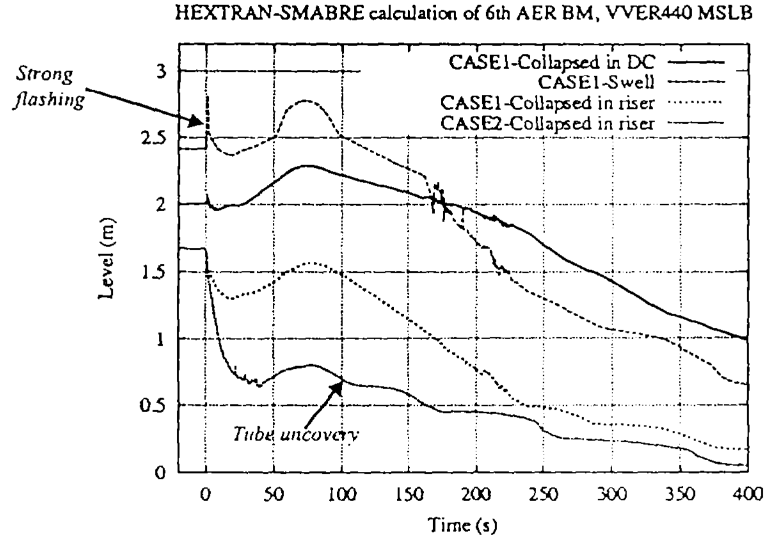

Figure 9. Steam generator water level in broken loop

2. CALCULATED VARIATIONS

As variations two further cases (2 and 3) were calculated, shown in table below.

Table 4. Calculated variations.

Case	Description
1	Base case: Moody model with dependency of quality in contraction coefficients
2	All water from steam generator upper part to break
3	Mixing junctions to establish vertical mixing in upper head

Studies were carried out with the HEXTRAN-SMABRE on the capability of steam to carry water from the steam generator to the break and its dramatic effect on the timing and maximum values of the recriticality already in the calculation of the OECD MSLB benchmark /ref. 8/. Generally this behavior is highly dependent on the geometry of the steam lines and the steam generators. A creation of detailed enough model for the secondary side to calculate this phenomenon may not be reasonable in coupled codes due to hundreds of meters of steam lines and large secondary volumes, but some assumptions could be done. In the MSLB benchmark the Once Through Steam Generator (OTSG) was involved and because of poor internal circulation in this kind of one dimensional steam generators, the water carry-over is more significant. In horizontal steam generators of the VVER-440, internal circulation could be expected. The open water level area is roughly 3.2 m x 11.6 m. In such a wide area, the behaviour is not only one dimensional and the phase separation is more effective when the circulation is properly modelled. A complex geometry in the steam generator outlet with five separate vertical tubes connecting the steam lines to the steam generator is the possible point for the flow to separate further. In order to find out the effects of the phase separation in case 2 homogeneous flow is used in the junctions starting from inside of the steam generator. This means that all the water from the uppermost node in the steam generator is carried away with the steam. The difference to the base case, case 1 is that drift flux phase separation model is not used in the case 2 in two junctions in the steam generator shown in Fig.2 (marked with circles).

Compared to the basic case the bigger amount of out-flowing water leads to faster decrease of both the total mass content of the broken steam generator and the core inlet temperature (Fig. 5). In this kind of case in the MSLB calculation, the return to power was earlier and more severe. On the other hand, in the VVER-440 horizontal steam generator, the faster decreasing steam generator water level uncovers the upper steam generator tubes, and due to poor heat transfer the decreasing of temperature in the cold leg stops. As a result this phenomenon proves to be less severe in the VVER-440. The uncovering of the steam generator in cases 1 and 2 may be seen as collapsed water level in risers in Fig 9.

As to the primary side related modifications, six artificial junctions from upper head of the reactor pressure vessel to each hot leg were included. Also forced mixing was created to the top of steam generator collectors. The aim of these junctions was to describe vertical mixing in these "dead ends" during the transient. When calculations are carried out with a one-dimensional thermal hydraulic code, the temperature stays about the initial level due to poor vertical mixing between nodes. Especially during the forced circulation it is obvious that temperature in the upper head drops near to the hot leg temperature. The major effect of these mixing junctions is that more realistic upper head temperature and pressurizer water levels are achieved. Small effects may be seen in the primary pressure and in the hot leg temperatures. In this analysis the flow rates of 65 kg/s (4,6 %) are used in steady state through these mixing junctions. Even smaller flow rates have the same effects. In Fig. 6, the effect of the mixing junctions into the upper head temperature are shown. Without mixing in case 1, the temperature in the uppermost node of the pressure vessel remains nearly constant during the whole transient, shown in figure.

The result in minimum primary pressure is here 3 bar lower in the case 3 and don't produce any dramatically different behaviour. The timing of HPIS injection is the same in all cases, because the calculated primary pressures don't deviate before the HPIS signal has been created at 55.9 s. When HPIS injection finally starts 180 s later, the flow rate is 8 % higher in case 3 due to lower pressure but now part of the boron is mixed in the upper head and the effect in the boron content of the core inlet is about the same.

4. CONCLUSION

The 6th AER benchmark is a double end break of one main steam line in a VVER 440 plant. The core is at the end of its first cycle in full power conditions. Several conservative assumptions were added compared to normal safety analyses to get the benchmark more interesting. The HEXTRAN code is used for the core kinetics and dynamics coupled to thermal hydraulics of the SMABRE code for this problem.

When the break opens in one steam line between the steam generator and the isolation valve MSIV, the pressure in the steam generators drops rapidly. The cooling of the core inlet water may lead quite soon to return to power. The resulting power level is maximized by the assumptions that the main circulating pumps are not stopped and the two control rods were supposed to stuck in the coldest sector of the core. Also the isothermal recriticality temperature was tuned to be very high in the calculation, 210 °C. Therefore the calculated cases here are nearly hypothetical and still only a mild power increase was seen, in maximum 58 MW at 253 s in the base case. Thereafter the subcriticality is guaranteed with increasing boric acid concentration in the core inlet, 0.5 g/kg at the end of calculation.

The steam line break analyses made for Loviisa NPP have been a basis of the models used in this benchmark problem. The results of the Loviisa analyses and the AER benchmark can not been compared directly: besides of the different assumptions, in Loviisa NPP the low primary pressure (10 MPa) causes the coast down of all main coolant pumps in this kind of double ended steam line break (200 %). For the Loviisa NPP a large spectrum of calculations were performed (50 % to 400 % break size) and as a result it was stated that the worst case may be reached also with smaller break size /ref. 10/. In Loviisa, the worst case was with 100 % steam line break.

In the comparison of results in the OECD MSLB benchmark for TMI-1, it was noticed that the effectiveness of steam to carry water to the break is more severe feature in the TMI plant with vertical once through steam generator. On the contrary, in VVER-440 this feature is clearly less severe due to the steam generator tube uncovering. This was seen when comparing the results of cases 1 and 2.

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