International Conference
Nuclear Energy in Central Europe 2001
Hoteli Bernardin, Portorož, Slovenia, September 10-13, 2001
www: http://www.drustvo-js.si/port2001/ e-mail: PORT2001@ijs.si
tel.:+ 386 1 588 5247, + 386 1 588 5311 fax:+ 386 1 561 2335
Nuclear Society of Slovenia, PORT2001, Jamova 39, SI-1000 Ljubljana, Slovenia

IMPROVEMENT OF MSLB TRANSIENT ANALYSIS FOR VVER BY THE COUPLED CODE SYSTEM KIKO3D/ATHLET

Gy. Hegyi, A. Keresztúri, I. Trosztel
KFKI Atomic Energy Research Institute Reactor Analysis Laboratory
H-1525 Budapest 114, POB 49, Hungary
ghegyi@sunserv.kfki.hu

ABSTRACT

An overview is given on the investigations of the **M**ain **S**team **L**ine **B**reak transient in a VVER-440 NPP by using the **KIKO3D/ATHLET 1.2.A** coupled code system. Special attention was paid for the influence of modeling the outcore detector signals and the malfunctioning of the emergency control system (scram with stuck rod). The conservatism of the calculations was assured even in the case of application of the 3D best estimate KIKO3D code. The consequence of MSLB accident is investigated at the end of cycle (EOC), at full power (FP) and shut down initial conditions. Even if very strong conservative assumptions were applied, dangerous hot spots were not found in the supposed scenarios.

1 INTRODUCTION

Asymmetric steam line break transients of a VVER-440 NPP are presented in the report as selected examples of the application coupled KIKO3D-ATHLET code. This problem can be characterized by significant deformation of the time dependent power and temperature distributions, therefore the use of 3D coupled neutronic and thermal-hydraulic codes is necessary. The circumstances in scram actuation were investigated, namely the role of the outcore detectors and the stuck control rods.

The occurrence of a recriticality during cool-down strongly depends on the negative moderator temperature reactivity coefficient, which characterizes the LWR. The strong cooling in the primary and the secondary side causes power increase before scram at FP case. The possibility of power increase and recriticality during cooling down was investigated, too.

The progress in computer technology enables the direct coupling of such complicate and separate code systems like the 3D-neutron kinetics, advanced thermo-hydraulics and plant dynamics. The integration of the analysis increases the accuracy as the conservative boundary conditions at the interfaces can be avoided. Only integrated codes are capable for the real estimate of the feedback effects in asymmetric cases, for instance in reactivity initiated accidents with strongly asymmetric neutron flux distribution caused by a perturbation in one of the primary circuit loops.

The hexagonal VVER specific space-time kinetics code KIKO3D and the system thermal hydraulic code ATHLET were coupled [1-2] and applied for the calculation of the above transients. The **KIKO3D** code [3], [4] developed in the KFKI Atomic Energy Research Institute solves the time-dependent neutron diffusion equation to analyze reactivity conditions and the spatial power distribution in the reactor core. In its core thermohydraulic model the fuel assemblies are considered as separate axial hydraulic channels. The **ATHLET** (**A**nalysis of **T**hermal-**h**ydraulics of **Le**aks and **T**ransients) code developed by the Gesellschaft fur Anlagen- und Reaktorsicherheit (GRS) [5-6] has a wide range of application for the analysis of anticipated and abnormal plant transients in PWRs and BWRs. In our calculations the 1.2.A version was used with the option of 5 equations. Two ways of the coupling have been developed [2]. In case of "internal" coupling ATHLET obtains the heat source from the KIKO3D and the system code ATHLET models the complete thermal hydraulics in the primary circuit including the core region. In the second case the two programs run in parallel, but the KIKO3D code uses its own thermohydraulic model in the core

2 ANALYSIS OF A STEAM-LINE BREAK ACCIDENT

Four sets of calculations were performed. In the first calculation (Case 1), the scram was actuated at 110 % of the initial core power (1375 MW). In the second calculation (Case 2), the effect of realistic response of outcore detectors due to an asymmetric power rise was investigated. It turned out that the scram occurred at a power level higher than 110 %, due to the outcore signal evaluation process corresponding to the asymmetric nature of the transient. In the last two scenarios an additive perturbation was supposed: 2 of the scram rods (37) were stuck in their uppermost position. The simulation was initiated from FP and shut down (HZP with scram) reactor state.

2.1 Initial conditions and the Input Data Set

The initial reactor state corresponds to the EOC in order to maximize the absolute value of the moderator temperature coefficient. Conservative assumptions were made concerning the isothermal recriticality temperature (210 ^{o}C) and the coincidence of a stuck control rod with the sector of cold water from the damaged steam generator. The so-called “frame parameters” [7] were chosen in a conservative way, too. For the effective delayed neutron fraction, conservative under-estimate value was used (β_{eff} =0.465%). The parameters of the parametrized group constant in KIKO3D were modified to achieve the conservative minimum of the coolant temperature reactivity coefficient: -70 pcm/K at FP EOC state. The best-estimate value of the fuel temperature reactivity coefficient: -3.5 pcm/K was used. After the scram the most effective control rod is stuck. The control rod albedo was tuned to achieve the 210 ^{o}C recriticality temperature.

The thermohydraulic data set describes the typical elements of the VVER-440 type power plant, horizontal steam generators, pumps etc. 93 Thermofluid Objects and 65 Heat Conductivity Objects were used to describe the plant. Mixture levels were defined for the pressurizer and for the secondary side of the two SGs. A double-ended break was assumed to occur in the steam line of one SG (No. 6.). The break location is immediately at the SG outlet. The cross sections of the break were A=0.24 m^2 and A=0.1244 m^2 on the SG and MSH side respectively, taking into account the different real cross sections of the steam line. The asymmetric behavior of the primary loops must be taken into account. The ATHLET input deck is a two-loop model with 1/6-5/6 distribution of the primary circuit. Several core super channels can be found in the two core segments. The grouping of the fuel assemblies into ATHLET super-channels is shown in Fig 1. The numbering of assemblies is shown in Table 3. The same nodalisation was used in all the 4 cases; nevertheless the following specific differences characterize only the shut down reactor:

- Decay heat is 10 MW in the core, no fission power and the average temperature is 260 ^{o}C (hot shut down state)
- The level of the pressurizer is 2 m below the nominal one, the mass of the water in the secondary is higher than the nominal one, the delivered heat is very small (aux. FWS works in the secondary side).

2.2 The effect of the outcore detector signal

The transfer functions between the core periphery and the ionization chambers were determined by the MCNP Monte-Carlo code.

In Case 2, the real evaluation process of the outcore detector signal was taken into account. The power level of the core is measured by 3 outcore detectors in each “chain” positioned in rotational symmetry of 120^{o} degree around the core. The relative position of the two possible chains is 15^{o} rotation and both of them contains one detector which is very close to the 6th loop. The orientation of the possibly closest detector is 30^{o} , while for the other one it is 45^{o}.(see Fig. 2).

The plant computer evaluates the signal of the outcore detectors and initiates scram, if two of the three detectors in any of the chains detect the 110 % power level. In case of asymmetric perturbation, the power is higher in the vicinity of the strongly cooled loop than in the other 5/6 part of the core and the scram signal can delay compared to Case 1. In this respect the damaged SG has been selected in a conservative way because the 6th loop is close to one of the detectors but one signal is not enough to actuate the scram. The two other distant detectors feel essentially lower power increase.

Both sets of outcore detectors were taken into account. The detector signals were calculated from the space and time dependent flux in the core, which were calculated by KIKO3D, and from predetermined transfer functions between the outgoing current at the core periphery and the detector reaction rate. It turned out, that the initiation of scram is really delayed due to the space dependent detector readings.(see Fig. 3).

2.3 Event description (FP Cases)

The concern is that the cooling of the secondary loop results in cooling of the primary loop, leading to reactivity and power increase. The power increase actuates the scram but further cooling can lead to recriticality and to a second power increase. The transient for the VVER-440 unit was calculated by the ATHLET-KIKO3D coupled code system.

The behavior of the plant in the two calculations is very similar, the delayed SCRAM signal shifts the actuation of the events. The chronology of the events during the two calculations is summarized in Table 1.

The break, which is modeled in the single main steam line loop (No. 6., connected to the broken loop), causes a rapid pressure decrease in the SG of this loop. The pressure decrease of the other loops due to the opened MSIV is slower (Fig. 4). There is a liquid flow through the break during the first 8-10 s. The maximum total flow is approximately 1800 kg/s.

The pressure difference between the main steam header and the steam generator exceeds the 0.5 MPa. This gives a closing signal to the single loop MSIV but this valve fails to close (single failure) and consequently the corresponding MCP does not stop. Although the pressure difference signal could stop the main feed water injection, it was not stopped in the calculation in order to maximize the primary cooling.

The first turbine is tripped just after the break due to the low pressure in the broken steam-line. This turbine is connected to three main steam lines and two of these steam lines belong to the five-fold loop. Consequently, in our model the tripped turbine modifies not only the flow-rate of the one-fold loop but also that of the five-fold loop.

The decrease of the cold leg and core inlet temperatures (Fig. 5) causes increasing reactivity (Fig. 6) and core relative power. The reactor trip signal comes about 10.5 s when the fission power reaches 110 % in the first calculation. In the second case the activation of SCRAM comes from the signals of outcore detector chosen conservatively. The distant detectors feel essentially lower power increase, which delays the scram actuation (see Fig. 3). Due to the time delay, the scram was initiated 17.5 s after the break when average core power increased to 125% of the nominal value. (Fig. 7).

After scram the reactivity and the power of the fuel assemblies decrease rapidly. As the scram rods reached their lowest position, the reactivity starts to increase again due to the continuous moderator temperature decrease. At time about 14 s after the scram signal, the second turbine is stopped, too and the injected feed water temperature is decreased from the nominal value to 159 ^{o}C.

Due to the intensive cooling of the primary circuit, the density of the primary coolant is increasing, and as a consequence the pressurizer level falls down to 2 m (Fig. 8). The decreasing level starts the HPIS injection and the boration is starting (Fig. 9). During this period the reactivity is near to zero, but further increase is moderated by the increasing boron concentration. The reactivity can not exceed zero and only a limited power rise can be seen up to 130 s. The reactivity influence of the injected boron with 40 g/kg is higher than that of the decreasing core inlet temperature which results in a decreasing reactivity and core power after 360 s. The 40 g/kg boron concentration is enough to close the reactor at any temperature.

The time dependent behavior of the core parameters was studied, using the above conservative assumptions. In spite of the strong cooling, recriticality did not occurred but the increasing reactivity resulted in increasing power level especially in the affected sector. After the scram the maximum of the linear heat rate was reached at about 130 s according to Fig. 7. The power rise due to the cooled moderator was larger before the scram.

The hot channel analysis was performed by the TRAB code. The time-dependent KIKO3D axial power distribution of the most loaded assembly was multiplied by the K_x radial power peaking factor. This factor was determined from the core design limits of the maximum linear heat rate (315 W/cm at

EOC) and the maximum pin power (57 kW). Assuming that these limits are valid at 104 % of the nominal power, the maximum value of K_x radial power peaking factor was limited to 1.59 due to the 57 kW pin power limit. As the initial value of K_q and K_z are known from the KIKO3D calculation, K_x is responsible for K_k and the engineering safety factor.

The result of the hot channel calculation is given in Fig. 11, only before the scram. Boiling crisis did not occur; the minimum of DNB ratio was 2.5 using the SMOLIN bundle correlation. The clad temperature remained below 334 C^o. The maximum centerline fuel temperature was 1825 C^o. The hot channel calculation proved, that heat transfer crisis did not occur and the PA acceptance criteria were fulfilled.

3 STUDY OF THE EFFECT OF 2 STUCK RODS

Additional calculations have been performed in order to investigate the effect if two control rods are stuck. A series of steady state calculations performed by GLOBUS36 nodal code were performed to find the strongest perturbation in the scram reactivity which can be achieved by sticking two control rods. It was found that the strongest perturbation could occur when the closest member of the 3rd and 4th bank are chosen.

The MSLB event calculations were performed using the same thermohyraulic input set and the same conservative method in the tuning of the reactor-physical parameters as in the previous cases. Only some small modification was performed in the super channel distribution according to the strongly changed power distribution.

Of course, the behavior of transient before the scram is the same as in the case of one stuck rod. Consequently, these calculations were focused on the investigation of the recriticality phase of transient. To reach the recriticality temperature as soon as possible before the HPSI actuation, the scram was initiated at 110 % average core power. There were no changes of the sequence of the events, however the events (actions) after the scram signal were delayed. Because of the same tuning of the temperature feedback at EOC FP state, the timetable of the events was unchanged before the scram.

In order to study the two stuck rod effect two calculations were performed. In the first case the scram was initiated with 1 stuck rod then the same calculation was performed with two ones but the other conditions were exactly the same.

According to the expectation, the effect of the scram is smaller in the second case (Fig. 13). The average core temperature after the significant power increase is higher in the second case as the sector with stuck rods produce more heat. This can be seen on the time dependent average core power, too (Fig. 12). The time dependent behavior of the secondary side is driven by the break and it is practically the same in both calculations. From the reactivity curve one can read that strictly speaking the recriticality is not occurred because the power is increased significantly already at small negative reactivity values preventing to reach positive reactivity and leading to a quasi-equilibrium state. In case of two-stuck rod this equilibrium power is higher. The transient is terminated by the HPSI actuation.

The reactor is found in a hot, shut down state by 35 CA-s in the last scenario. The core has a 10 MW decay heat and the average temperature is 260 ^oC. The cronology of the events is summarised in Table 2, and Figs.14-19. The cooling of the secondary loop caused by the same double-ended break as in the former calculations results in cooling of the primary loop, leading to a reactivity increase: recriticality, then prompt criticality occurs. The prompt criticality is stopped by the fast increase of the fuel temperature (Doppler effect). In the damaged loop the mass flow decreases and such a way the heat removal decreases too. The outlet temperature is higher than in the 5 fold loop. The last phase of the transient the reactivity decreases due to the HPIS. The hottest assembly was chosen again to investigate the boiling crisis. Even the TRAB input meets the conservative EOC HZP case, the boiling crisis did not occur (DNBR=2.13, T_{mod}=334 ^oC, T_{fuel}=1954 ^oC).

4 CONCLUSION

MSLB transients were calculated by KIKO3D/ATHLET coupled code system for a VVER-440 NPP. The time dependent behavior of the core parameters was studied using conservative assumptions. In spite of the strong cooling, recriticality did not occurred at the FP cases but the increasing reactivity resulted in increasing power level especially in the affected sector. However the power rise due to the cooled moderator was larger before the scram. If the transient is initiated at a shut down EOC state, recriticality occurred but it is terminated by the fuel feedback.

Conservative hot channel calculations were performed by the TRABCO code for these cases. The minimum DNBR was larger than 2.1 as a consequence of the low coolant temperature. It was found out that strictly speaking dangerous hot spots were not found during the MSLB event, even the perturbation of the two stuck rods caused a significant power rise.

REFERENCES

[1] Gy.Hegyi, A.Keresztúri, I.Trosztel, S.Langenbuch, W.Horche K.Velkov: Improvement of Plant Transient Analysis for VVER by Coupling KIKO3D with ATHLET, ICONE-6, San Diego CA USA, May 10-14,1998

[2] A.Kereszturi, Gy. Hegyi, M. Telbisz, I. Trosztel: Development, Validation and Application of Tools and Methods for Deterministic Safety Analysis of RIA and ATWS Events in VVER-440 Type Reactors, CSNI Workshop on Advanced Thermal-hydraulic and Neutronic Codes: Current and Future Applications, 10-13 April, 2000

[3] A.Kereszturi: KIKO3D - a three-dimensional kinetics code for VVER-440. Transactions of the ANS Winter Meeting, Washington, 1994

[4] R.Kyrki-Rajamaki, U.Grundman, A.Kereszturi: Results of three-dimensional hexagonal dynamic benchmark problems for VVER type reactors, Proc. of the PHYSOR'96, Mito,Ibaraki, Japan, 1996

[5] G.Lerchl, H.Austregesilo: The ATHLET Code Documentation Package, GRS-P-1 / Vol.1.: User's Manual, October, 1995

[6] S.Langenbuch, H.Austregesilo, P.Fomitschenko, U.Rohde, K.Velkov: Interface Requirements to Couple Thermal-Hydraulic Codes to 3D Neutronic Codes, OECD/CSNI Workshop on Transient Thermal-Hydraulic and Neutronic Codes Requirement, Annapolis, Md, USA, 5th -8th Nov.1996

[7] I. Nemes, L. Korpás, A. Keresztúri, P. Siltanen: Determination of Reload Margins on the Basis of Safety Analysis of NPP Paks. Proc. of the fifth Symp. of AER. Dobogoko, Hungary, 1995.

Time (s) (Case 1/2)	Event
0.0/0.0	Break open
0.3/0.3	Δp (MSH-SG) > 0.5 MPA
0.3/0.3	Turbine trip, valve 1 close
10.5/17.5	Reactor power > 110 %
10.51/17.5	Scram
24.6/30.6	Turbine trip, valve 2 close
59.3/65.3	Pressurizer heaters off
66.7/72.8	Reactor outlet press.< 11.8 MPa & PRZ level < 2.7 m (SI signal)
107. 7/113.8	HPIS injection starts
162.7/168.8	AFW pump start
356.6/364.1	PRZ heaters on

Table 1 Chronology of events (EOC FP)

Time (s)	Event
0.0	Break open
0.3	Δp (MSH-SG) > 0.5 MPa
16.5	Outlet pressure of the core < 11.8 MPa
17.0	recriticality (T*=220 ^{o}C)
20.0	Prompt criticality
50.3	Pressurizer heaters off
62.3	Reactor outlet pressure < 11.8 MPa & PRZ level<2.7m
103.3	HPIS injection starts

Table 2 Chronology of events (EOC Shut down case)

Name of TFO	Marker of assemblies	Number of assemblies
V-AV1-5		13
V-AV2-5		28
V-AV3-5		37
V-AV4-5		40
V-AV5-5		142
FOLLOW5		30.83
V-AV1-1		1
V-AV2-1		1
V-AV3-1		6
V-AV4-1		2
V-AV5-1		9
V-AV6-1		11
V-AV7-1		10
V-AV8-1		13
FOLLOW1		5.17

Table 3 Core pattern with the 15 ATHLET super-channels.

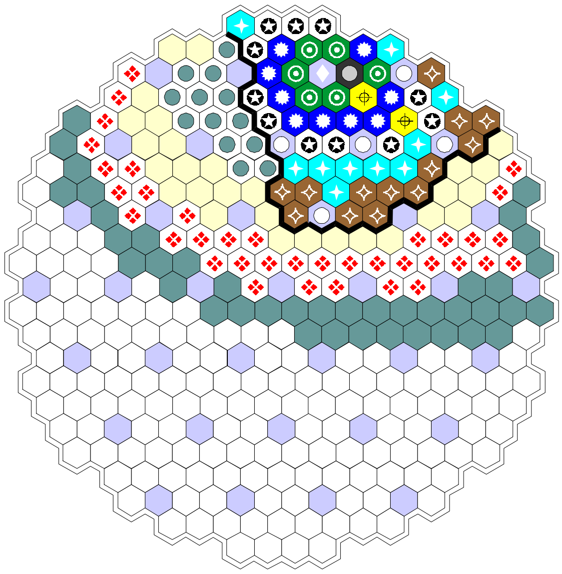
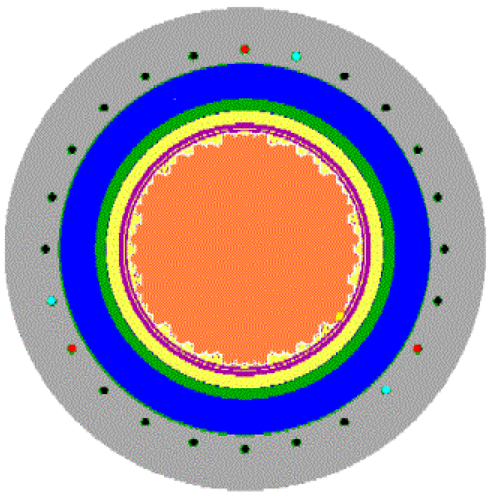


Fig. 1: Nodalization of the core into super-channels



Outcore detector set No.1

Outcore detector set No.2

Fig. 2:Positions of Outcore Detectors around the core

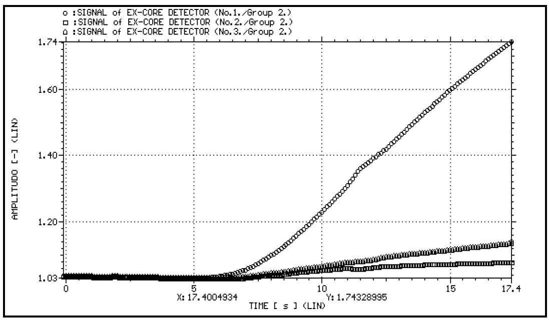


Fig. 3 Signal of ex-core detectors

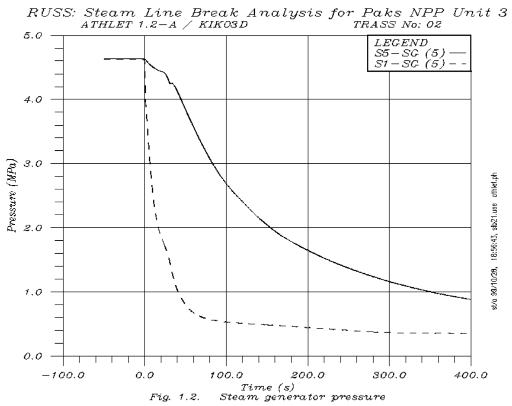


Fig.4: Pressure of the steam-generators

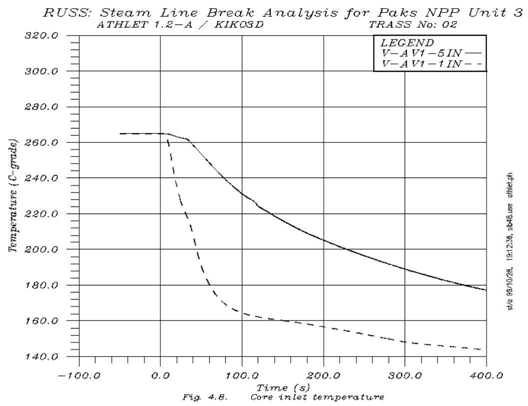


Fig.5: Core inlet temperature

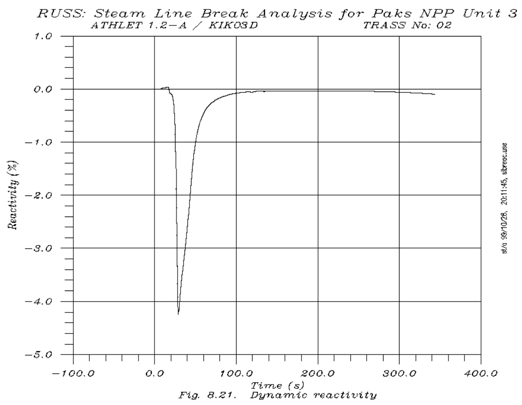


Fig.6: Dynamic reactivity

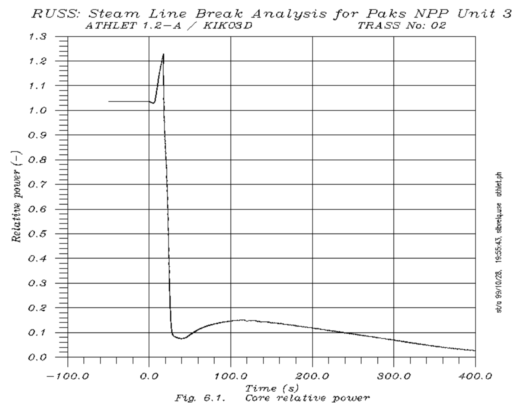


Fig.7: Relative core power

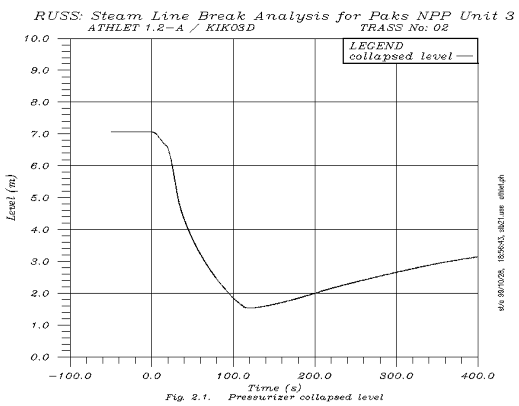


Fig.8: Pressuriser collapsed level

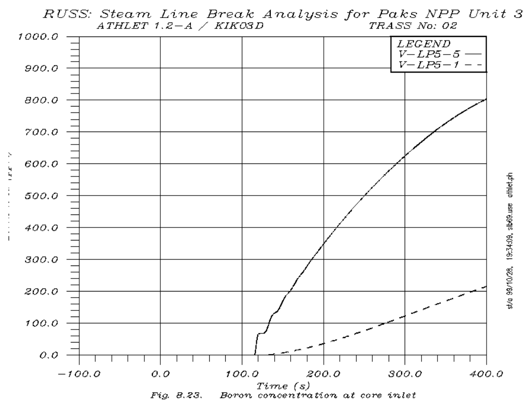


Fig.9: Core inlet boron concentration

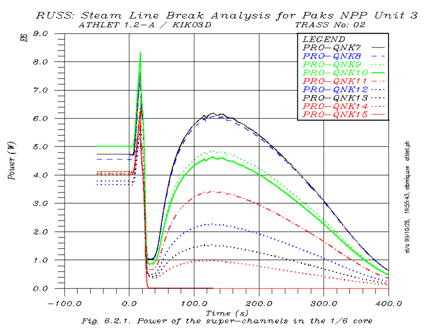


Fig.10: Assembly power in various super-channels

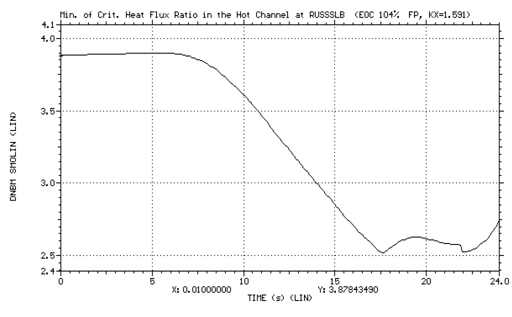


Fig. 11: Minimum of DNB ratio in the

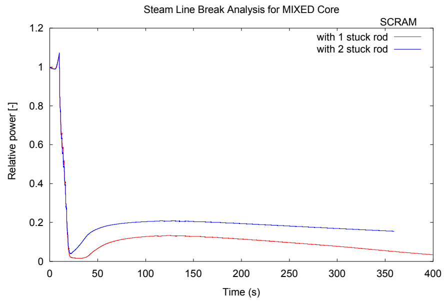


Fig. 12: The Relative Core Power during MSLB, calculated for the two types of SCRAM

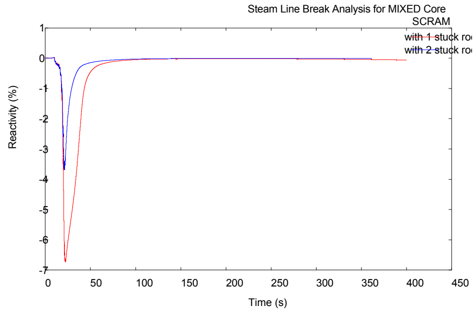


Fig. 13: The Reactivity of the core during MSLB, calculated for the two type of SCRAM

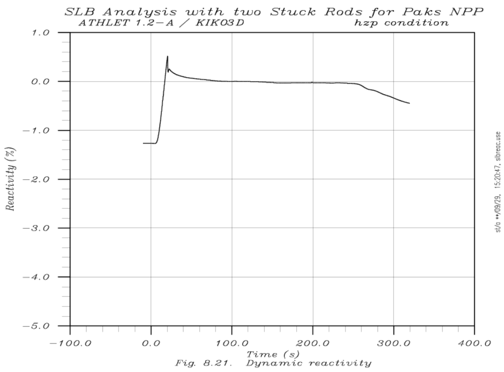


Fig.14 : Dynamic reactivity

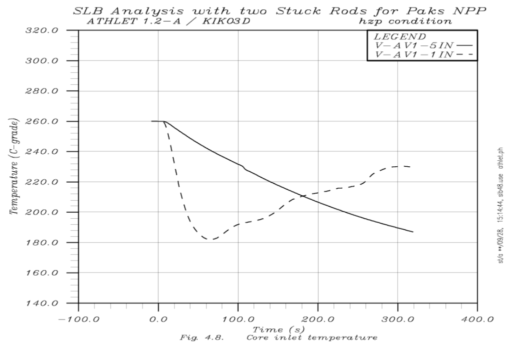


Fig.15 : Core inlet temperature

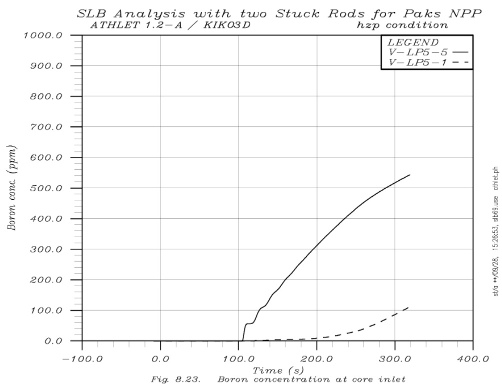


Fig.16 : Core inlet boron concentration

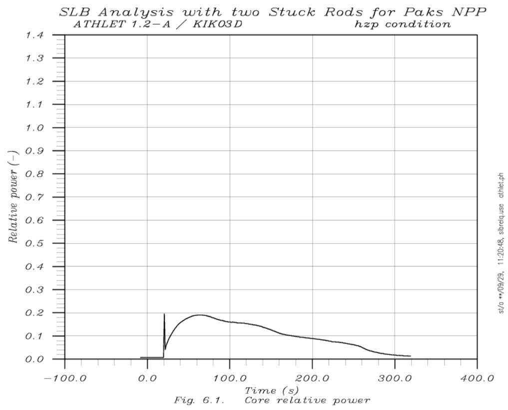


Fig. 17 : Relative core power

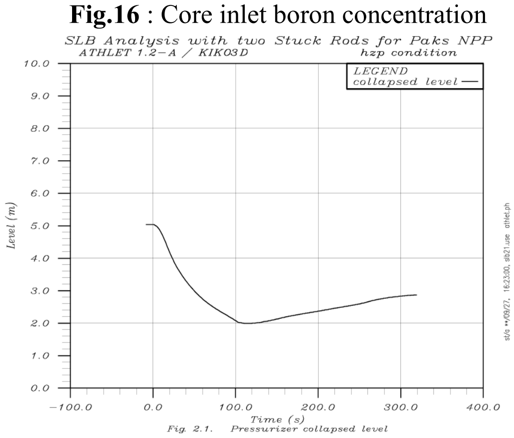


Fig.18 : Pressuriser collapsed level

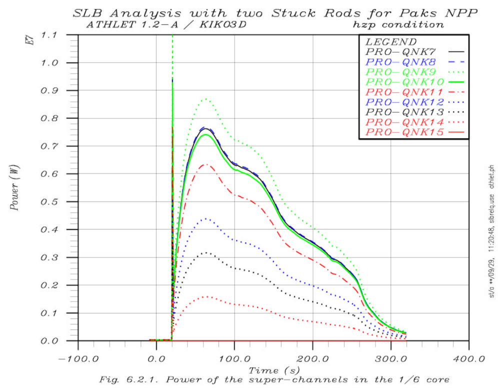


Fig.19 : Assembly power in various super-channel