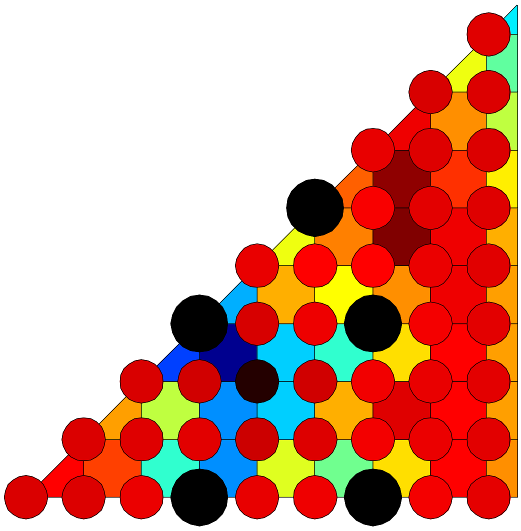
RESEARCH REPORT

VTT-R-09072-10



Sensitivity studies for the sub-channel calculations of PWR fuel assembly

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Confidentiality: Public

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Summary

Behaviour of the hottest fuel rods has in VTT's reactor dynamics analysis modelled with the TRAB-CORE model. Hot channel is an isolated thermohydraulic channel with one hot fuel rod. Core neutronics and whole core thermalhydraulics is calculated either with the 1-dimensional TRAB or 3-dimensional TRAB-3D or HEXTRAN code and hot channel calculation does not affect the whole core neutronics or thermohydraulics. Hot channel conditions are defined with a hot channel factor.

One defect of the present hot channel methodology is that cross-flows and mixing inside the assembly and also between the assemblies can not be modelled with 1-dimensional thermal-hydraulics models. It is assumed that the assumption of isolated channels brings additional conservatism to the calculations. Aim of this work was to study effect of mixing on the hot channel analysis with the sub-channel code COBRA.

Especially the hot channel factor for enthalpy rise has been defined in VVER/PWR analysis very conservative way assuming that local linear power is in its maximum allowed value at normal operation. The benefit of this procedure is that the analysis covers all possible allowed core configurations not only that used in the current safety analysis. However, it was noticed that the same methodology cannot be utilized with reactor cores with bulk boiling at core exit and for fuel assemblies with more uneven positions of heated fuel rods.

Confidentiality	Public

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1 Introduction

Behaviour of the hottest fuel rods has in VTT's reactor dynamics analysis been modelled with the TRAB-CORE model. Hot channel is an isolated thermohydraulic channel with one hot fuel rod. Core neutronics and whole core thermal-hydraulics is calculated either with the 1-dimensional TRAB or 3-dimensional TRAB-3D or HEXTRAN code. Power of each axial node of fuel rod, pressure balance and inlet conditions are transferred from that main calculation to the TRAB-CORE code. Hot channel calculation does not affect the whole core neutronics or thermohydraulics. Hot channel conditions are defined with a hot channel factor. The hot channel factor has in VVER analyses been selected thus, that the hot channel analysis covers all allowed core configurations, not only the one used in the main calculations.

One defect of the present hot channel methodology is that cross-flows and mixing inside the assembly and also between the assemblies can not be modelled with 1-dimensional thermal-hydraulics models. It is assumed that the assumption of isolated channels brings additional conservatism to the calculations. Aim of this work is to get better understanding about the effect of mixing on the hot channel analysis.

2 COBRA-EN code

2.1 General

COBRA is a traditional subchannel code, developed originally at the Pacific Northwest Laboratory in the seventies. Code development has been branched when new models are implemented. The modified version of COBRA-IV code has been in use also at VTT. Many of these modifications are combined to the code version COBRA-EN, which is available in the NEA databank.

If compared to COBRA-IV code, besides the two-phase homogeneous model, also four-equation model is available in COBRA-EN. Also two solution schemes are available: an implicit algorithm called pressure gradient solution and an implicit solution based on a Newton-Raphson iteration for non-linear systems. Several new correlations have been added for friction, boiling, void fraction and critical heat flux. There are new possibilities to define the properties of steam and water. It is possible to calculate also some simple transients. SI-units are allowed in input and output, but inside the code, calculation is still performed with British units. Input is still based on Fortran's fixed format. However, input includes several new cards and some cards are removed, so input files of COBRA-IV cannot be used with COBRA-EN.

These developments are not adequate for comparisons to TRAB code, and some modifications were needed. Main modifications are an option for the use of time-dependent data for node powers and inlet flows and new models for fuel and cladding capacity and conductivity. Also some modifications to input and output were made.

2.2 Changes in COBRA-EN code

2.2.1 Input changes without changes in code properties

Card 29 has been divided to two cards in order to increase field width to allow sufficient accuracy for the input values in SI-units. Instead of Card 29 [1], Cards 29a and 29b are read:

Card 29a	Operating conditions	(I6,4E12.0)
	IH	Inlet enthalpy option
	HIN	Inlet enthalpy
	GIN	average inlet mass flux
	PEXIT	System pressure
	DPS	the inlet flow model
Card 29b	Operating conditions continue	(I6,6E6.0)
	IPS	Option for pressure drop calculation
	FNORM	Power normalization factor
	CQ	Fraction of fission power appearing a direct heating in coolant
	GINBP	Average inlet mass flux for by-pass channels
	BORIN	Inlet boron concentration
	CGIN	
	HOUT	Exit enthalpy

2.2.2 Time-dependent boundary conditions

Possibility to read time-dependent data from additional input file (unit=15) has been added. Card 5 [1] is changed:

Card 5a (2I6) NAXP, POW

If POW=1, input reading is changed as follows:

Card 5a2

	PT(1)	location of time-data in file (unit 15)
	PT(2)	location of pressure
	PT(3)	location of pressure difference or inlet pressure
	PT(4)	location of enthalpy
	PT(5)	location of first power value
	PT(6)	number of axial power values

Card 5b	as in manual	
Card 5c	not read	
Card 5d	(6E12.5)	
	RADIAL(I)	Relative power of each rod

FNORM in Card 29 can be used also if power distribution is given with the additional file. Nodal power is thus:

$$QF(rod, axial) = FNORM * RADIAL(rod) * POWER(axial) \tag{1}$$

where $POWER(axial)$ is given in unit 15. Default value for $FNORM = 1$. In the source code this modification demanded changes in files COBRAENV.f, COBRATWG.f and EXTRA. New subroutine POWERT in its own file was added.

2.2.3 Correlations for fuel and cladding properties

New correlations have been added for conductivity and specific heat of the fuel pellet and cladding. With the new correlations it is possible to use same models as in the TRAB-code.

If $KFUEL < -1000\frac{W}{mK}$ in Card 12b, thermal conductivity of fuel pellet is calculated with the correlation

$$\lambda_p = C_1 \left(\frac{1}{C_2 + C_3 T + C_3 Bu + C_4 B^2 + C_5 \frac{1}{1+e^{A_1}}} + C_6 \left(\frac{T}{1000} \right)^4 + C_7 \frac{1}{T^2} e^{A_2} \right) \tag{2}$$

Parameters A_i are defined in source code in function CONDUP and parameters $C_1 - C_7$ are read with additional Card 12d1-12d3:

Card 12d1	(E12.0)	BURNUP	Burnup in MWD/kgU
Card 12d2	(6E12.0)	CONPHT(I), I=1,6	Parameters in correlation for fuel pellet conductivity
Card 12d3	(E12.0)	CONPHT(I), I=7	

If $CFUEL < -1000\frac{J}{kgK}$ in Card 12b, fuel specific heat is calculated with the equation

$$C_p = C_1\left(1 + C_2\left(\frac{T}{1000}\right) + C_3\left(\frac{T}{1000}\right)^2 + C_4\left(\frac{T}{1000}\right)^3 + C_5\left(\frac{T}{1000}\right)^4 + C_6\left(\frac{T}{1000}\right)^5\right) \tag{3}$$

Parameters C_i are read with new input card 12e:

Card 12e	(6E12.0)	CAPPHT(I), I=1,6	Parameters in correlation for specific heat of fuel

If $KCLAD < -1000\frac{W}{mK}$ in card 12b, thermal conductivity of cladding is calculated with the equation

$$\lambda_{clad} = C_1\left(1 + C_2T + C_3T^2\right) \tag{4}$$

Parameters are read with new input card 12f:

Card 12f	(3E12.0)	CONDZ(I), I=1,3	Parameters in correlation for cladding conductivity

If in card 12b CCLAD<-1000J/kg/K, specific heat of cladding is calculated with the equation

$$C_{clad} = C_1\left(1 + C_2T + C_3T^2\right) \tag{5}$$

Parameters are read with new input card 12g:

Card 12g	(3E12.0)	CAPCHT(I), I=1,3	Parameters in correlation for cladding specific heat

Gap conductance can now be given with a temperature-dependent table. If $HGAP < -100$ in card 12b, HGAP table is given with Cards 12h. Card 12c is given after these new cards 12d-12g. Card 12c is given only if 0>HGAP>-100 W/m2/K, thus 12h and 12c are never given in same input.

Card 12h	(I6)	NHGAP	Number of points where HGAP is given
NHGAP times card 12h2	(2E12.0)	GAPTTAB(I) GAPTAB(I)	Temperature gap conductance (W/cm2K)

2.2.4 Output modifications

New output file *.DIS has been introduced. Subchannel and rod distributions are written to this new outputfile. At the moment following variables are printed:

- pressure at channel inlet
- coolant enthalpy at channel outlet

- coolant temperature at channel outlet
- coolant density at channel outlet
- steam quality at channel outlet
- void fraction at channel outlet
- coolant mass flow rate at channel outlet
- coolant mass flux at channel outlet
- minimum DNB ratio of rod

2.3 Remarks on COBRA-EN code

For the reading of input data, the fixed format of FORTRAN is used. Thus if a computer run fails already at beginning, the reason may be for example numbers in the wrong column. In some cases fields can be too small for reasonable accuracy, especially with SI units. If this kind of problem occurs, field widths can be easily changed from the source code.

According to the user's manual, in some cases different models are used depending on the value of some input parameter. For example, the original code includes three alternatives for fuel thermal conductivity, depending on the value of KFUEL in card 12b.

KFUEL>0	KFUEL=Constant value of conductivity
-10<=KFUEL<=0	MATPRO models are used
KFUEL <-10	NEA correlations are used

If SI-units are used in input, these kinds of comparisons are not made with the actual values given in input. Instead, the limit values are in British units. This is not mentioned in the manual. For variables KFUEL,CFUEL,KCLAD,CCLAD and HGAP in card 12 the conditions have been modified so that comparisons are made in SI-units and with the assumption that SI-units are used in input.

Converge problems occur quite often. Convergence problems were met also in the COBRA manual [1], where it is mentioned that for example modelling of a PWR assembly with the four-equation model failed. In our test calculations some test cases succeeded also with the four-equation model, but in some cases convergence was not achieved or it demanded more trials with convergence parameters than with three-equation model. Test results shown in this report are calculated with the three-equation model, because convergence is achieved with that model more easily.

Converge parameters are given in card 27 and convergence may be improved with these parameters. Changing of the damping factors DAMPP and DAMPF affects the convergence. In these calculations the damping factors were from 0.5 to 0.9.

Changing of convergence criteria also affects the results. The axial flow convergence criterion FERRO varied in the calculations from 0.001 to 0.004. In most calculations 0.002 was a suitable value. If convergence fails, already small changes in FERRO, for example from 0.002 to 0.0022 may lead to success in calculations. When convergence criteria are changed, it is important to remember that sometimes also a more strict criterion may lead to a succeeded computer run.

In some cases also the convergence criterion for cross-flows was increased from 0.01 to 0.02 or even to 0.03. In most calculations convergence criterion for fuel rod heat transfer was -0.025 instead of the default value 0.01. Negative value means that internal iterations are activated and convergence of heat transfer coefficient is required at each external iteration. Convergence information is written to the output file *.OUT. If the calculation is interrupted, that information helps to find out where problems occurred and thus to find suitable values for parameters.

3 PWR assembly

3.1 Geometry and correlations

As a test case, a control rod ejection transient was calculated with 1/8 of a PWR assembly. Numeration of subchannels and rods is shown in figure 1. Power of each rod is transferred to four surrounding subchannels, except in fuel rods on the symmetry line, i.e. rods number 2-9,10,18,31,40,43 and 45, in which part of the power is neglected. There are five rod positions, numbers 4,7,25,28 and 35, where there is no heated rod. Instead, there are guide tubes for control rods or instrumentation. The diameter of those unheated rods is 32 % bigger than the diameter of the fuel rods.

Fission power, inlet enthalpy and pressure at assembly inlet and outlet were calculated with the TRAB-3D/SMABRE code. The axial fission power distribution of one fuel assembly with relative power 1.4457 was given as a time-dependent boundary condition for the COBRA calculations. Relative power of each fuel rod was defined in the COBRA input, and in some cases also the total power of assembly was increased.

The EPRI void fraction model that is as a default in COBRA, was used. Power of each fuel rod was assumed to be transferred to each four surrounding subchannels, one quarter of the power to each.

In this report, in the figures presenting void fraction etc. coolant properties, the scale of the colourbar is valid only for the coolant. The colour of the fuel rods is defined so that black corresponds to pin power=0 and bright red corresponds to the fuel pin with the highest power. If only fuel rods are shown in the figure, then the scale of the colourbar is valid for fuel rods. It is noteworthy that scale of the colourbar differs from figure to figure.

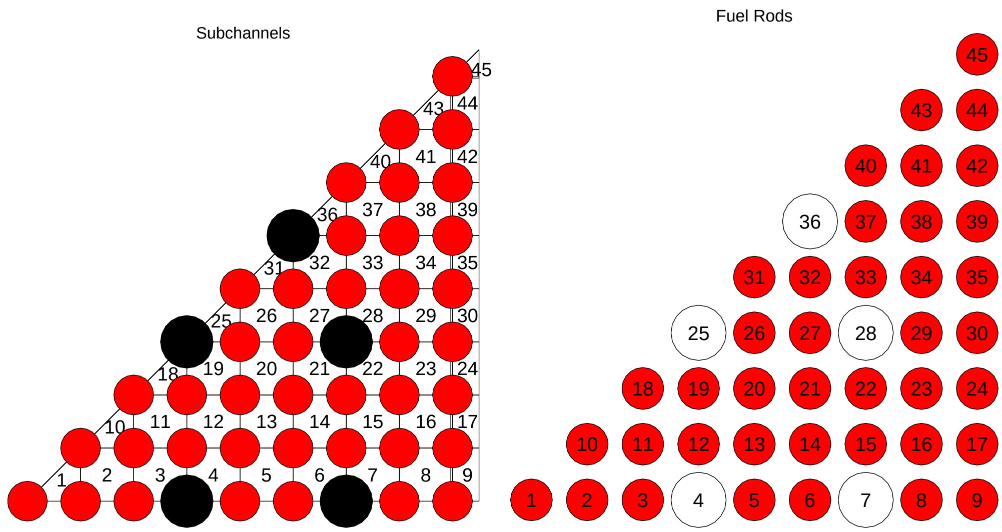

Figure 1: **Numeration of subchannels and fuel rods.**

3.2 Remarks on hot channel methodologies

In the present VVER/PWR hot channel methodology the power of the fuel rod is maximized with the assumption that both of the following conditions are fulfilled:

- Linear power in any point does not exceed the maximum allowed linear power
- Enthalpy rise in a subchannel is such that the subchannel exit temperature does not exceed the maximum allowed exit temperature

In other words it is assumed that at the initial state fuel rod is in extreme, but still allowed conditions even if manufacturing tolerances are included. In Loviisa NPP, the hot subchannel outlet temperature is limited to bulk boiling, which means a temperature limit 325 C [4], and thus the maximum allowed enthalpy rise can easily be calculated. The corresponding condition is more complicated to set and observe if bulk boiling is allowed.

Also other approaches are possible. For example in the Final Safety report of the U.S. EPR [2] the enthalpy rise hot channel factor is defined as a ratio of the highest integrated rod power to the average rod power, where average is calculated of all rods of the core. Enthalpy rise hot channel factor is based on set of power distributions, and value for LOCA calculations is 1.70. Engineering and measurement uncertainties are included in the linear power hot channel factor.

According to the Final safety report of AP1000 [3], in DNBR analysis of the AP1000, the enthalpy rise hot channel factor is defined in a similar way, but the surrounding rods are assumed to have the same axial profile as the hot rod with rod average powers which are typical distributions found in hot assemblies. Hot channel analysis is made with the VIPRE-01 code, which is also based on the COBRA. Thermal diffusion coefficient in equation 6 is 0.0359, and the value is assumed to be conservative due to mixing tests.

3.3 Realistic power distribution

In the first test case the total fission power of the assembly was 109% of the fission power in the TRAB-3D/SMABRE calculation. As an example of a realistic power distribution, steady state pin power distribution of one fuel assembly was used. Pin power distribution was calculated by the Simulate code and is shown in figure 2. The maximum pin power was 9.5 % higher than average pin power in that assembly. Since relative power of the assembly is 1.4457, the maximum relative rod power is 1.09*1.4457*1.095=1.73. The distribution is not for the same fuel assembly whose power distribution was calculated by TRAB-3D/SMABRE code, but initial power is in both assemblies quite high and both are fresh fuel assemblies. This assembly was chosen as a boundary condition, because it is quite near to the ejected rod and thus its fission power changes more during transient.

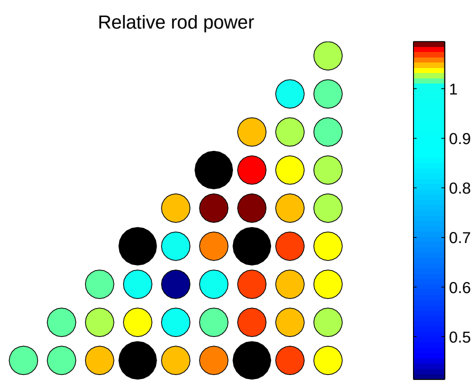

Figure 2: **"Realistic" power distribution in fuel assembly.**

In the first test calculation open subchannels were used. Turbulent crossflow through gap k between subchannels l and l' was calculated with the model [1]:

$$w'_k = aRe_k^b s_k G_k \tag{6}$$

where Re is Reynolds number, s_k gap width and G_k axial mass flux around the gap, computed as the average value in channels l and l'. a and b are constants given in input. In these calculations value $a = 0.02$ and $b = 0$.

Void fractions in several calculated cases that are introduced later in this report are shown in figure 13. Maximum values are achieved at approximately the same time in all cases. Thus distributions are studied in most cases at 6.2 seconds. Void fraction at core outlet calculated with the "realistic" pin power distribution is shown in figure 3. The maximum value is 9.6 % in subchannel 33 and the minimum value 0% in subchannel 19. Average enthalpy rise at initial state is 303 kJ/kg and enthalpy rise in subchannel 33 is 313 kJ/kg, 103 % of the average.

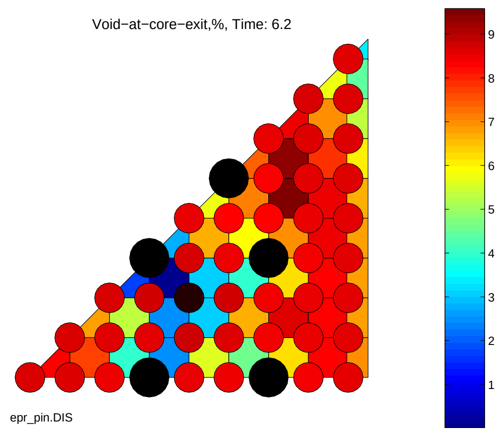

Figure 3: **Void fraction at core exit with "realistic" pin power distribution.**

In figure 4 is shown the void fraction distribution with isolated subchannels and without turbulent mixing, i.e. with the coefficient $a = 0$ in equation 6. Maximum void fraction with isolated channels is 16.9 % and 14.7% without turbulent mixing. Average enthalpy rise at the initial state is 304 kJ/kg with isolated subchannels and enthalpy rise in subchannel 33 is 337 kJ/kg, 111 % of average and 8 % more than with open subchannels.

The same void fraction as with isolated subchannels is achieved by modelling only one rod and one subchannel with the same subchannel area than in the 1/8 geometry. Power of the rod was the same as the average power of rods connected with subchannel 33. However, in the present methodology flow area of a subchannel in TRAB-CORE calculation has not been the same as the area of a regular subchannel. Instead, it is assumed that the flow area of a hot channel is the same as the average flow area per fuel rod inside the fuel assembly shroud. In

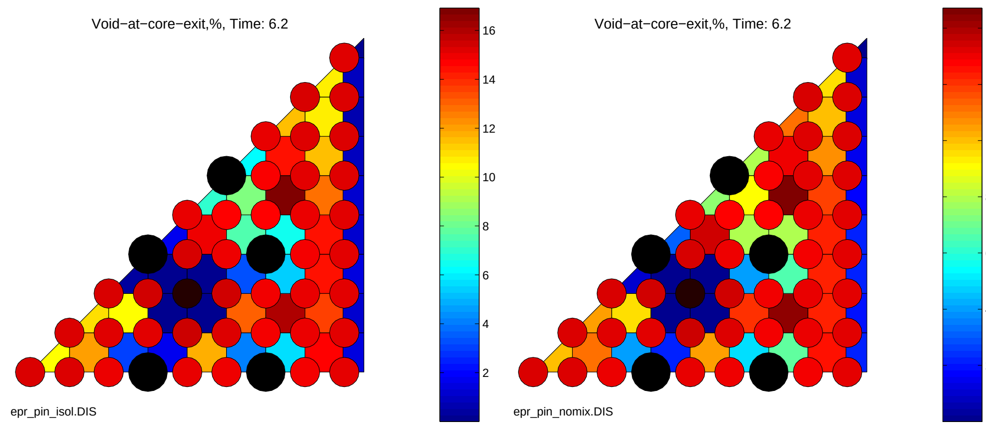

Figure 4: **Void fraction at core exit with "realistic" pin power distribution. On the left isolated subchannels. On the right open subchannels without turbulent mixing.**

this PWR geometry, average flow area per fuel rod is 14 % higher than the area of a regular subchannel. With that subchannel area, the void fraction at core outlet is less than 2 %. On the other hand, if total flow area is divided by 289, i.e. nonheated guide tubes are included, flow area per rod is 97 % of the area of regular subchannel. With that area, maximum void fraction during transient is 23 % and enthalpy rise at the initial state 363 kJ/kg. The void fraction is the same as with open subchannels, if flow area is 105 % of the area of regular subchannel, table 1.

It seems quite obvious, that due to irregular fuel rod positions the same kind of flow area definition cannot be done as for example with the VVER assembly.

As an example, according to a FLUENT-analysis of Loviisa NPP, enthalpy rise peaking factor is smoothed out due to a mixing in assembly 5-7% compared to isolated subchannels. [4]. However, it has to be remembered that the geometry and also the operation conditions of a VVER-440 assembly are quite different compared to a western type PWR assembly.

The power of each rod is transferred to four surrounding subchannels, and correspondingly each subchannel receives heat from each of the four fuel rods that are connected to the subchannel. This equalizes differences between the subchannels. On the other hand some subchannels remain quite cold, because one of the rods is not heated. The pin-wise distribution with isolated subchannels corresponds to previous methodology in such a way that also in previous methodology it is assumed that average power of the rods connected to one subchannel is less than the maximum rod power. The minimum DNB value with open and isolated channels is shown in figure 5. The minimum value with open subchannels is 1.42 and with isolated subchannels 1.34, both in rod number 33. COBRA-EN calculates

Table 1: **Maximum void fraction and minimum DNBR during transient with different subchannel geometry. Realistic pin power distribution, maximum pin power is same in each case.**

Area of hottest sub-ch	number of rods and subchannels	cross-flows, a	α_{max}	$DNBR_{min}$
A_0	45	yes, 0.02	9.6 %	1.414
A_0	45	yes, 0.01	10.9 %	1.401
A_0	45	yes, 0.03	8.9 %	1.423
A_0	45	no	16.9 %	1.343
$A_f/265 = 1.14\ A_0$	1	-	1.8 %	1.557
$A_f/289 = 0.97\ A_0$	1	-	23 %	1.296
$1.05A_0$	1	-	9.6 %	1.426

A_0=area of regular subchannel, A_f=total flow area for one fuel assembly, a=coefficient in equation 6.

the DNB value for each rod-subchannel pair at each axial level. The value shown in the figure is the minimum of these values. Especially with isolated channels the DNB values at different sides of a fuel rod might be quite different. For example in rod number 33 with relative power 1.095, the DNBR at 39th axial point from the bottom is 1.41-1.43 on the surfaces between the rod and subchannels 27,28 and 32, but 1.34 on the surface between the rod and subchannel 33.

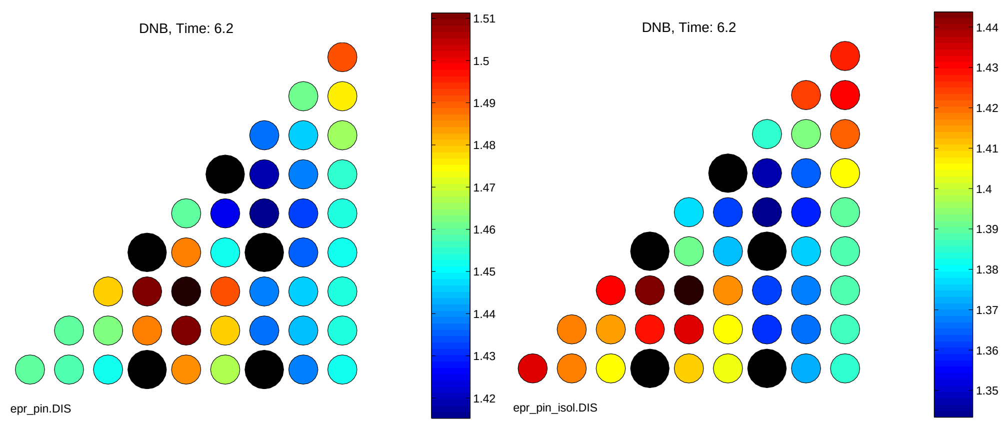

Figure 5: **Minimum DNB with "realistic" pin power distribution with open and isolated subchannels.**

3.4 Flat power distribution

The second tested power distribution is a flat distribution - all fuel rods have the same power apart from unheated rods. Total power is the same as in the previous case. Void fraction at core outlet in 6.2 seconds is shown in the figure 6 for open channels. There is more void in the central part of the assembly than in the outer region, the maximum void fraction is 8.7 % in subchannel 1, which is slightly less than the maximum value with realistic pin power distribution. Minimum DNB, 1.45 is encountered in fuel rods 1, 2 and 10. The calculation was repeated with different modelled regions, with 1/4 assembly and with the central part of an assembly, bounded by the innermost guide tubes. Similar maximum values were achieved with different modelled regions.

With isolated subchannels the maximum void fraction at core outlet is 10.9% in the subchannels containing only heated rods, figure 7. Void fraction is 1.7 % if one of the rods is a quide tube, except on the outermost subchannels, where the void fraction ranges from 0 to 0.7%. The minimum DNB is 1.43 for all heated fuel rods. The maximum enthalpy rise at the initial state is 312 kJ/kg with open subchannels and 318 kJ/kg with isolated subchannels.

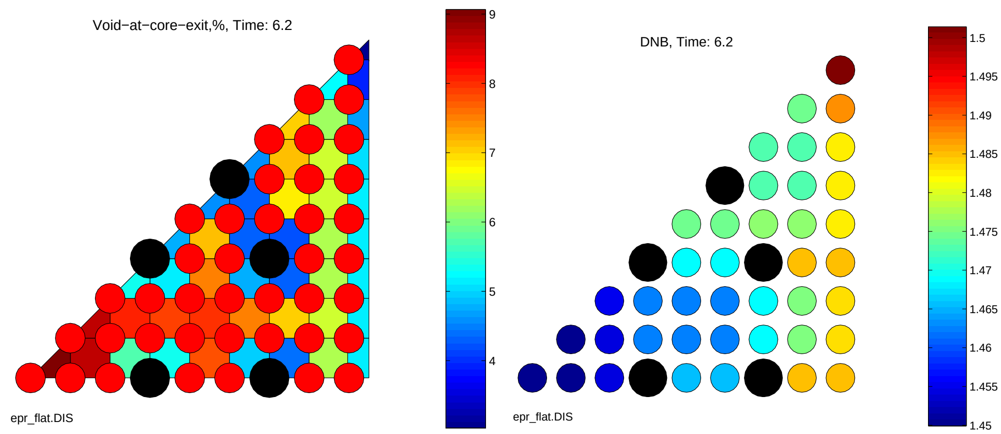

Figure 6: **Void fraction at core exit (on the left) and minimum DNB (on the right) with flat pin power distribution.**

Flow area of the outermost subchannels is approximately 56 % of that of the normal subchannels with four fuel rods and 65% of the flow area of the subchannels with one guide tube. The power of two rods is released to these boundary channels, thus the ratio of flow area to released power is higher, which may lead to cross-flows.

An other reason for big differences inside the assembly are the unheated rod positions. Instead of fuel rods, some positions are occupied by guide tubes for control rods or other instrumentation. Especially the isolated subchannels with a guide tube and only three fuel rods do not reach as high temperatures as the subchannels with a fuel rod in each corner. In figure 9 the void fraction and minimum DNB are shown in a modified assembly, in which all rods have the same power. The total power is again the same as in the previous cases. The

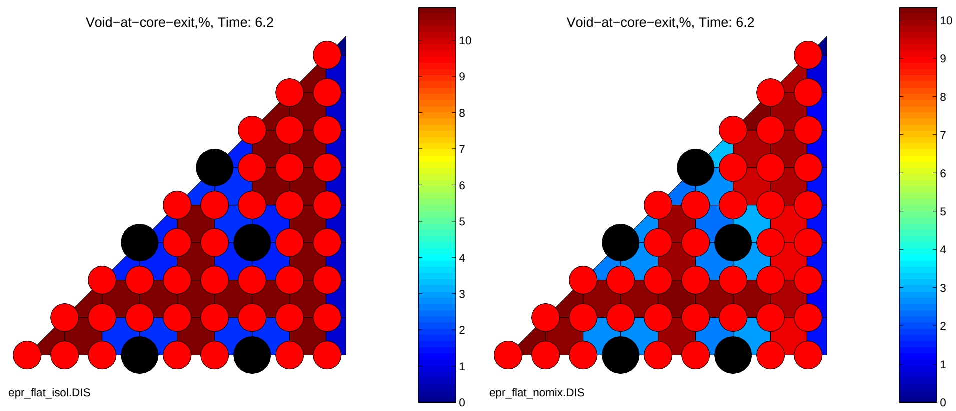

Figure 7: **Void fraction at core exit with flat power distribution. On the left isolated subchannels. On the right open subchannels without turbulent mixing.**

subchannels are not similar either in this case, because some rods still have a larger diameter. The void fraction is the highest, 12.4 % in the vicinity of these bigger rods because the flow area in those subchannels is smaller. Void is no more concentrated in the central subchannels.

Void fraction with a flat power distribution is shown in figure 8. The power is scaled so that the power of each heated rod is the same as with the realistic pin power distribution in the rod with maximum pin power. Total power is thus 7,5 % higher than in the previous cases. This corresponds to the method used in FSAR of US. EPR [2]. The Maximum void fraction is 18.6 % in subchannel 1 and the minimum DNB 1.33 in fuel rod 1. These extreme values are quite close to the case with realistic power distribution with isolated subchannels. The difference between open and isolated subchannels is bigger than in cases with a lower total power.

3.5 One hot rod

In one test case the pin power was assumed to be peaked. The power of one rod was 1.3 times the average power. Pin powers were scaled so that the total power remains same as in the case 3.3. The maximum void fraction with open subchannels is approximately the same as with the realistic pin power distribution, figure 10. With isolated subchannels the void fraction in the vicinity of the hot rod is 19.6 %.

As a test case the power of the hot rod was increased in order to find power that produces same void fraction than with isolated subchannels. With rod power 2.2 times the average, the same 18 % void fraction was achieved. The total power is in that case 2,2 % higher.

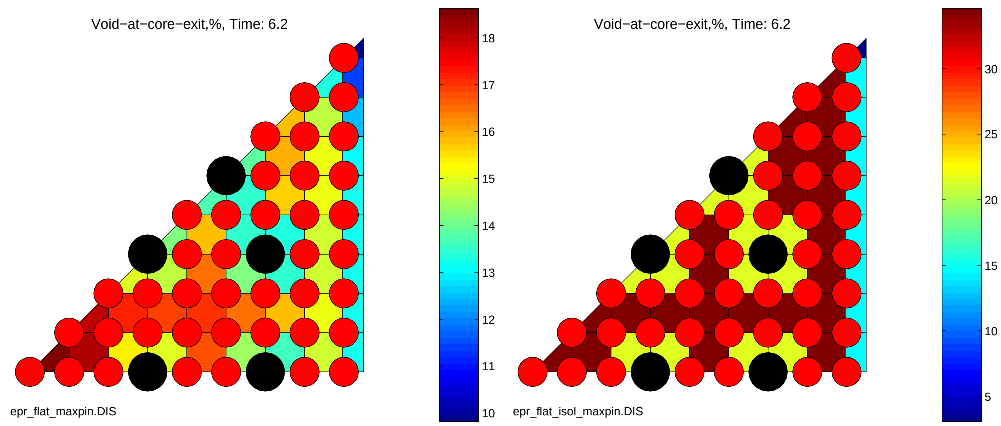

Figure 8: **Void fraction with flat high power distribution. On the left open and on the right isolated subchannels.**

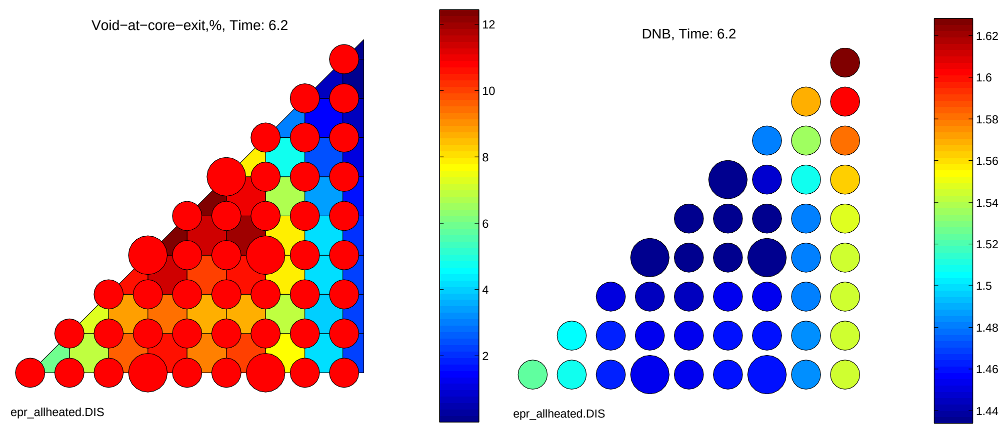

Figure 9: **On the left void fraction at core exit and on the right minimum DNB with flat power distribution and without unheated rod positions.**

In figure 12 is the void fraction at core exit with different locations of hot rod (power 1.3*average). Effect on the maximum void fraction is quite small, the maximum void fraction in these calculations varied from 7,9 % to 9,6% at the initial state.

This kind of peaking is quite unrealistic, because also in asymmetric transients the power of each rod increases, not only the power in one rod in the inner part of an assembly. With open channels a strong peaking changes the cross-flows compared to a flat distribution. Thus large differences in pin powers inside the assembly may lead to too high cross-flows in the calculations and thus to non-conservative results. However, it seems that several non-heated rod positions have a strong effect on the cross-flows.

Especially if peripheral subchannels are studied, we have to remember that in

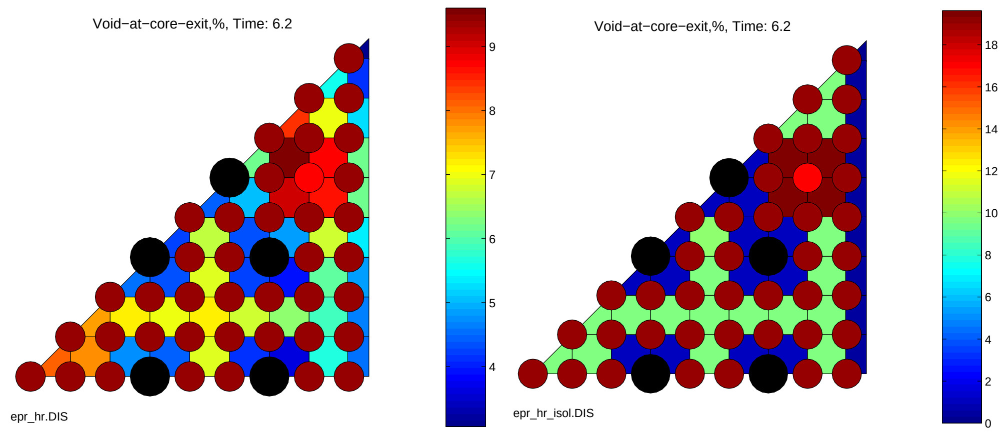

Figure 10: **Void fraction with 1 hot rod. On the left open and on the right isolated subchannels.**

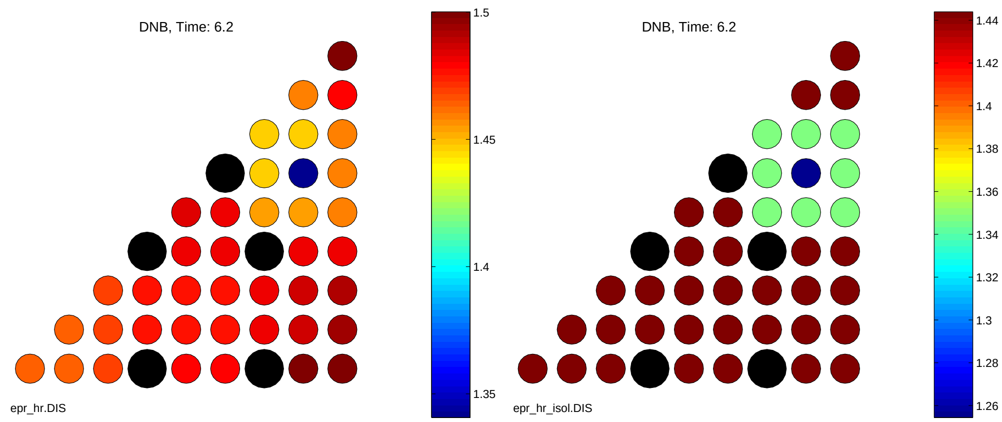

Figure 11: **Minimum DNB with one hot rod. On the left open and on the right isolated subchannels.**

these calculations only part of one assembly was modelled. In an open reactor core there would be only a slightly broader gap between assemblies and after that more fuel rods. Correspondingly, results of the triangular subchannels are not comparable to other subchannels, because in those subchannels one colder or hotter fuel rod affects results more than in “normal” subchannels.

In the TRAB-3D/SMABRE calculation the coolant is homogeneous over the cross-section of an assembly. If void fraction would vary inside the assembly, it would also affect to the power distribution inside the assembly due to the feedback effects. Now this dynamics has not been modelled.

In figure 13 is shown the void fraction during the transient in several cases. As can be seen, the transient is quite mild and the void fraction does not increase much after the control rod ejection.

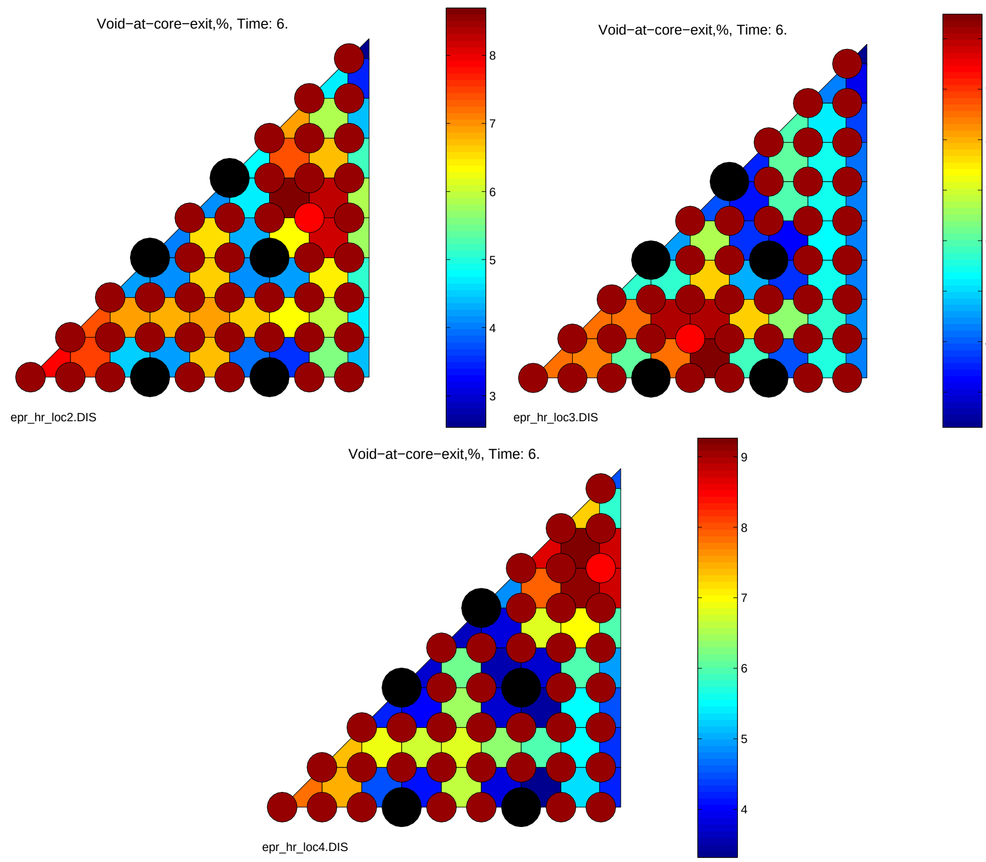

Figure 12: **Void fraction at core exit. Position of one hot rod changed.**

4 Conclusions

The traditional way to perform DNB calculations in VVER/PWR safety analysis at VTT has been very conservative. Especially the hot channel factor for enthalpy rise has been defined in very conservative way assuming that local linear power is in its maximum allowed value at normal operation. The benefit of this procedure is, that the analysis covers all possible allowed core configurations, not only that used in the current safety analysis. However, the same methodology cannot be utilized with reactor cores with bulk boiling at core exit and for fuel assemblies with more uneven positions of heated fuel rods.

The void fraction distributions show that void fraction varies across the fuel assembly. The feedback effect of this variation to neutronics should be studied. It is also possible, that the radial power distribution changes in transients. At the moment the transient analysis codes TRAB-3D and HEXTRAN can not model rod power distribution.

Flow mixing in an open core is itself a complicated phenomenom, but in safety

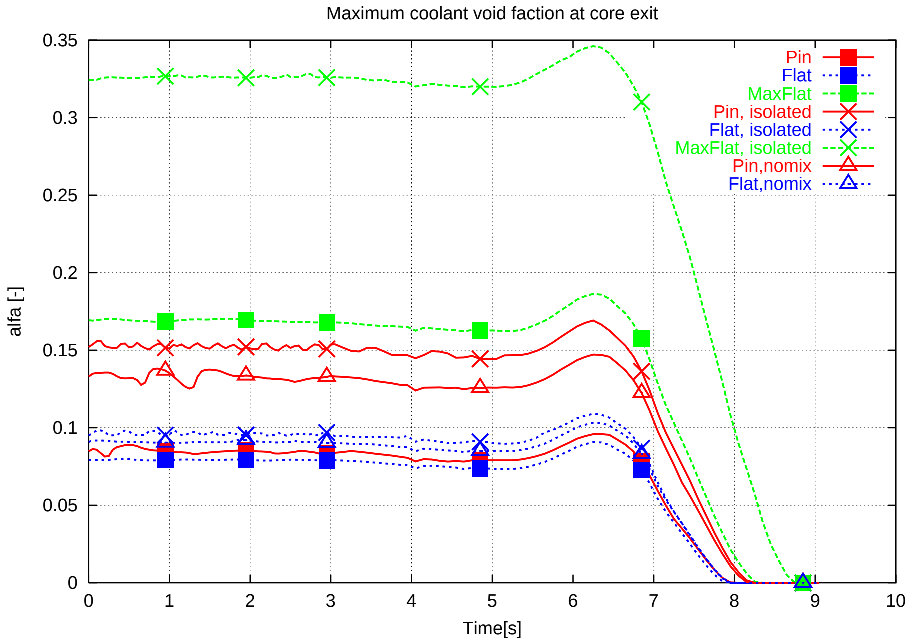

Figure 13: **Maximum void fraction at core exit with realistic (=Pin) and Flat power distributions and with increased power (=MaxFlat). Subchannels open, isolated or without turbulent mixing (=nomix)**

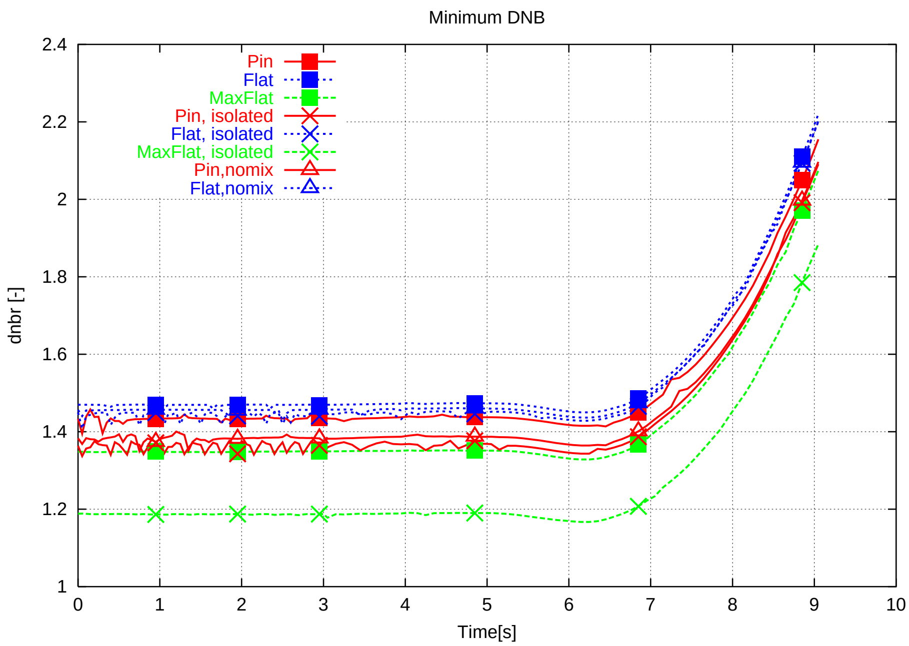

Figure 14: **Minimum DNB with realistic (=Pin) and Flat power distributions and with increased power (=MaxFlat). Subchannels open, isolated or without turbulent mixing (=nomix)**

analysis point of view realistic but still conservative pin power distribution is needed, if one wants to model cross-flows inside the fuel assembly. Also the dynamic behaviour of pin powers would be needed. It is also worth of remembering, that COBRA is not really a three-dimension code and with COBRA code we can get only some crude insight of cross-flows and mixing inside the fuel assembly.

It's also important to emphasize, that these calculations are not made for a real reactor. Particularly the fuel properties in the calculations are not the same as used in a real safety analysis. Several cases were calculated with very high coefficients for fuel rod power or even for fuel assembly powers.

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