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ANALYSIS OF A PWR BORON DILUTION ACCIDENT USING THE BARS-RELAP CODE

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ABSTRACT

An analysis of a boron dilution accident following a small break loss of coolant accident in a pressurized water reactor of the Three Mile Island Unit 1 was carried out with the coupled BARS-RELAP code. Intercomparison of the results with those obtained using the PARCS-RELAP code demonstrated good agreement for the peak fuel pellet enthalpy. A sensitivity study of the peak fuel enthalpy to a number of neutronic and thermal-hydraulic parameters showed that the major effect was due to the moderator reactivity coefficient. The uncertainty in the peak fuel pellet enthalpy was estimated as 50%. An analysis of effects of spatial non-uniformity in the inlet boron concentration on the core power and peak fuel enthalpy was performed. The results of the analysis pointed at possibility of very large deformations of the core power distribution during the transient due to asymmetrical radial distribution of the boron concentration. However, power deformations did not effect on the peak fuel enthalpy, thus an increase in the peak fuel enthalpy was practically proportional to a change in the reactivity inserted by deborated water.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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INTRODUCTION

In previous studies a rod ejection accident (REA) in a pressurized water reactor (PWR) of the Three Mile Island Unit 1 (TMI-1) was analyzed using the BARS-RELAP dynamic code, which allows a 3-D pin-by-pin neutronics and assembly-by-assembly thermal-hydraulics simulation of a light water reactor (LWR) [1-3]. Intercomparison of results from BARS-RELAP was carried out with the results obtained by the PARCS-RELAP (USA) [4] and CRONOS2-FLICA4 (France) [5] codes for initial steady state and for the central REA. The transient was considered for the end of cycle at hot zero power (HZP) conditions. The intercomparison showed [6] that PARCS and CRONOS2 results based on 3-D assembly-by-assembly nodal neutron diffusion method underestimate the peripheral rod worth by 40% in comparison with BARS pin-by-pin results. Good agreement in the results was found for the rest control rods and for main safety parameters of the central REA in the TMI-1 PWR.

The uncertainty analysis of main safety parameters to a number of neutronic and thermal-hydraulic quantities was performed with BARS-RELAP for the central REA starting from the HZP conditions [2]. The results demonstrated that uncertainties in key parameters of the accident were caused to a great extent by the uncertainty in the ejected rod worth. Uncertainty in local fuel enthalpy was estimated as 110% for the rod worth of 1.2β (β - delayed neutron fraction) under 15%-uncertainty in the rod worth.

Since peak local fuel enthalpy depends directly on a spatial distribution of the energy deposition in the core, a study of spatial effects was carried out for REAs in a PWR [3]. Four cases with the same worth of the ejected control rod were considered for the TMI-1 model with BARS-RELAP: ejection of the central or peripheral control rod at the end of cycle or the beginning of cycle. It was found that the core peak power and total energy deposition are inversely proportional to the power peaking factor. As a result the increase in peak local fuel enthalpy practically did not depend on power deformations.

The analysis of the event with ejection of the peripheral rod at the end of cycle showed also that the hottest fuel pin does not belong to the assembly with peak power. This fact indicated that a problem of proper definition of the hottest pin location is essential. In the considered case the incorrect definition of the hottest pin location using an assembly-by-assembly approach, lead to 15%-underestimation in the peak local enthalpy rise.

Since a PWR REA is a rather simple transient it is important to analyze more complicated one, such as a boron dilution accident.

The objectives of this study were the following.

- Calculate the TMI-1 boron dilution accident with BARS-RELAP and compare the results with those obtained by PARCS-RELAP.
- Perform sensitivity study for the transient to a variety of neutronic and thermal-hydraulic parameters and estimate calculational uncertainty in peak fuel enthalpy.
- Analyze effects of spatial non-uniformity in inlet boron concentration on peak fuel enthalpy.

The TMI-1 boron dilution accident following a small break loss of coolant accident (SBLOCA) at beginning of cycle was studied using a plenum inlet boron concentration obtained from a simulation carried out by Framatome Technologies [7].

Section 1 presents the calculational results for the TMI-1 boron dilution accident with BARS-RELAP, and an intercomparison with results obtained using the PARCS-RELAP code. In Section 2 sensitivity of the peak fuel pellet enthalpy and core power is assessed to a number of neutronic and thermal-hydraulic parameters. Section 3 focuses on an analysis of effects of spatial non-uniformity in the inlet boron concentration on the peak fuel enthalpy and core power deformations.

1. CALCULATION OF BORON DILUTION ACCIDENT

The boron dilution accident considered in this study is initiated after a SBLOCA when natural circulation is disrupted and reflux condensation allows deborated water to build up in the cold leg. Calculations performed for the Crystal River Unit 3 (CR-3) PWR by Framatome Technologies predicted prompt criticality with significant heat generation when natural circulation was reestablished [7]. The calculations were carried out with the RELAP5 thermal-hydraulics code [8] using a quasi-three-dimensional core thermal-hydraulic model incorporating with a point neutron kinetics model. Based on results of these calculations, boundary conditions for coolant flow at the vessel inlet nozzles and pressure at the vessel outlet nozzles were obtained to approximate modeling the restart of natural circulation following the SBLOCA. To simulate the boron dilution accident under these boundary conditions, a simplified scenario of the event was elaborated in Brookhaven National Laboratory (BNL). The scenario was used for simulations of TMI-1 at BOC with the 3-D coupled PARCS-RELAP code [9].

1.1. Accident Scenario

To bring the TMI-1 core from initial HZP steady state conditions to the conditions after the SBLOCA and before the restart of natural circulation and the boron dilution event, an additional artificial stage was included into the transient [8]. So, the simplified scenario consisted of two stages.

The first stage started from HZP steady state conditions with the coolant temperature of 551 K, coolant pressure of 15 MPa, coolant flow rate of 17,374 kg/s and boron concentration of 1700 ppm at the low inlet plenum. This stage had duration of 100 s. During the first 10 s the reactor was scrammed, at the inlet plenum the boron concentration was linearly increased to 2500 ppm, the coolant temperature was linearly decreased to 422 K, the coolant flow rate was linearly decreased to 3% of nominal, and the pressure was maintained at 6.6 MPa.

The second stage had duration of 500 s and modeled the boron dilution event according to the boundary conditions obtained by Framatome Technologies. During this stage the boron concentration at the inlet plenum decreased to 969 ppm, and then gradually increased to 2500 ppm as shown in Figure 1.1.

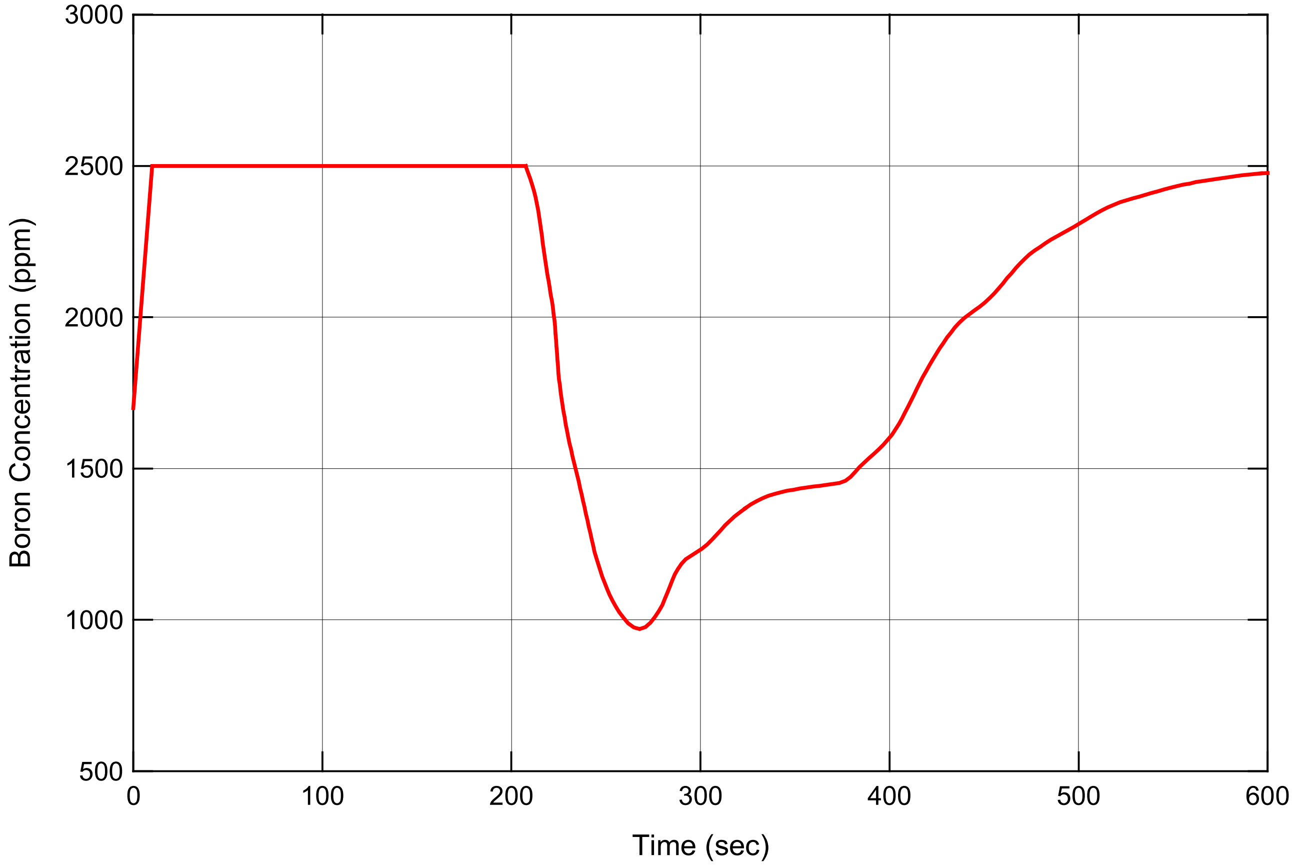


Figure 1.1. Boron Dilution Curve at Plenum Inlet

1.2. Calculational Model

Calculations of the TMI-1 boron dilution accident were carried out using the 3-D BARS-RELAP coupled code [1]. The BARS code is based on a pin-by-pin heterogeneous method that allows performing very fine mesh full-scale steady state and transient calculations of LWR cores. The reactor of 2772 MW rated power, having one-eight symmetry, contains 177 fuel assemblies (FAs) with fuel burnup ranged from 0.14 to 48.2 GWd/t (at the BOC) as shown in Figure 1.2. The figure shows also the arrangement of all control rod banks in the TMI-1 core model [10]. Banks 1, 2, 3, and 4 are safety banks that are inserted to shut down the reactor. Banks 5, 6, and 7 are regulating banks. Bank 8 contains axial power-shaping rods (APSRs).

Fuel assembly map used by BARS is shown in Figure 1.3. Neutronic calculations of the TMI-1 was carried out in the following approximations:

- number of energy groups – 4;
- number of delayed neutron groups – 6;
- number of axial harmonics – 24;
- number of fuel pins – 36,816;
- total number of calculational cells – 54,225.

The BARS neutron database, boundary conditions matrices, was calculated by the TRIFON code [11]. For the TMI-1 PWR, the matrices were calculated depending on a number of thermal-hydraulic parameters. For fuel pins, the parameters were the following:

- fuel temperature;
- coolant density;
- boron concentration.

For other cells the parameters were the coolant density and boron concentration.

In the BARS-RELAP calculations the same thermal-hydraulic model of the TMI-1 and RELAP input deck were used as in the PARCS-RELAP calculations [9]. The RELAP5 model represents the TMI-1 core as 30 parallel one-dimensional thermal-hydraulic channels, as shown in Figure 1.4, joined by common mixing volumes at the inlet and outlet. The bypass reflector region was treated as a single channel (No.30).

	8	9	10	11	12	13	14	15
H	30.69 Bank 7	0.16 Gd + B	29.50 Bank 2	0.18 Gd + B	24.53 Bank 7	0.16 Gd + B	36.51 Bank 6	48.20
K		32.26 Bank 2	0.17 Gd + B	29.30 Bank 4	0.17 Gd + B	29.25 Bank 5	0.15 Gd + Gd	40.34
L			31.69 Bank 6	0.18 Gd + B	30.12 Bank 8	0.17 Gd + B	0.14 Bank 1	39.62
M				24.52 Bank 5	0.18 B	31.73 Bank 3	26.73	
N					24.89 Bank 7	0.17	32.22	
O						24.82		

30.69	- fuel burnup (GWd/t)
Bank 7	- No. of control rod bank

Gd	- 4 fuel pins with Gd
B	- B_4C burnable poison rods

Figure 1.2. One-Eight Core Layout (BOC Conditions)

					1	2	3	4	5					
			6	7	8	9	10	11	12	13	14			
		15	16	17	18	19	20	21	22	23	24	25		
	26	27	28	29	30	31	32	33	34	35	36	37	38	
	39	40	41	42	43	44	45	46	47	48	49	50	51	
52	53	54	55	56	57	58	59	60	61	62	63	64	65	66
67	68	69	70	71	72	73	74	75	76	77	78	79	80	81
82	83	84	85	86	87	88	89	90	91	92	93	94	95	96
97	98	99	100	101	102	103	104	105	106	107	108	109	110	111
112	113	114	115	116	117	118	119	120	121	122	123	124	125	126
	127	128	129	130	131	132	133	134	135	136	137	138	139	
	140	141	142	143	144	145	146	147	148	149	150	151	152	
		153	154	155	156	157	158	159	160	161	162	163		
			164	165	166	167	168	169	170	171	172			
					173	174	175	176	177					

Figure 1.3. BARS Fuel Assembly Map

					30	30	30	30	30	30	30					
			30	30	30	21	15	8	15	21	30	30	30			
		30	30	28	25	20	14	7	14	20	25	28	30	30		
	30	30	29	27	24	19	13	6	13	19	24	27	29	30	30	
	30	28	27	26	23	18	12	5	12	18	23	26	27	28	30	
30	30	25	24	23	22	17	11	4	11	17	22	23	24	25	30	30
30	21	20	19	18	17	16	10	3	10	16	17	18	19	20	21	30
30	15	14	13	12	11	10	9	2	9	10	11	12	13	14	15	30
30	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	30
30	15	14	13	12	11	10	9	2	9	10	11	12	13	14	15	30
30	21	20	19	18	17	16	10	3	10	16	17	18	19	20	21	30
30	30	25	24	23	22	17	11	4	11	17	22	23	24	25	30	30
	30	28	27	26	23	18	12	5	12	18	23	26	27	28	30	
	30	30	29	27	24	19	13	6	13	19	24	27	29	30	30	
		30	30	28	25	20	14	7	14	20	25	28	30	30		
			30	30	30	21	15	8	15	21	30	30	30			
					30	30	30	30	30	30	30					

Figure 1.4. RELAP Thermal-Hydraulic Channel Map

1.3. Analysis of Results

Before the transient calculations, an intercomparison of the BARS and PARCS results for assembly averaged power distribution, control rod worths, and reactivity effects was carried out for initial HZP steady state conditions. Various positions of control rod banks 5, 6, 7, and individual control rods of Bank 7 were considered. Safety banks 1 to 4 were fully withdrawn; Bank 8 was partially inserted. Good agreement was found for the assembly averaged power distribution with the maximum difference of 4.7% for the peripheral fuel assembly. Differences in rod worths were about 5% for banks 5, 6, and 7, and about 10% for individual rods of Bank 7 [9]. Very good agreement was found for the Doppler and boron reactivity effects. However, a significant difference of 80% was found for the moderator density effect at the boron concentration of 1700 ppm, because the absolute value of the effect is close to zero at such boron concentration [12].

The results of the intercomparison between BARS and PARCS [13] for the boron dilution transient are presented in Figures 1.5 through 1.10. The power history vs. time is shown in Figures 1.5 and 1.6 using logarithmic and linear scales, respectively. The power curves demonstrate that the transient is very complicated. There are three power peaks during about 60 s. Nevertheless, the BARS and PARCS results agreed qualitatively. For the first power peak BARS gave 255% of nominal power at 267.1 s, whereas PARCS gave 185% of nominal at 263.1 s. For the second peak the BARS and PARCS values are very close, but the BARS value for the third power peak is smaller in comparison with the PARCS one.

A quantitative difference between BARS and PARCS results for the power behavior can be understand by the analysis of the reactivity history vs. time, shown in Figures 1.7 and 1.8. At the beginning of the second stage before the boron dilution, BARS brought the core to the state with more deep subcriticality in comparison with PARCS one. To bring the core to up critical state under the boron dilution conditions it needs more time for the first state, then for the second one. As a result, just before the first power peak, BARS gave larger rate of the reactivity insertion by deborated water into the core, which brought to of 38% excess in the peak power with delay of 4 s in comparison with PARCS. A difference in the BARS and PARCS results for the third power peak may be explained by the difference in the distribution of the boron concentration over the core under the complicated core thermal-hydraulic transient. Since the power level at the third peak is very small, the difference in the results for this peak does not affect on accident consequences. It should be noted that the difference in the results for the core subcriticality before the event is mainly due to the difference in the moderator density reactivity coefficient. This effect was found at the end of the transient too.

Figure 1.9 demonstrates good agreement of the results in the maximum fuel pellet enthalpy. The BARS curve is shifted on time in respect to the PARCS one by the reason discussed above. The peak values in the fuel enthalpy are in very good agreement within 4.7%. For the BARS and PARCS calculations the hottest fuel pellets were found in FA-151 at 37 cm above the bottom of the core.

The results of intercomparison for the axial power distributions are shown in Figure 1.10 for the initial steady state, for the time of the peak fuel enthalpy, and for the final stage of the transient. In spite of very large deformations of the axial power shape during the transient, agreement between BARS and PARCS results is very good. We note that the axial power shapes for the initial steady state and for the end of the transient are very different because of the strong effect of the delayed neutron source on the power distribution under the large core subcriticality at the end of the transient.

Figure 1.11 shows the assembly averaged power distribution calculated with BARS for the initial steady state and at the time of the peak power. During the reactor scram, positions of the assemblies with maximum power were shifted from the center of the core to the periphery because of the effect of the scram rods. After the scram the maximum power has FA-151 with the fresh fuel, surrounded by only two assemblies containing control rods. Figure 1.12 illustrates a complicated pin-by-pin power distribution for a half of the core at the time of the peak power. The main results of the intercomparison between BARS and PARCS for the TMI-1 boron dilution accident are presented in Table 1.1.

Table 1.1. Calculational Results of TMI-1 Boron Dilution Accident

Parameter	PARCS	BARS
Reactivity before boron dilution (β)	-14.9	-16.9
Maximum inserted reactivity (β)	1.078	1.132
First peak power (% of nominal)	185.0	254.9
Time of the first peak power (s)	263.1	267.1
Maximum fuel pellet temperature (°C)	850.2	842.5
Time of maximum fuel temperature (s)	272.8	277.5
Maximum fuel enthalpy (cal/g)	56.70	59.37
Maximum increase in fuel enthalpy (cal/g)	47.81	50.91

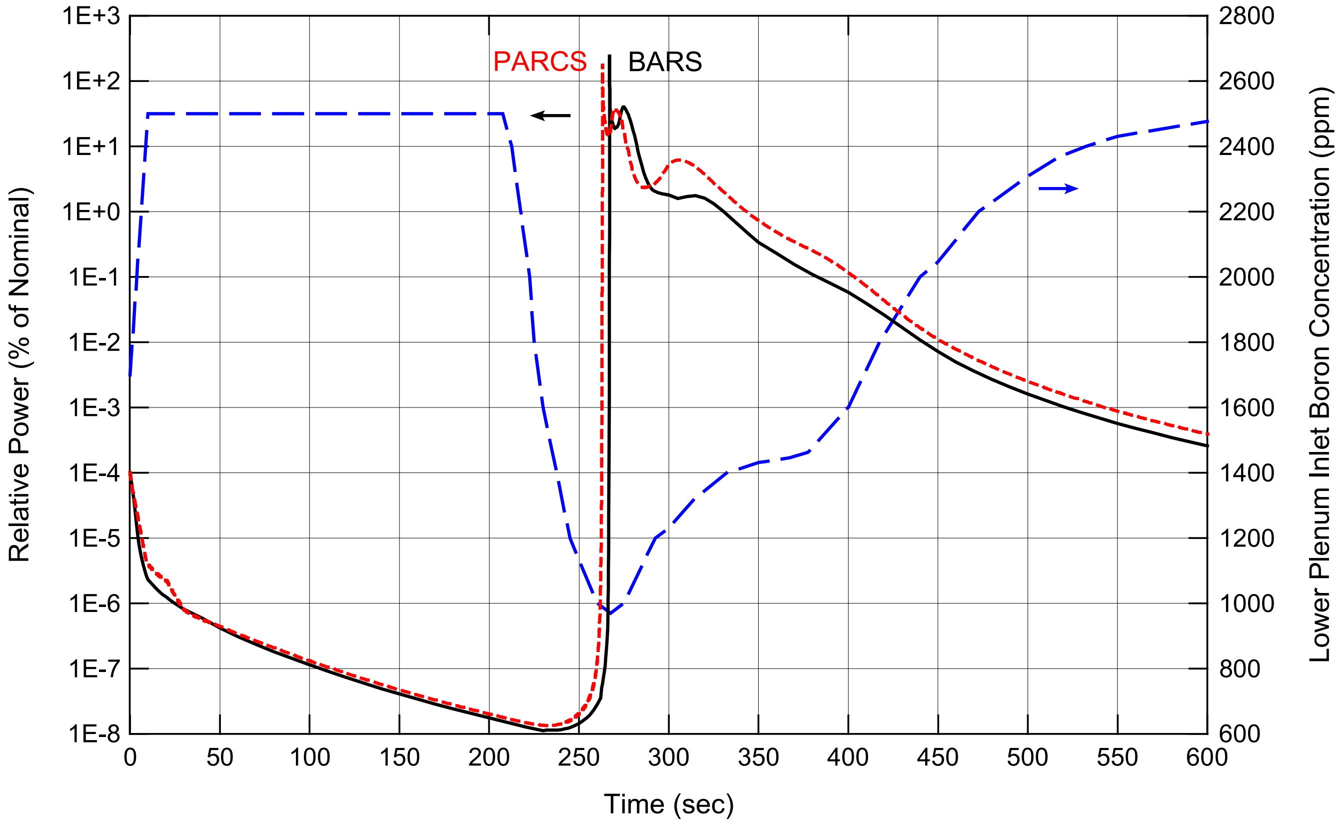


Figure 1.5. Power History (Logarithmic Scale)

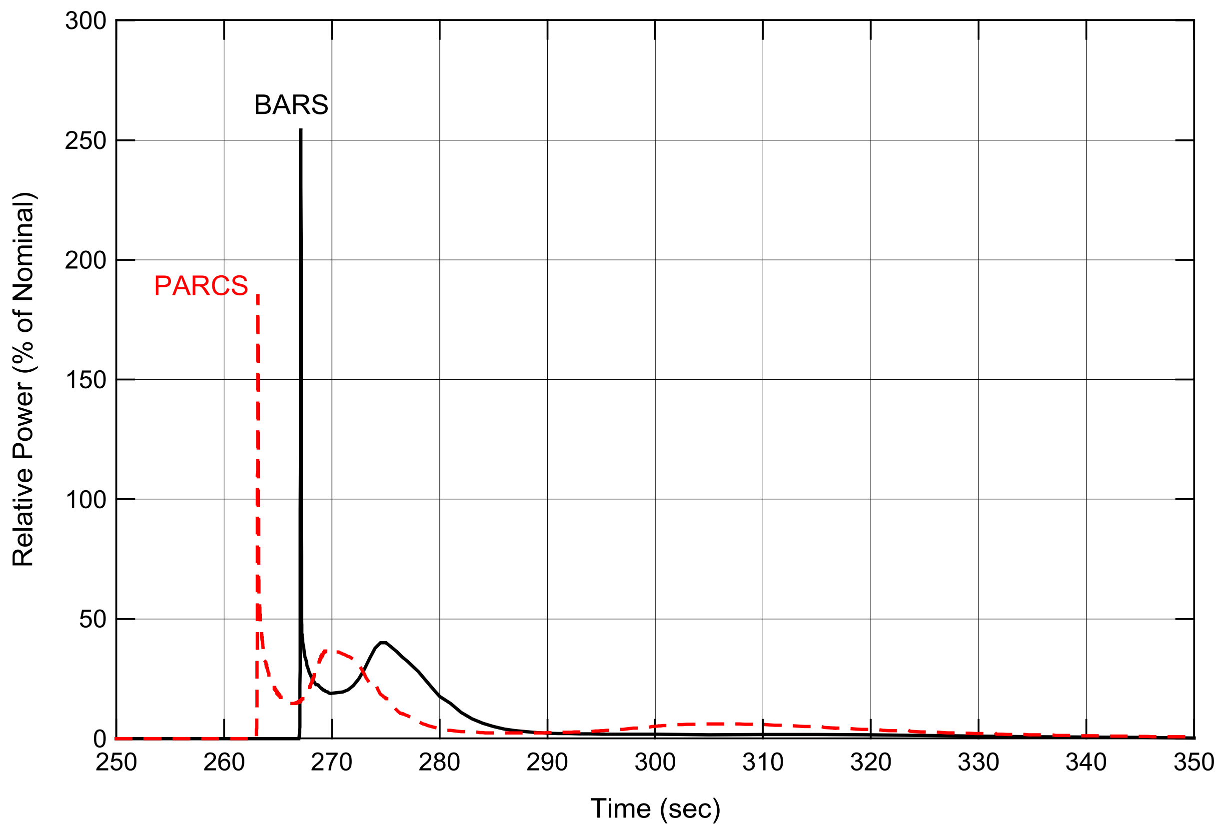


Figure 1.6. Power History (from 250 to 350 s)

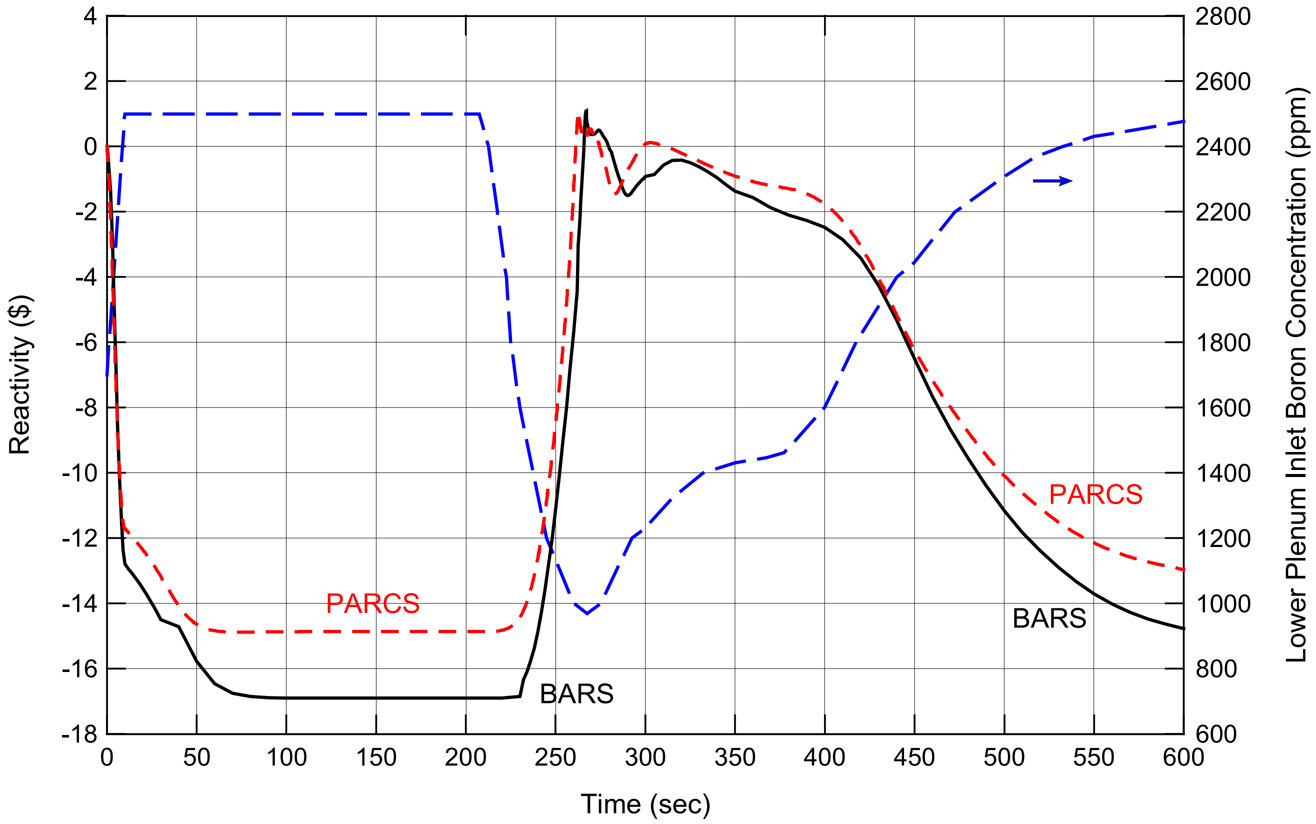


Figure 1.7. Reactivity vs. Time

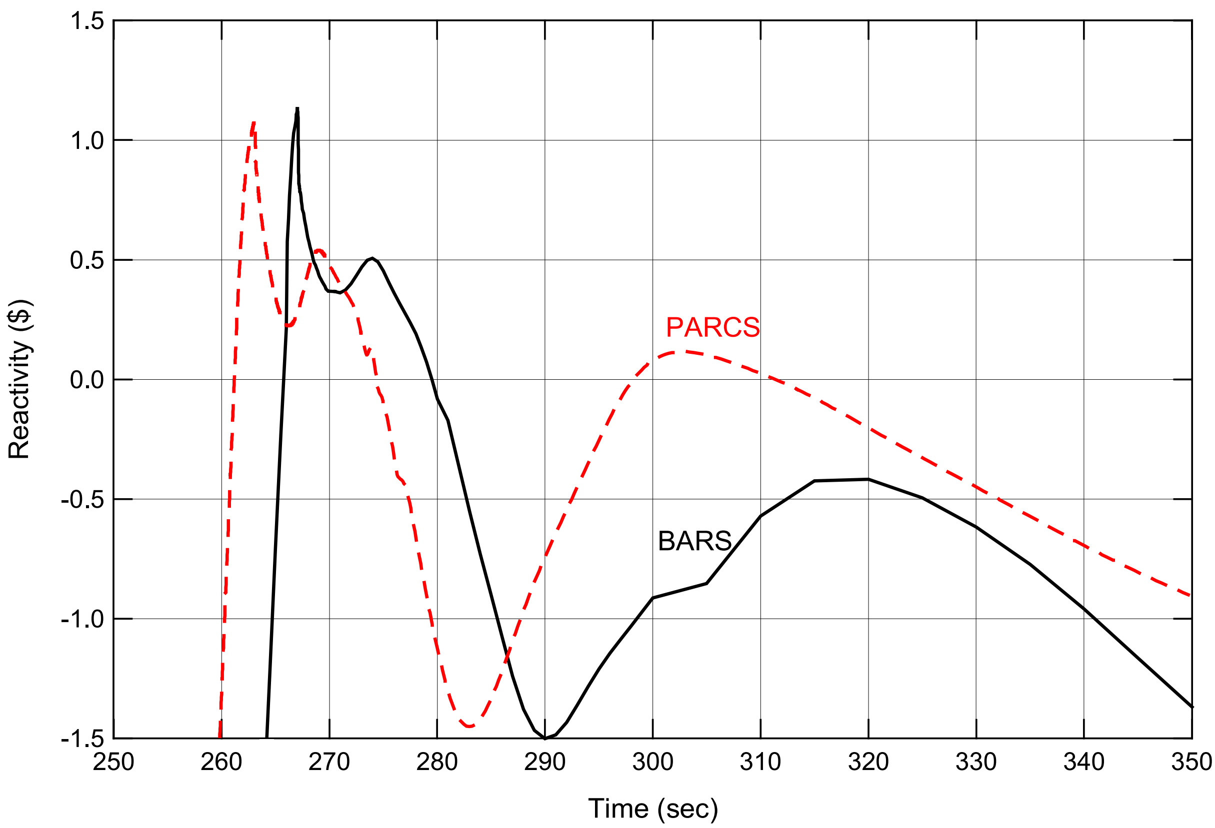


Figure 1.8. Reactivity vs. Time (from 250 to 350 s)

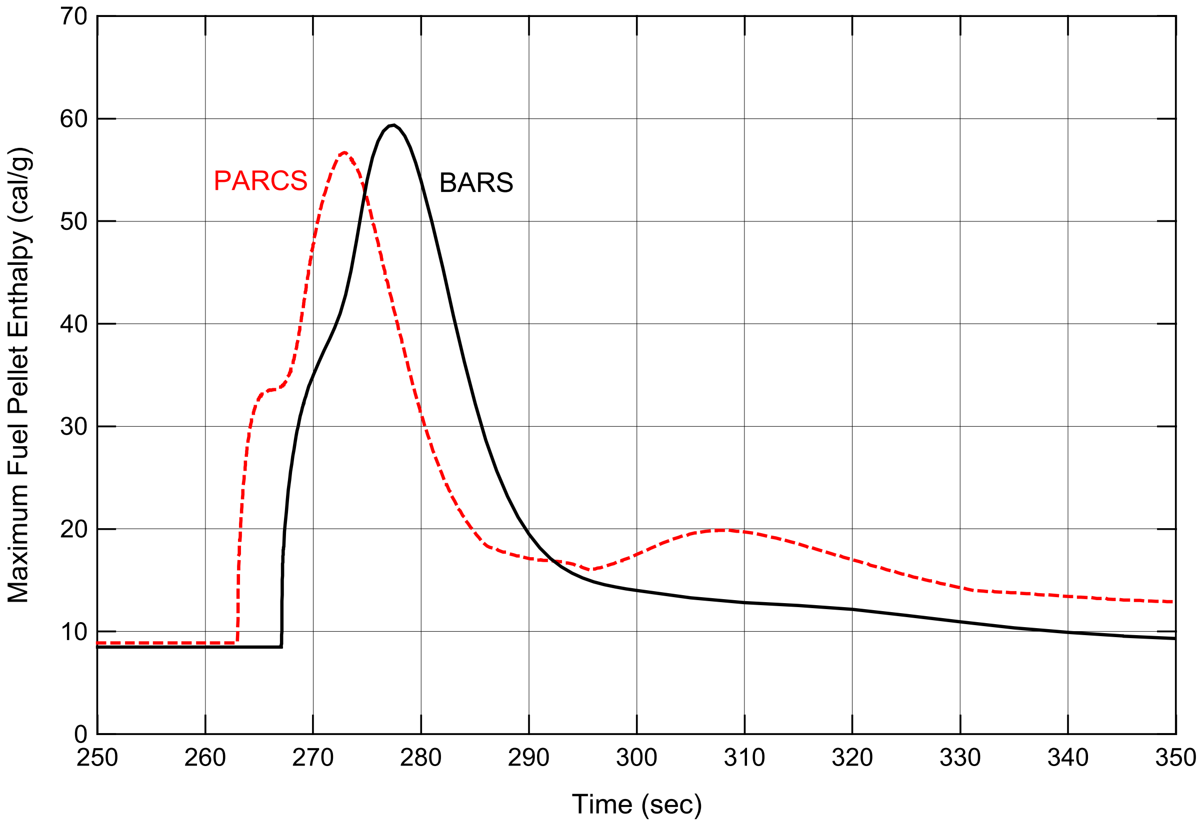


Figure 1.9. Maximum Fuel Pellet Enthalpy vs. Time (from 250 to 350 s)

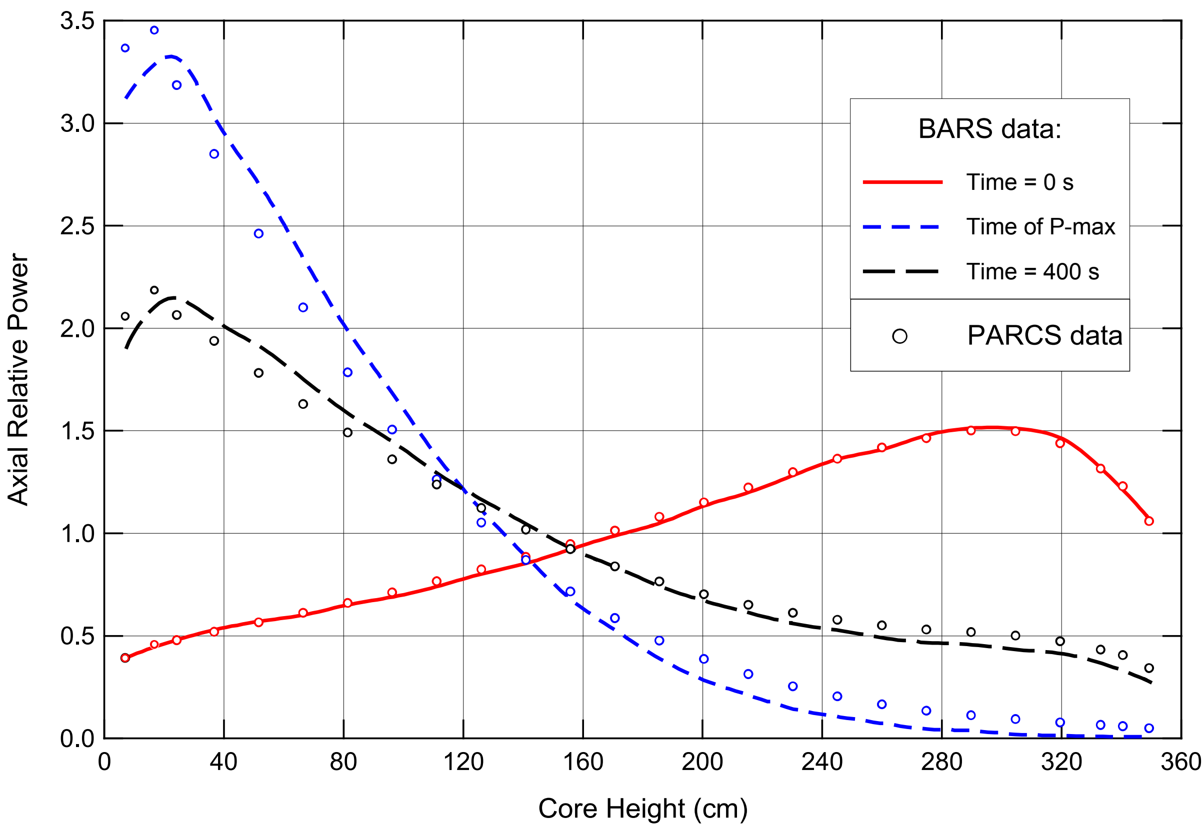


Figure 1.10. Axial Power Distributions

	8	9	10	11	12	13	14	15
H	0.939 0.430	1.822 0.778	1.709 0.631	1.587 1.047	0.712 0.769	0.779 1.064	0.362 0.491	0.188 0.221
K		1.600 0.558	1.718 0.957	1.365 0.807	1.196 1.354	0.662 0.855	0.948 1.062	0.288 0.302
L			0.915 0.773	1.292 1.461	1.123 1.505	1.247 1.461	1.167 0.811	0.314 0.245
M				0.746 1.110	1.231 1.847	1.061 1.015	0.706 0.702	
N					0.827 1.404	1.283 2.087	0.459 0.632	
O						0.649 1.096		

Time = 0 s →

Time at P_{max} →

Figure 1.11. Assembly Averaged Power Distributions

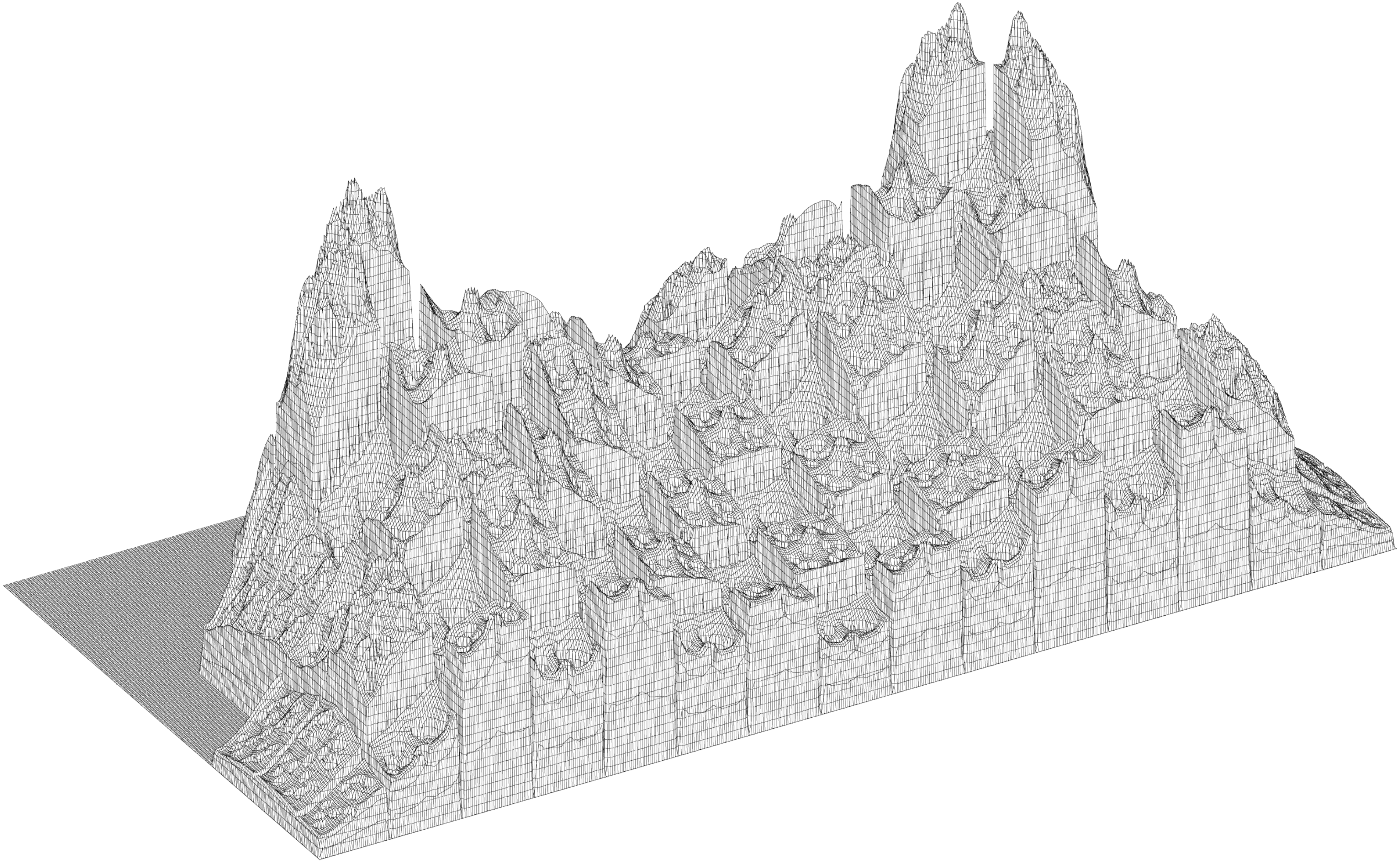


Figure 1.12. Pin-by-pin Power Distribution at Time of Peak Power

2. UNCERTAINTY ANALYSIS

Although it was found very good agreement in peak fuel enthalpy between the BARS and PARCS results, we cannot guarantee its conservative estimation for the PWR boron dilution accident. Presented below uncertainty analysis allows to estimate the real uncertainty in peak fuel enthalpy for such complicated transient. To understand a rather large difference between the BARS and PARCS results for the peak core power, a sensitivity study was carried out for this parameter too.

2.1. Methodology

A methodology of the uncertainty analysis, which was used for the PWR boron dilution accident, is close to that developed in BNL [14]. It is based on a sensitivity study to global parameters that are explicitly used in point kinetics equations or can be taken into account implicitly in point kinetics through thermal-hydraulic feedback. The methodology was applied in a previous study for an analysis of the PWR rod ejection accident with BARS [2].

Assuming that a peak fuel enthalpy (h_f) is a function of a number of above parameters (x) and a random error in each parameter is normally distributed, the square of the uncertainty in the fuel enthalpy can be written as:

$$(\delta h_f / h_f)^2 = \Sigma (S_x)^2 (\delta x/x)^2,$$

where $\delta x/x$ is the uncertainty in the parameter x, S_x is the sensitivity of the fuel enthalpy to the parameter x, and the summation is over all parameters of interest. The same formula was applied for the uncertainty analysis in the peak core power.

Values of S_x were obtained from a set of the BARS-RELAP transient calculations with perturbed values of neutronic and thermal-hydraulic parameters x. The uncertainties in the parameters $\delta x/x$ were estimated by engineering judgement, using evidences from available references and validation results for the BARS code.

The following 14 neutronic and thermal-hydraulic parameters were taken into the consideration (in order of their contribution to the uncertainty in the peak fuel enthalpy):

- moderator density reactivity coefficient (α_m);
- worth of inserted control rods (ρ_{trip});
- boron reactivity coefficient (α_B);
- lower inlet plenum boron concentration ($C_{B\ inlet}$);
- Doppler reactivity coefficient (α_D);
- gap conductance (h_g);
- lower inlet plenum coolant flow rate (G_{inlet});
- lower inlet plenum coolant temperature (T_{inlet});
- delayed neutron fraction (β);
- pellet heat capacity (C_p);
- pellet conductivity (K_f);
- clad-moderator heat transfer coefficient (h_w);
- fraction of energy deposited directly in the moderator (γ);
- radial power peaking factor for the pellet (F_p).

2.2. Results of Uncertainty Analysis

The BARS-RELAP results for sensitivity of the peak fuel pellet enthalpy S_x to parameters x, as well as uncertainties in parameters, and contributions of each parameter to the uncertainty in fuel enthalpy $(S_x)^2(\delta x/x)^2$ are presented in Table 2.1 for seven parameters. Contributions of other considered parameters to the uncertainty in peak fuel enthalpy are very small. The results show that the uncertainty in the peak fuel enthalpy is caused to a great extent by the uncertainty in the moderator density reactivity coefficient because of a large value of this uncertainty under conditions of the boron dilution transient. The peak fuel enthalpy is very sensitive to the worth of inserted control rods, boron reactivity coefficient, and lower inlet plenum boron concentration. However, contributions of these parameters to the uncertainty in the peak fuel enthalpy are rather small because of small values of their uncertainties. It should be noted that unlike the rod ejection accident [2], for the boron dilution transient the Doppler feedback effect on fuel enthalpy is positive ($S_{\alpha_D}>0$) and minor in comparison with the moderator feedback effect.

Table 2.1. Sensitivity of Fuel Enthalpy and Uncertainties of Parameters

$x \quad \Rightarrow$	α_m	ρ_{trip}	α_B	$C_{B\ inlet}$	α_D	h_g	G_{inlet}
S_x	-0.43	-2.26	2.32	-3.54	0.40	-0.10	0.61
$\delta x/x$, %	100	8	5	3	15	50	5
$(S_x)^2(\delta x/x)^2$	0.1833	0.0327	0.0134	0.0113	0.0037	0.0026	0.0009

Based on the results, presented in Table 2.1, the total uncertainty in the peak fuel pellet enthalpy was estimated as 50%.

Corresponding results for sensitivity of the peak core power are shown in Table 2.2. The peak power is extremely sensitive to the lower inlet plenum boron concentration and coolant flow rate. Contributions of the lower inlet plenum boron concentration, coolant flow rate, fraction of energy deposited directly in the moderator, moderator density reactivity coefficient, and worth of inserted control rods to the uncertainty in the peak power are very large. The total uncertainty in the peak core power was estimated as 220%. It is clear that under such very large sensitivity of the peak power to a number of neutronic and thermal-hydraulic parameters, a difference of 40% between BARS and PARCS for the peak core power seems to be a quite good result.

Table 2.2. Sensitivity of Peak Core Power and Uncertainties of Parameters

$x \quad \Rightarrow$	$C_{B\ inlet}$	G_{inlet}	γ	α_m	ρ_{trip}	α_B	h_g
S_x	-38.6	19.8	-4.9	-0.9	-10.5	7.2	-0.4
$\delta x/x$, %	3	5	20	100	8	5	50
$(S_x)^2(\delta x/x)^2$	1.34	0.98	0.94	0.73	0.7	0.13	0.04

3. ANALYSIS OF SPATIAL EFFECTS

Since in the RELAP5 model of the TMI-1 core all thermal-hydraulic channels are connected to a common mixing volume at the core inlet, a radial distribution of the boron concentration is uniform at a bottom of the core. For the boron dilution accident such a distribution of the boron concentration is not conservative, because a non-uniform distribution of deborated water at the core inlet may cause an additional deformation in a power distribution over the core and bring to insertion of an additional reactivity. To study an effect of a spatial non-uniformity in the inlet boron concentration on peak fuel enthalpy a number of calculations were carried out with BARS-RELAP for different distributions in the boron concentration at the core inlet.

Two types of a spatial distribution in the inlet boron concentration were considered: radial symmetrical and asymmetrical ones. The boron concentration in the radial reflector was not changed in both cases and was the same as in the reference case.

For the first type the inlet boron concentration was increased by 10% at the central part of the core (in 97 FAs) in comparison with the reference case and was decreased by 12.125% at the peripheral part (in 80 FAs). This case is shown in Figure 3.1 with shaded assemblies having the increased boron concentration. So, the average value of the boron concentration at the core inlet was not changed. Since this type of the boron distribution is symmetrical, the same thermal-hydraulic channel map was used in the RELAP5 calculations as in the reference case. The BARS-RELAP calculation for the boron distribution of the symmetrical type gave the following results.

- The power peaking factor increased by 25% in comparison with the reference case.
- The super prompt reactivity (excess in reactivity above the delayed neutron fraction) increased by 3.3%.
- The peak fuel enthalpy increased by 11%.

Thus, the symmetrical change in the inlet boron concentration does not bring the transient to a large power deformation and to a significant increase in the peak fuel enthalpy. Another transient with decreased inlet boron concentration at the core center and increased one at the core periphery was considered too. However, this transient gave a decrease in the peak fuel enthalpy in comparison with the reference case.

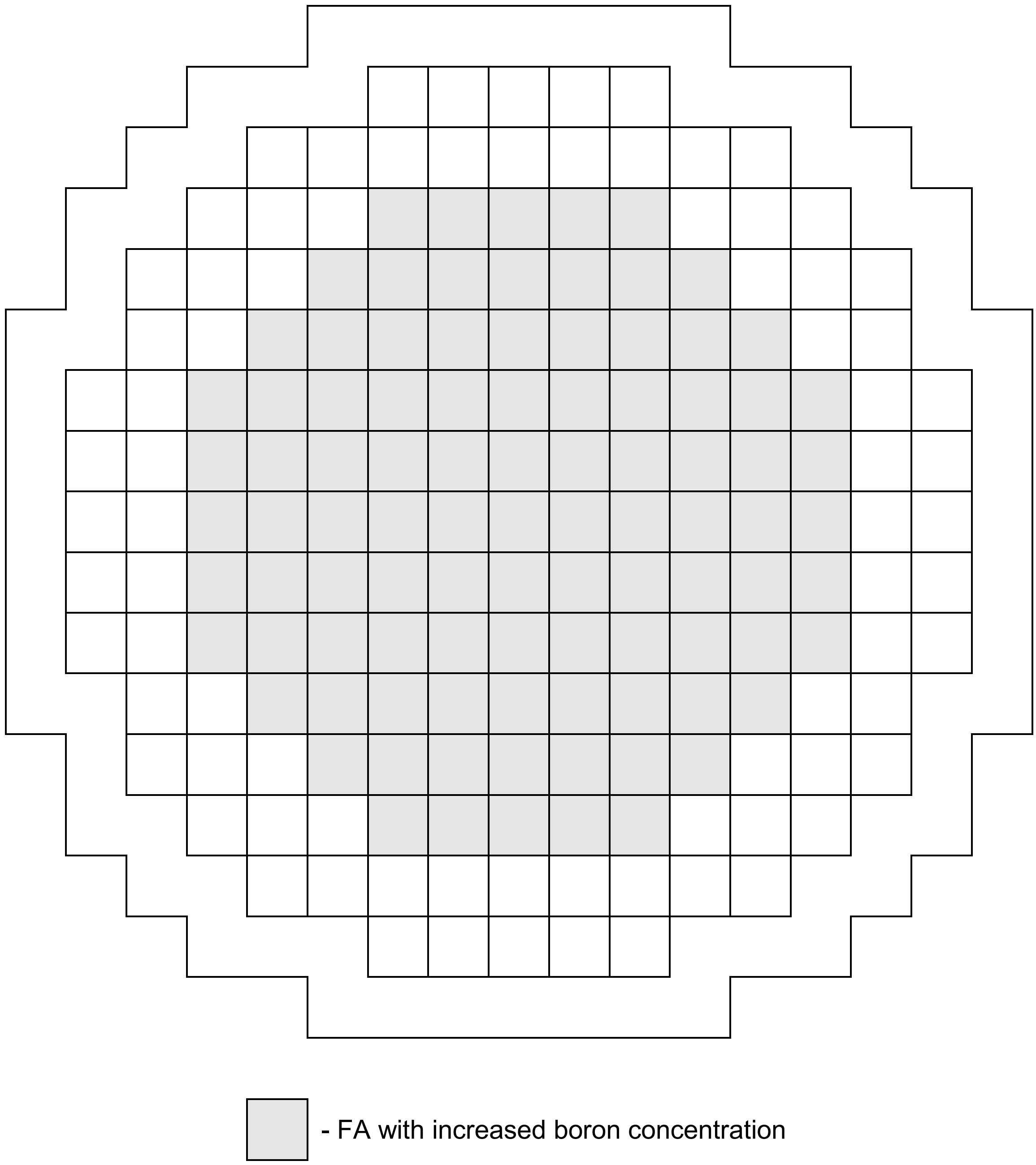


Figure 3.1. Symmetrical Distribution in Inlet Boron Concentration

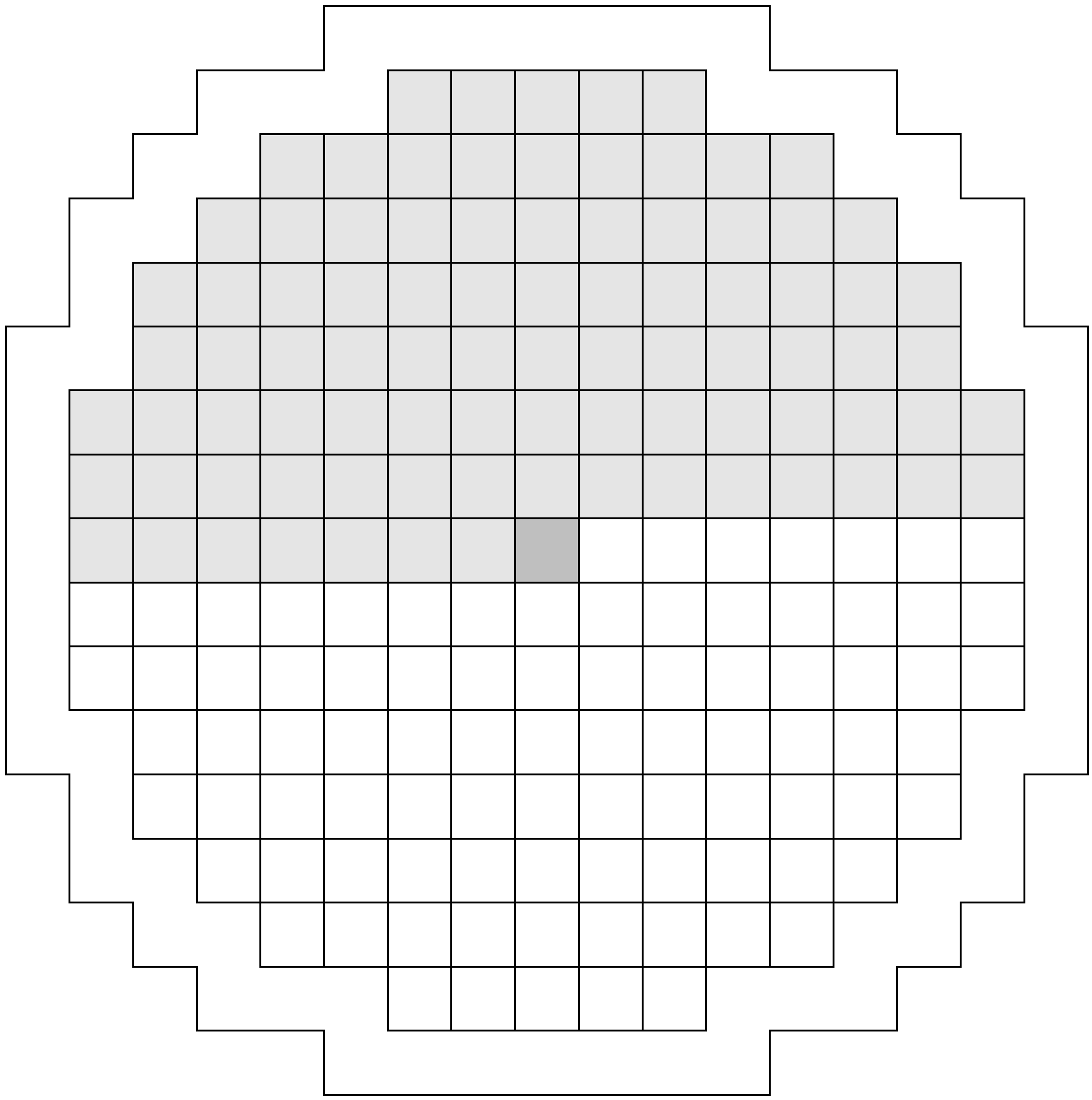
For the distribution of the second type the inlet boron concentration was increased at one half of the core and was decreased at another half by the same value as shown in Figure 3.2. The boron concentration at the central assembly was not changed. To calculate this case with the asymmetrical distribution in the inlet boron concentration with BARS-RELAP, the thermal-hydraulic channel map was changed. The modified channel map used in the RELAP calculations of an asymmetrical boron transport is shown in Figure 3.3. A total number of the thermal-hydraulic channels was the same as before.

Two transients were calculated with a half-core change in the inlet boron concentration of 10 and 20%. Results of calculations for a change in a power peaking factor ($\delta F_q/F_q$), super prompt reactivity ($\delta\rho/(\rho-\beta)$), and peak fuel pellet enthalpy ($\delta h_f/h_f$) in comparison with the reference case are shown in Table 3.1. Figure 3.4 illustrates a pin-by-pin power distribution at the time of a peak power for the transient with a half-core change in the inlet boron concentration of 10%.

Table 3.1. Calculational Results for Half-Core Changes in Inlet Boron Concentration

Change in $C_{B\ inlet}$	$\delta F_q/F_q$, %	$\delta\rho/(\rho-\beta)$, %	$\delta h_f/h_f$, %
10%	109	28	25
20%	133	43	44

The results show very large power deformations for the both transients with asymmetrical boron distributions at the core inlet. The power peaking factor increased more than two times in comparison with the reference transient. The asymmetrical distribution of deborated water brought to a rather large increase in the inserted reactivity of 28% and 43% for the changes in the boron concentration of 10% and 20% respectively. However, the peak fuel enthalpy increased by 25% and 43%, and these values are practically proportional to the corresponding changes in the inserted reactivity by deborated water. So, the reason for the increase in the peak fuel pellet enthalpy is the increase in the reactivity inserted by the asymmetrical distribution of deborated water, rather than power deformations due to an asymmetrical boron distribution over the core. This confirms our previous results for the analysis of the PWR rod ejection accident [3] where it was found that the peak fuel enthalpy does not depend on power deformations over the core during the transient.



- FA with increased boron concentration

- central FA with normal boron concentration

Figure 3.2. Asymmetrical Distribution in Inlet Boron Concentration

					30	30	30	30	30	30	30					
			30	30	30	21	15	15	15	21	30	30	30			
		30	30	25	25	21	13	7	13	21	25	25	30	30		
	30	30	29	27	27	19	13	7	13	19	27	27	29	30	30	
	30	29	25	27	23	23	19	5	19	23	23	27	25	29	30	
30	30	25	23	23	17	17	11	5	11	17	17	23	23	25	30	30
30	21	21	19	19	17	17	11	3	11	17	17	19	19	21	21	30
30	15	13	13	11	11	9	9	3	9	9	11	11	13	13	15	30
30	15	7	7	5	5	3	3	1	2	2	4	4	6	6	8	30
30	20	14	14	12	12	10	10	2	10	10	12	12	14	14	8	30
30	20	20	18	18	16	16	10	2	10	16	16	18	18	20	20	30
30	30	28	24	24	22	12	10	4	10	12	22	24	24	28	30	30
	30	28	26	26	22	18	12	4	12	18	22	26	26	28	30	
	30	30	28	24	24	18	14	6	14	18	24	24	28	30	30	
		30	30	28	24	20	14	6	14	20	26	28	30	30		
			30	30	30	20	20	8	8	14	30	30	30			
					30	30	30	30	30	30	30					

Figure 3.3. Modified Thermal-Hydraulic Channel Map

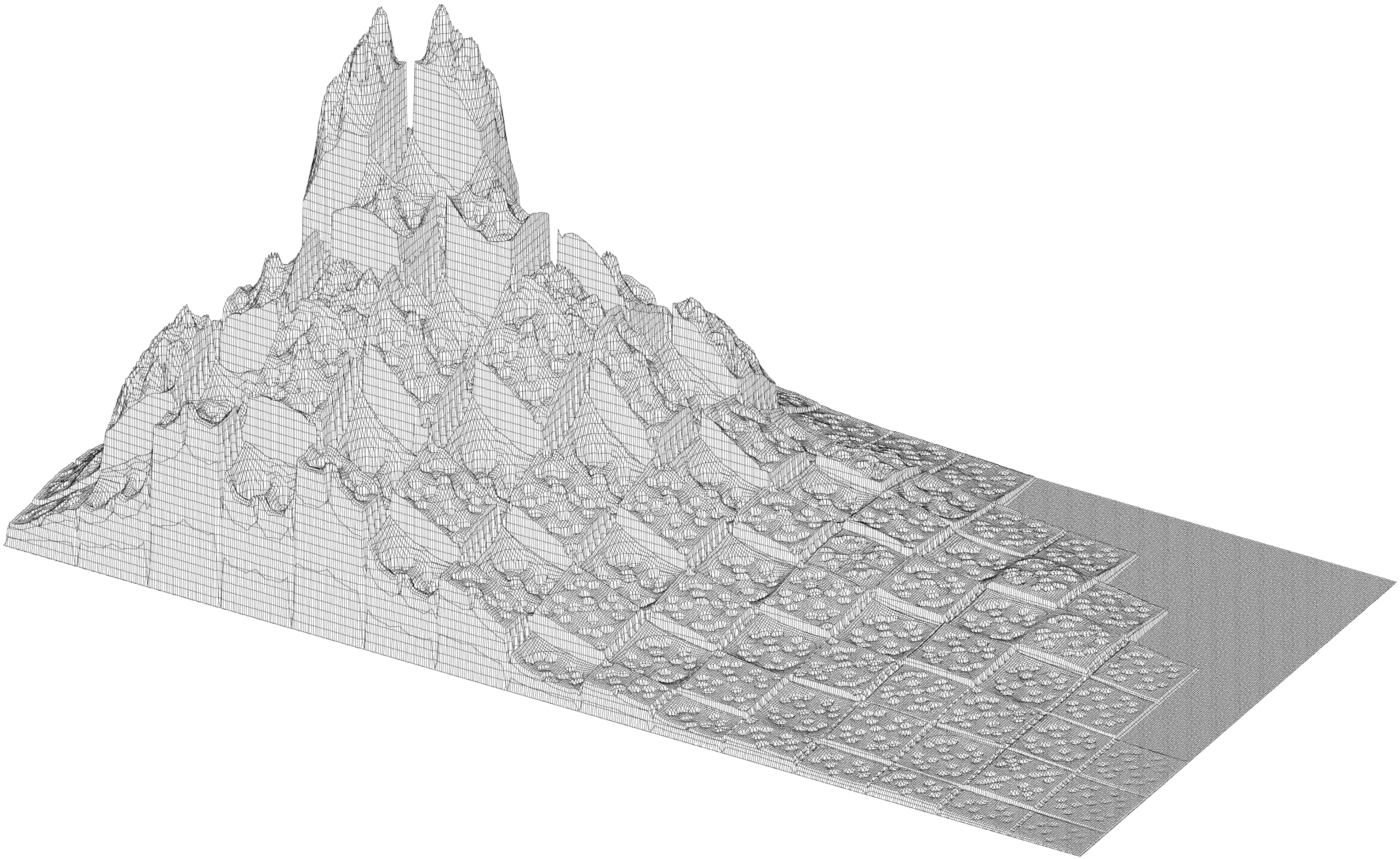


Figure 3.4. Pin-by-pin Power Distribution at Time of Peak Power for Half-Core Change in Inlet Boron Concentration

CONCLUSIONS

This study was undertaken to analyze a complicated reactivity transient – a boron dilution accident in a PWR. The TMI-1 boron dilution transient following an SBLOCA at beginning of cycle was considered with BARS-RELAP. The study was focused on an intercomparison of the BARS-RELAP results with those obtained using the PARCS-RELAP code. A sensitivity analysis of the transient to a variety of neutronic and thermal-hydraulic parameters and a study of effects of spatial non-uniformity in the inlet boron concentration on the peak fuel pellet enthalpy were performed. The transient calculations were carried out using a plenum inlet boron concentration obtained from a simulation by Framatome Technologies.

The intercomparison of the BARS-RELAP and PARCS-RELAP results showed that both calculations are qualitatively in very good agreement. Good agreement with 5%-difference was found for the peak fuel enthalpy. However, the BARS value of the peak core power was about 40% higher compared with the PARCS result.

The sensitivity analysis of the transient showed that the moderator reactivity coefficient gave the major effect to the uncertainty in the peak fuel enthalpy due to large uncertainty of this coefficient under conditions of the boron dilution accident. The uncertainty in the peak fuel pellet enthalpy was estimated as 50%. The analysis demonstrated very large sensitivity of the peak core power to uncertainties in the lower inlet plenum boron concentration, coolant flow rate, fraction of energy deposited directly in the moderator, moderator density reactivity coefficient, and worth of inserted control rods. This fact may be a reason for rather large difference in the BARS and PARCS results for the peak core power.

The study of effects of spatial non-uniformity in the inlet boron concentration on the peak fuel pellet enthalpy was performed for two types of a spatial boron distribution. It was found that a symmetrical boron distribution did not bring the transient to large power deformations and a considerable increase in the peak fuel enthalpy. But an asymmetrical type of the distribution with a half-core change in the inlet boron concentration gave very large power deformations. However, these deformations did not effect on the peak fuel enthalpy. An increase in the peak fuel enthalpy was proportional to a change in the reactivity inserted by deborated water during the transient.

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