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ABSTRACT

A preliminary analysis of reactivity insertion transients that were protected by the control rods but had zero reactivity feedback coefficients at the BR2 reactor was presented at RERTR2009 in Beijing. The admissible reactivity insertion rate, which can be tolerated in the BR2 was determined for nominal reactor operation and at manipulation conditions (low reactor power and no flow) with respect to the accepted safety limits in SAR-BR2. The calculations were performed by PARET/ANL V7.5 for a simplified 12-channel model representing the hot assembly in the BR2 core.

In the present paper a detailed 48-channel model has been developed which describes the reactor core in four clusters representing the typical BR2 fuel assemblies. The distribution of the power and reactivity feedback in each cluster of the HEU representative core is obtained from a best-estimate MCNPX calculation.

The sensitivity of the reactor response to power, temperature and energy distributions is studied for protected and unprotected reactivity insertion transients, with and without reactivity feedback coefficients. The 48-channel model is compared vs. the 12-channel model and vs. a 24-channel model representing the reactor as one hot cluster and the remainder of the core – as an average cluster.

1. INTRODUCTION

One of the objectives of the BR2 Conversion project is to set limiting conditions for the reactivity insertion transients in order to protect the cladding from overheating or insufficient cooling. There are two classes of reactivity insertion transients which need to be analyzed. The first class represents incidents with automatic power reduction caused by insertion of the control rods, assuming zero reactivity feedback from coolant temperature or density changes. A preliminary analysis for this class, performed with the ANL – transient thermal-hydraulics analysis code PARET/ANL V7.5 [1], was presented in Beijing [2]. The calculations were performed using a simplified 12-channel model representing the hot fuel assembly. For the case of protected transients with zero reactivity feedback, this model proved to give adequate results which were in a good agreement (within 5 to 10%) with the safety margins for HEU in SAR-BR2 [3]. That analysis was performed for different situations of the initial reactor state – at nominal power and nominal flow and for low power and no flow at manipulation conditions. A preliminary analysis of the power, energy and temperature variations in UMo core at nominal reactor power was performed and compared with HEU.

The second class of transients are unprotected with excluded overpower and period trips, in which the negative reactivity feedback from coolant temperature change and density change is considered. This class of transient is important in events such as control rod blockage or large reactivity insertions. A more refined multi-channel model representing the hot and not hot assemblies, coupled through the reactivity feedback effects to the whole core is necessary for this type of transient.

The objectives in this paper are as follows:

- To develop a detailed multi-channel PARET model representing the different fuel assemblies in the BR2 reactor core, organized such that there are one or more fuel clusters in each PARET channel.
- The power and reactivity feedback distributions in the different fuel clusters is obtained from best-estimate MCNPX [4] calculations using the detailed whole core model of the BR2 reactor.
- The 48-channel model is validated on transients with zero reactivity feedback vs. the simplified 12-channel model representing the whole core as one hot assembly, and vs. 24-channel model, in which the reactor is composed of one hot cluster and one average cluster representing the remainder of the core.
- Comparison of the models is performed for nominal power and nominal flow at operation conditions for the HEU core.
- The sensitivities of transient characteristics (power, energy, temperature distributions) derived from the different models are tested on a few reactivity insertion transients with reactivity feedback from coolant temperature and density change for the HEU core.

The final purpose is to have a detailed multi-channel model with best-estimate power and reactivity feedback distribution which can be used in the future analysis of unprotected transients in the HEU and LEU cores.

Section 2 introduces the PARET models for comparison. Section 3 gives a description of the different fuel assemblies in the BR2 reactor core, organized into several representative fuel clusters. In Section 4 we give the power distribution in the different clusters, obtained from MCNPX calculations for the HEU representative core. Tables with the reactivity feedback from voids and coolant temperature feedback for the chosen clusters of fuel assemblies are presented in Section 5. In this paper the axial distribution of the feedback is assumed to be similar to the axial power peaking factors and the Doppler feedback is not considered, since the major purpose is to test the sensitivities of the transient characteristics derived on the used multi-channel model.

Section 6 presents a comparison of power, energy and temperature distributions, obtained with the different models. Section 7 discusses the conclusions from the comparison.

2. DESCRIPTION OF PARET MODELS

Steady-state analysis of BR2 cores was performed using the PLTEMP/ANL code [5]. That work defined some of the input parameters for the PARET models, such as the geometrical details of the fuel tubes and coolant channels, the nominal coolant inlet temperature and mass flow rate, and the resulting peak heat flux generated by each fuel tube in the cluster. The PARET models were validated under steady-state conditions to show that they were equivalent to the PLTEMP model results [6]. The following PARET models have been used and compared in this paper:

- 12-channel model representing the hottest Cluster 2 in the reactor. The power distribution is averaged over the hot assemblies in the reactor with burn up 16%, loaded in 5 channels A & B (see the next Section 3 and Section 4).
- 24-channel model representing the reactor core as 1 'hot' cluster of 5 hot fuel assemblies in channels A & B and 1 'average' cluster that represents the remainder of the core. This model is an approximate representation of the whole core model: the power distribution in the 'hot' cluster is the same as in the hottest Cluster 2, however the power distribution in the 'average' cluster is obtained averaging the total power and the power peaking factors in the remaining clusters 1, 3 and 4. The MCNPX calculation of the reactivity feedback coefficients for this model is performed using the whole core model with the real hottest Cluster 2 (5 fuel assemblies, each with 16% burn up) and average power distribution and average burn up of ~ 30% in the remaining 27 assemblies (see the next Section 3 and Section 4).
- 48-channel model representing the reactor core as 4 different clusters of fuel assemblies. This model is most close to the real reactor core. The power distribution in each cluster is obtained from best-estimate MCNPX calculations using the whole core geometry model for the HEU representative core (see the next Section 3 and Section 4).

3. DESCRIPTION OF BR2 REPRESENTATIVE FUEL ASSEMBLY CLUSTERS

This Section describes the reference core load [7] which has been selected for the different neutronic studies [8]. The same core load is used in the calculation of MCNPX parameters needed for the transient analysis by PARET. The following terminology with regard to the reference core load is used in this paper: a representative HEU core load, which is typical of the non-converted BR2 reactor and similar to the load of the cycle, 04/2008A.7 [7]. The burn up of the fuel assemblies in the core varies between 0% (fresh fuel) and 46%. The selected representative model contains the following types of fuel assemblies, which are organized into 4 typical clusters of fuel assemblies:

- Cluster 1: 6 fresh FA (channels C, 0% burn up, this cluster has the maximum peaking factors, but not the highest power).

- Cluster 2: 5 burned FA (channels A and B) having 16% average burn up (this is the hottest cluster with the highest power, but the power peaking factors are lower than in the 'C' channels in Cluster 1).
- Cluster 3: 12 burned FA (channels B and D) with 32% average burn up.
- Cluster 4: 9 burned FA (channels F and G) having 46% average burn up.

The criteria for creating a cluster are: 1. similar power distribution in fuel assemblies having equal average burn up; and 2. located in similar channels (see Section 4). It should be noted that the fuel assembly loaded in the central channel H1/C is excluded from calculations by PARET in this paper. The cross section of the MCNPX geometry model of the BR2 reactor core with the different clusters is given in Fig. 1.

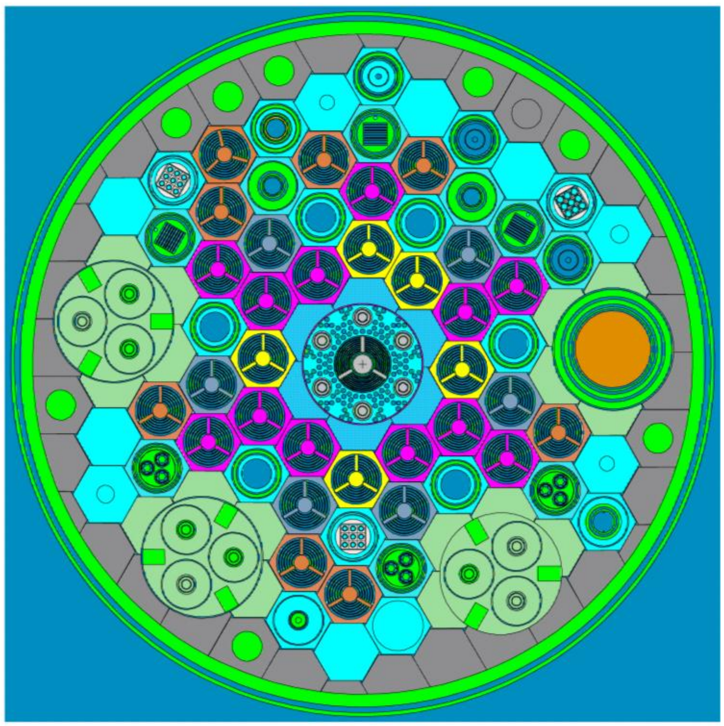


Figure 1. Cross section of the MCNPX geometry model of the BR2 reactor core with clusters, represented in different colors.

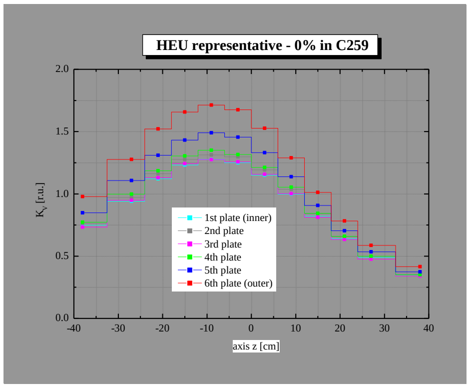
4. POWER DISTRIBUTION IN THE REPRESENTATIVE CORES

The detailed power distribution in the core has been calculated by MCNPX for the HEU representative core and for the fully converted UMo core and presented in the part for the neutronics studies of the Feasibility Report (see Section 3.3 in [9]). Table I in this Section uses the same data for HEU core from Table 3.7 in [9], but normalized to 100 MW and excluding the power of the fuel assembly in H1/C as it was mentioned in Section 3. A total BR2 power of 100 MW has been used in the safety studies about the reactivity insertion transients in SAR-BR2 [3]. The power distribution in Table I is adapted to represent the average power in each fuel assembly belonging to a given cluster (each cluster of fuel assemblies has a different color in Table I) for the corresponding PARET model. The power distributions and the values of FACT3 used with the three different PARET models are listed in Table I. FACT3 is an input for PARET describing the ratio of the power of a fuel assembly to the average core power.

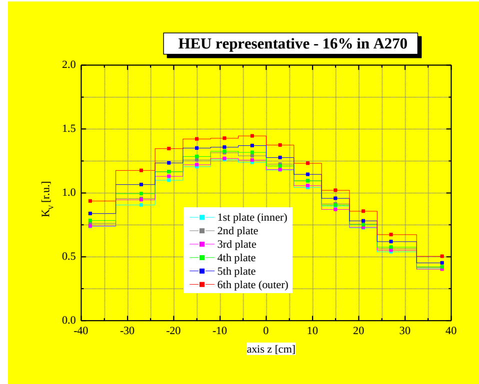
Table I. Fuel assembly average burn up, average power and FACT3 in the fuel assembly clusters at BR2 power 100 MW for HEU core used in the different multi-channel PARET models.

	Cluster	48-channel model			24-channel model			12-channel model		
		U5 burn up [%]	Power P_i [MW]	FACT3= P_i/P_{aver}	U5 burn up [%]	Power P_i [MW]	FACT3= P_i/P_{aver}	U5 burn up [%]	Power P_i [MW]	FACT3= P_i/P_{aver}
A30	2	16	4.25	1.36	16	4.25	1.36	16	4.25	1.36
A90	2	16	4.25	1.36	16	4.25	1.36	16	4.25	1.36
A150	3	32	3.47	1.11	30	2.92	0.934	–	–	–
A210	3	32	3.47	1.11	30	2.92	0.934	–	–	–
A270	2	16	4.25	1.36	16	4.25	1.36	16	4.25	1.36
A330	3	32	3.47	1.11	30	2.92	0.934	–	–	–
B0	2	16	4.25	1.36	16	4.25	1.36	16	4.25	1.36
B60	3	32	3.47	1.11	30	2.92	0.934	–	–	–
B120	3	32	3.47	1.11	30	2.92	0.934	–	–	–
B180	2	16	4.25	1.36	16	4.25	1.36	16	4.25	1.36
B240	3	32	3.47	1.11	30	2.92	0.934	–	–	–
B300	3	32	3.47	1.11	30	2.92	0.934	–	–	–
C41	1	0	3.32	1.06	30	2.92	0.934	–	–	–
C101	1	0	3.32	1.06	30	2.92	0.934	–	–	–
C161	1	0	3.32	1.06	30	2.92	0.934	–	–	–
C199	1	0	3.32	1.06	30	2.92	0.934	–	–	–
C259	1	0	3.32	1.06	30	2.92	0.934	–	–	–
C319	1	0	3.32	1.06	30	2.92	0.934	–	–	–
D0	3	32	3.47	1.11	30	2.92	0.934	–	–	–
D60	3	32	3.47	1.11	30	2.92	0.934	–	–	–
D120	3	32	3.47	1.11	30	2.92	0.934	–	–	–
D240	3	32	3.47	1.11	30	2.92	0.934	–	–	–
D300	3	32	3.47	1.11	30	2.92	0.934	–	–	–
F14	4	46	1.92	0.61	30	2.92	0.934	–	–	–
F46	4	46	1.92	0.61	30	2.92	0.934	–	–	–
F106	4	46	1.92	0.61	30	2.92	0.934	–	–	–
F166	4	46	1.92	0.61	30	2.92	0.934	–	–	–
F194	4	46	1.92	0.61	30	2.92	0.934	–	–	–
F254	4	46	1.92	0.61	30	2.92	0.934	–	–	–
F314	4	46	1.92	0.61	30	2.92	0.934	–	–	–
F346	4	46	1.92	0.61	30	2.92	0.934	–	–	–
G180	4	46	1.92	0.61	30	2.92	0.934	–	–	–
Average	–	28	3.125	1.0	30	3.125	1.0	16	4.25	1.36

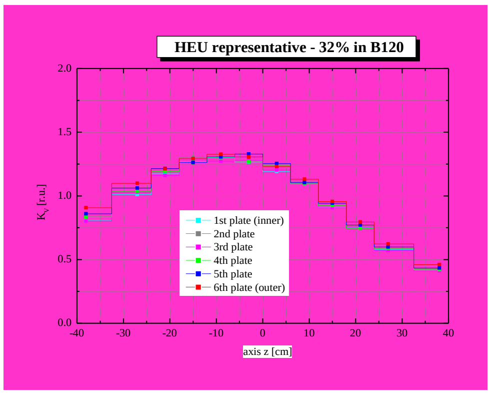
A similar methodology has been applied to the axial power peaking factors, i.e. the power distribution in the fuel plates of fuel assemblies having equal burn up and located in similar channels is assumed to be equal. The axial peaking factors in the fuel rings of the fuel assemblies representing the different clusters used in the corresponding PARET models are given in Fig. 2.



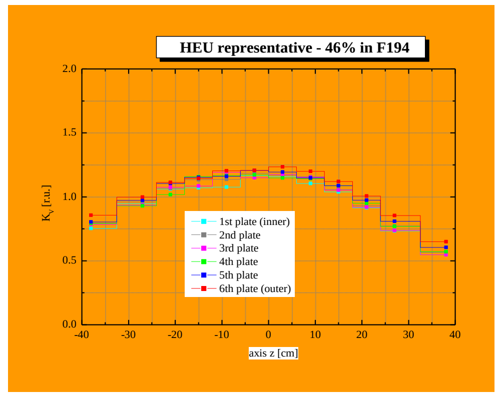
Cluster 1



Cluster 2



Cluster 3



Cluster 4

Fig. 2. Axial power peaking factors in the fuel plates of fuel assemblies representing the different fuel clusters: C259 (0% burn up, Cluster 1), A270 (16% burn up, Cluster 2), B120 (32% burn up, Cluster 3), F194 (46% burn up, Cluster 4) in the HEU Representative core.

5. MCNPX REACTIVITY FEEDBACK FROM COOLANT VOIDS AND TEMPERATURE CHANGES

In this section we present tables with calculated reactivity feedback from voiding different parts of the reactor core represented by the four chosen clusters as described in the previous sections. The calculations of the feedback for each PARET model are performed by MCNPX using the corresponding whole core model of the HEU representative core. For the 12-channel model the feedback is the same as for the hottest Cluster 2 in the 48-channel model. The reactivity feedback used for each PARET model calculated for 5% is given in Table II. Similar methodology is applied for the calculation of the coolant temperature feedback: the coolant temperature is changed in the whole cluster for a given PARET model and this temperature is kept constant in all axial segments of the fuel plates. In this paper it is assumed that the axial distribution of the feedback is similar to the axial power peaking factors. The reactivity coolant temperature feedback is calculated for 500°K compared to 300°K (see Table III). The Doppler reactivity feedback is not considered and not taken into account in this paper (it has been shown [10] that it is negligible for HEU).

The methodology for the application of the reactivity feedbacks in the chosen three PARET models is: A. to introduce one single value for the whole core reactivity feedback calculated by MCNPX for the corresponding PARET model (e.g., using the sum of the clusters), this value is introduced in $/% void and in $/1°K, correspondingly; B. Then the values DVOID and DTEMP in each PARET channel are adapted for the corresponding model in Table II and Table III.

Table II. MCNPX reactivity feedback calculated for 5% void of the different parts of the HEU reactor core represented by the chosen clusters of fuel assemblies and used in each one of the three PARET multi-channel models. In brackets is given the fraction for a given cluster from the total sum of the feedback. The burn up and the average power in the fuel assemblies in the different clusters for each considered PARET multi-channel model is given in Table I.

Cluster (burn up in %)	MCNPX reactivity feedback $ (fraction from total sum)		
	48-channel model	24-channel model	12-channel model
Cluster 1	0.17 $ (0.22)	–	–
Cluster 2-hot	0.19 $ (0.24)	0.18 $ (0.25)	0.18 $ (0.22)
Cluster 3	0.36 $ (0.46)	–	–
Cluster 4	0.06 $ (0.08)	–	–
Sum in clusters 1&3&4	0.59 $ (0.76)	0.54 $ (0.75)	0.62 $ (0.78)
Sum of all clusters	0.78 $ (1.0)	0.72 $ (1.0)	0.8 $ (1.0)

Table III. MCNPX coolant temperature reactivity feedback (500 to 300 °K) calculated in the different parts of the HEU reactor core represented by the chosen clusters of fuel assemblies and used in each one of the three PARET multi-channel models. In brackets is given the fraction for a given cluster from the total sum of the feedback. The burn up and the average power in the fuel assemblies in the different clusters for each considered PARET multi-channel model is given in Table I.

Cluster (burn up in %)	MCNPX reactivity feedback $ (fraction from total sum)		
	48-channel model	24 channel model	12-channel model
Cluster 1	0.47 $ (0.14)	–	–
Cluster 2-hot	0.79 $ (0.23)	0.72 $ (0.22)	0.64 $ (0.22)
Cluster 3	1.7 $ (0.49)	–	–
Cluster 4	0.51 $ (0.15)	–	–
Sum in clusters 1&3&4	2.68 $ (0.78)	2.61 $ (0.78)	2.2 $ (0.78)
Sum of all clusters	3.47 $ (1.0)	3.33 $ (1.0)	2.84 $ (1.0)

6. COMPARISON OF TRANSIENT CHARACTERISTICS BETWEEN THE DIFFERENT MULTI-CHANNEL PARET MODELS

In this section we compare results from calculations of reactivity insertion transient tests using the 48-channel, 24-channel and 12-channel PARET models. A step reactivity addition of 0.2 $ is considered in all tests. Two types of transients are considered:

A. With zero reactivity feedback coefficients.

B. With reactivity feedback coefficients from Table II and Table III in Section 5.

Section 6.1 describes the input data for PARET for the initial state of the reactor, the used thermo-hydraulics and kinetics parameters.

Section 6.2 compares the different models for protected by the control rods transients A and B with an overpower trip at 120% (the period trip is excluded).

In Section 6.3 the different models are compared for unprotected transients A and B without an over power and period trips.

6.1 Description of input data for PARET

The initial state of the reactor is critical at nominal operating conditions. The total BR2 power is the same as in Section 4.3.2.1 of SAR-BR2 [3]. The maximum heat flux in the core for these conditions is equal to 520 W/cm^2 as in [3], which corresponds to a power level of 100 MW. Table IV summarizes the input data for the initial reactor state conditions used in the different PARET models. For the 12-channel model we introduce the hottest fuel assembly power density QAVE=520 W/cm^2. For the 48-channel model and for the 24-channel model we introduce the average fuel assembly power (3.125 MW) which corresponds to QAVE=382 W/cm^2.

In Table V are listed the kinetic characteristics assumed to be equal for all considered PARET models for the load of the HEU representative core. In this paper we limit our point-kinetics models to 6 delayed neutron groups. We do not take into account the photo-neutrons from the beryllium matrix (see Table I, [11]).

The axial integral control rod worth is calculated by MCNPX for the HEU representative core (see Section 3.4, [9]). The rod drop time from different control rod positions is obtained from measurements ([12]). In Table VI are listed the values of the reactivity worths and drop times with flow for different axial control rod positions.

Table IV. Input data for the initial state of the BR2 reactor used in the 48-channel, 24-channel and 12-channel PARET models (see Section 4.4.6 in [3]).

Representative core load [7]	HEU
Number of fuel assemblies loaded	32
Total reactor power, MW	100
Fuel assembly average power, MW	4.25 (12-ch. Model)
	3.125 (24-ch. Model)
	3.125 (48-ch. Model)
Average core heat flux, QAVE, W/cm^2	520 (12-ch. Model)
	382 (24-ch. Model)
	382 (48-ch. Model)
Reactor pressure, MPa	1.24
Inlet temperature, °C	40
Coolant flow (down), kg/s/m^2	10520.8
Fuel thermal conductivity, W/m°K	80
Cladding thermal conductivity, W/m°K	150
Fuel volum. heat capacity coefficients, J/m^3-°K	1014, 2.0114E+6
Cladding volum. heat capacity coefficients, J/m^3-°K	1243.4, 2.0709E+6

Table V. Input data for point-kinetics parameters used in the different multi-channel PARET models for the HEU representative core.

Representative core load [7]	HEU
Number of delayed neutron groups	6
λ_6, sec^{-1}	0.01246
λ_5, sec^{-1}	0.03053
λ_4, sec^{-1}	0.11142
λ_3, sec^{-1}	0.30130
λ_2, sec^{-1}	1.13607
λ_1, sec^{-1}	3.01304
β_6	0.00025
β_5	0.00166
β_4	0.00149
β_3	0.00299
β_2	0.00087
β_1	0.00032
β_{aver}	0.00758
Prompt neutron lifetime, sec.	5.0E–5

Table VI. Input data for axial control rod reactivity worth (for situation of poisoned beryllium matrix at mid-2016) and drop law with flow used in in the different multi-channel PARET models for the HEU representative core.

Control rod axial position [mm]	Drop time [msec]	Reactivity worth [$]
0	0	0
50	0.029	0.18
100	0.057	0.36
150	0.084	0.75
200	0.112	1.16
250	0.14	2.05
300	0.167	2.93
350	0.194	4.1
400	0.222	5.28
450	0.25	6.68
500	0.277	8.08
550	0.31	9.38
600	0.342	10.67
650	0.372	11.54
700	0.402	12.41
750	0.474	12.94
800	0.547	13.46
850	0.614	13.79
900	0.682	14.1

6.2 Protected reactivity insertion transients

In this section we present comparison between the different PARET models for reactivity addition of 0.2 $ during 0.1 second. The reactivity insertion transients are protected by the control rods and by an over-power trip at 120%. The calculations are performed for both types of transients (A and B) described in the beginning of Section 6. As can be seen from Fig. 3 and Fig. 4 all PARET models give identical results for the transient characteristics with and without reactivity feedback coefficients, because the core is protected by the large negative reactivity worth of the control rods**.**

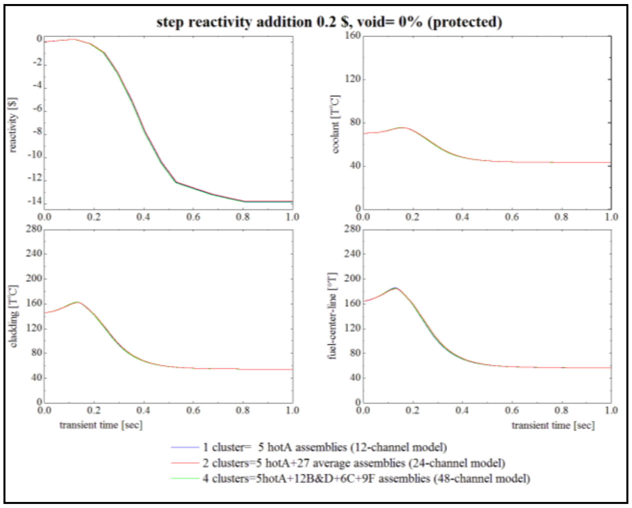


Fig. 3. Comparison of transient characteristics between 12-channel model, 24-channel model and 48-channel model for protected transients **with zero reactivity feedback coefficients**.

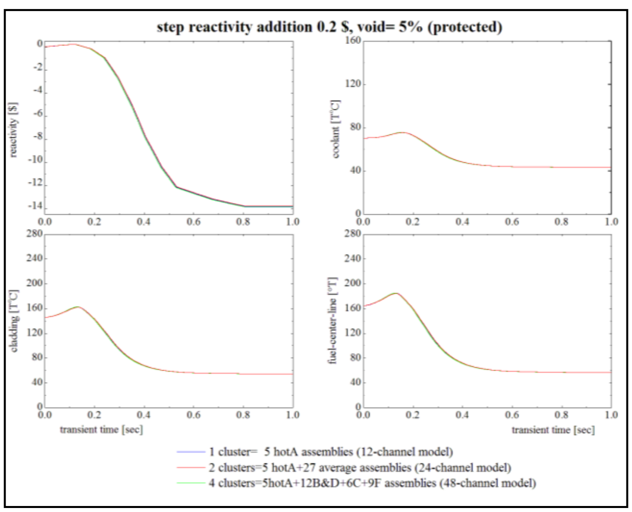


Fig. 4. Comparison of transient characteristics between 12-channel model, 24-channel model and 48-channel model for protected transients **with reactivity feedback coefficients**.

6.3 Un-Protected reactivity insertion transients

In this section we consider reactivity insertion transients in which the over-power and period trips are excluded. The calculations are performed for both transients (A and B) described in the beginning of Section 6.

6.3.1 Type A transients (with zero reactivity feedback coefficients)

Considered are unprotected transients type A with zero reactivity feedback coefficients. The power increases during the transient and the control rods, which are at highest position Sh=900 mm, do not move since the overpower trip is excluded. The transient characteristics are compared in Fig. 5 for the different PARET models. As it is seen for this type transients all considered models give identical results for the transient characteristics.

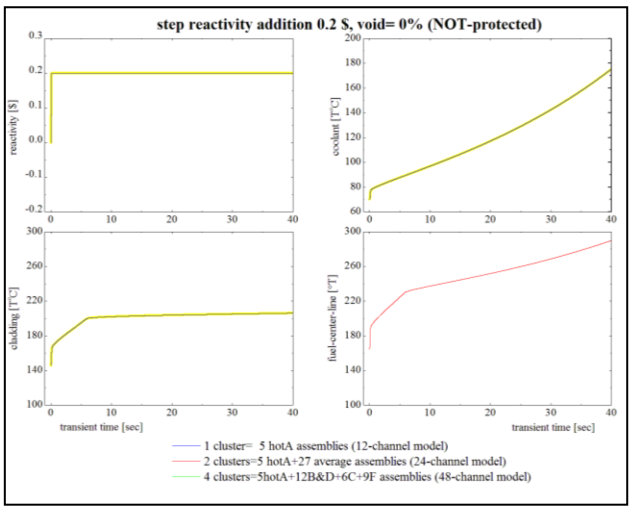


Fig. 5. Comparison of transient characteristics between the different multi-channel PARET models for **unprotected transients with zero reactivity feedback coefficients**.

6.3.2 Type B transients (with reactivity feedback coefficients)

Considered are unprotected transients of class B with reactivity feedback coefficients taken from Table II and Table III in Section 5. The power increases during the transient and the control rods, which are at highest position Sh=900 mm, do not move. The over-power and period trips are excluded. The only protection is from the inherent reactor feedback characteristics. The transient characteristics are compared in Fig. 6 for the different models for 0.1 $ and 0.2 $ reactivity step addition. As can be seen from the graphs, the transient characteristics are sensitive to the used model for the case of included reactivity feedback from coolant void and density change. According to this graph the 48-channel model is more conservative showing higher T-distributions compared to the fewer-channel models. A possible explanation is that the fewer-channel models represent an approximation of the real reactor core in which the core power distribution will be also approximate and consequently will reflect the coolant and fuel T-distributions. The power and T-distributions in the different clusters in the 24-channel and 48-

channel models are compared in Fig. 7. The T-distributions in the full core represented by the 48-channel model show two 'hot' clusters: the hottest Cluster 2 represented by 5 fuel assemblies with burn up 16% and highest fuel assembly power loaded in channels A & B; and almost so hot Cluster 1 represented by 6 fresh fuel assemblies with highest peaking factors loaded in channels C. The presence of two 'hot' clusters instead of one as we consider in the few-channel models can be a possible reason for the difference in the power and T-distributions.

In the future analysis of the unprotected reactivity insertion transients with included feedback the intention will be to refine the multi-channel and few-channel models by mutual comparison and by comparison on available data in SAR-BR2.

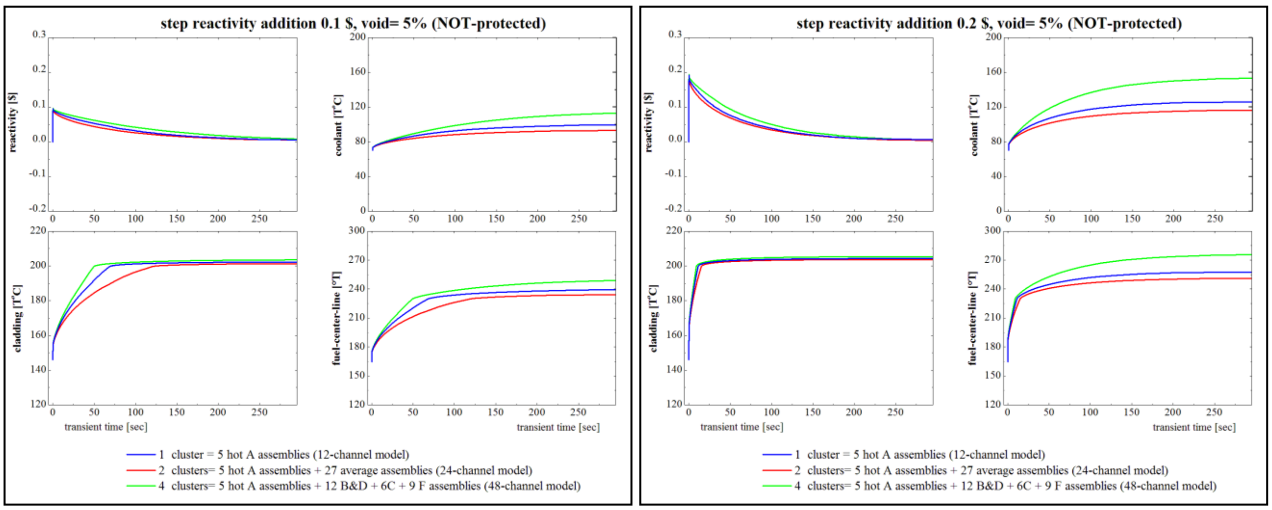


Fig. 6. Comparison of transient characteristics **IN THE HOT CLUSTER** between different PARET multi-channel models for **unprotected transients with reactivity feedback coefficients**.

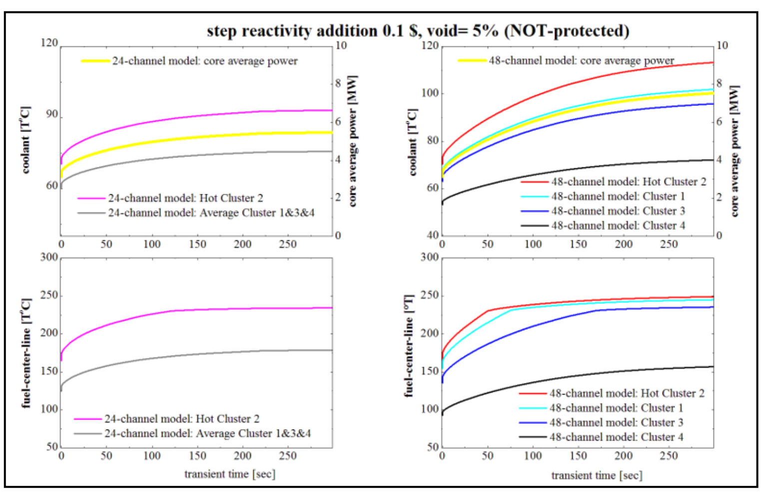


Fig. 7. Comparison of core average power, coolant and fuel T-distributions **IN DIFFERENT CLUSTERS** of 24-channel and 48-channel model for **unprotected transients with reactivity feedback coefficients**.

7. CONCLUSIONS

A preliminary analysis for the sensitivity of transient characteristics of the BR2 HEU core on the used various multi-channel models is presented. The transient behavior of the BR2 HEU representative core is compared for protected and unprotected by the control rods reactivity insertion transients, with and without reactivity feedback from coolant voids and density changes. All considered models give identical results for protected and unprotected transients with zero reactivity feedback coefficients. For protected transients with feedback, the models also give identical results because of the much larger reactivity worth of the control rods compared to the inserted reactivity. For unprotected transients with included feedback the preliminary conclusion is that the full core 48-channel model give more conservative results for the temperature distributions than the fewer-channel models. A possible explanation of these effects is that the few-channel models represent approximation of the real reactor core by averaging power and feedback distribution over large reactor core volumes. The purpose in the future transient analysis of the BR2 core will be to refine the multi-channel and few-channel models by mutual comparison and validation vs. available data in the SAR of the BR2 reactor.

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