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Summary of Comparison and Analysis of Results from Exercises 1 & 2 of the OECD PBMR Coupled Neutronics/Thermal Hydraulics Transient Benchmark

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Abstract

The Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) has accepted, through the Nuclear Science Committee (NSC), the inclusion of the Pebble-Bed Modular Reactor 400 MW design (PBMR-400) coupled neutronics/thermal hydraulics transient benchmark problem as part of their official activities. The scope of the benchmark is to establish a well-defined problem, based on a common given library of cross sections, to compare methods and tools in core simulation and thermal hydraulics analysis with a specific focus on transient events through a set of multi-dimensional computational test problems. The benchmark includes three steady state exercises and six transient exercises. This paper describes the first two steady state exercises, their objectives and the international participation in terms of organization, country and computer code utilized. This description is followed by a comparison and analysis of the participants' results submitted for these two exercises. The comparison of results from different codes allows for an assessment of the sensitivity of a result to the method employed and can thus help to focus the development efforts on the most critical areas. The two first exercises also allow for removing of user-related modeling errors and prepare core neutronics and thermal-hydraulics models of the different codes for the rest of the exercises in the benchmark.

KEYWORDS: Benchmark, PBMR, Computer codes, Comparison

1. Introduction

The Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) has accepted, through the Nuclear Science Committee (NSC), the inclusion of the Pebble-Bed Modular Reactor (PBMR) coupled neutronics/thermal hydraulics transient benchmark problem as part of their official activities. The PBMR is a High-Temperature Gas-Cooled Reactor (HTGR) concept, which has attracted the attention of the nuclear research and development community. The deterministic neutronics, thermal-hydraulics and transient analysis tools and methods available to design and analyze HTGRs have, in many cases, lagged behind the state of the art compared to other reactor technologies. This fact has motivated the testing of existing methods for HTGRs but also the development of more accurate and efficient tools to analyze the neutronics and thermal-hydraulic behavior for the design and safety evaluations of the PBMR. In addition to the development of new methods, it is very important to define appropriate benchmarks to verify and validate the new methods

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in computer codes.

The scope of the benchmark is to establish a well-defined problem, based on a common given set of cross sections, to compare methods and tools in core simulation and thermal hydraulics analysis with a specific focus on transient events through a set of multi-dimensional computational test problems [1]. The benchmark includes three steady state exercises and six transient exercises. The three steady state exercises include a standalone neutronics calculation, a standalone thermal-hydraulic core calculation, and a coupled neutronics/thermal-hydraulic simulation. Six case studies, covering the range from slow to fast neutronic transients, as well as feedback effects from thermal-hydraulic parameters and fission products, are defined in the transient benchmark exercises. The reference design for the PBMR-400 benchmark problem is derived from the PBMR 400 MW Nuclear Power Plant (NPP) design being constructed in South Africa. Several simplifications were made to the design in the benchmark specification in order to limit the need for any further approximations to a minimum. During this process care has been taken to ensure that all the important characteristics of the reactor design were preserved. This ensures that the results from the benchmark will be representative of the actual design's characteristics. The simplifications make the core design essentially two-dimensional (R-Z). More detail on the benchmark and specification can be found in reference [2].

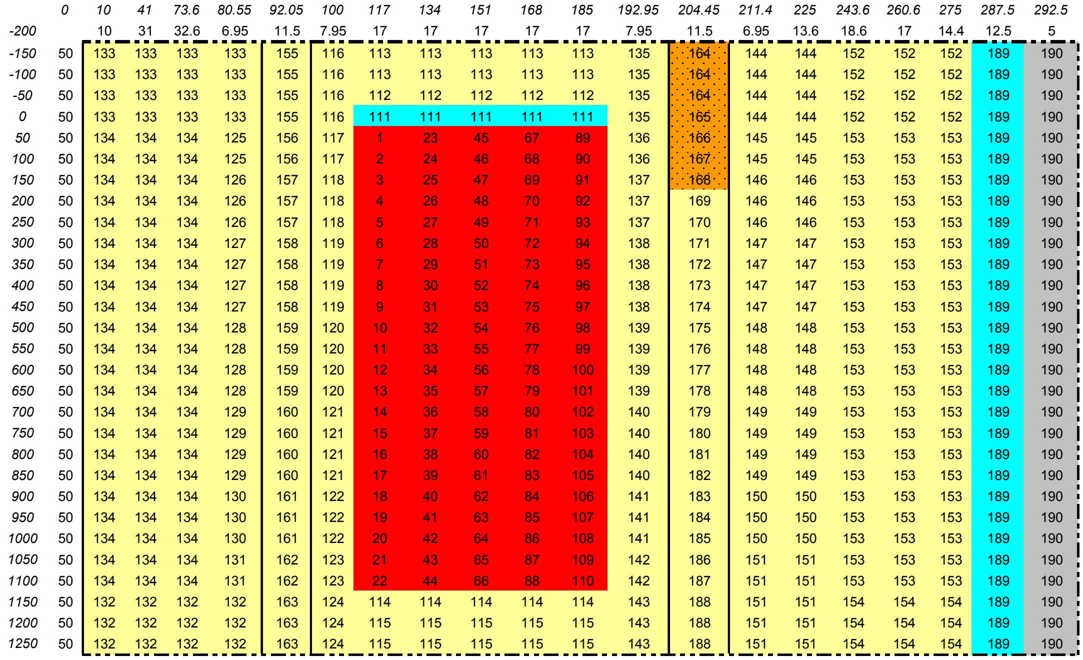
2. Description of Exercise 1

The Exercise 1 is defined as a neutronics solution with fixed cross sections for an equilibrium core in which the reactor operational state is achieved after a considerable time of operating at a specific set of conditions. Operating conditions are defined to be at full power and with the control rods inserted 2.0 m below the bottom of the top reflector (therefore 1.5 m alongside the pebble-bed). Once equilibrium is reached no significant changes can be observed in the properties of the core. For example the k_{eff}, power profile, temperatures and isotopic concentration distribution do no longer change. Participants have to make use of model description, provided in the benchmark specification, and to use the simplified cross section set with no state parameter dependence. In such way no thermal-hydraulic solution is required. The participants are requested to report k_{eff}, two-dimensional (2-D) R-Z power profile, 2-group flux profiles, and core leakage. The calculation mesh has to be determined by each participant, which means that each participant has to obtain spatial mesh converged solution with the utilized code and this solution is submitted to the benchmark team for a comparative analysis.

The benchmark definition provides the macroscopic cross sections required to perform the steady state. The cross-sections are generated making use of the isotopic distribution calculated with VSOP99 [2]. This approach facilitates better and well-defined comparisons but also allows broader participation in the benchmark. The simplified cross section set is generated from the VSOP equilibrium core calculation. The calculation was performed in two energy groups with a thermal cut-off of 3.059eV. In total 190 data sets are included in the library with the materials simply numbered from 1 to 190 as indicated in Figure 1. The 5 flow channels, each with 22 axial regions, make up 110 materials with the balance mainly made up by graphite at different temperatures and with different fine group spectra and therefore different few-group cross sections. The different material numbers correspond with the so-called spectrum regions selected in the VSOP model and can therefore also be used as a first estimate of the mesh to be used to determine state parameters and then reconstruct cross sections on.

Fifteen participants from thirteen organization representing seven countries have submitted results for Exercise 1 as shown in Table 1. The utilized neutronics codes are based mostly on the diffusion theory except EVENT, and the numerical methods vary from finite-difference to finite element (CRONOS2), and nodal techniques (NEM and TOPS). The Idaho National Laboratory (INL) has submitted two sets of results – one with PEBBED and another with NEM, and for each set there are two submitted solutions – with directional dependent diffusion coefficients for void regions (PEBBED-ddc and NEM-ddc) and with one diffusion coefficient for void regions (PEBBED-1dc and NEM-1dc). In the neutronics specification only two “void” regions have been specified, being (i) the 50 cm between the top of the pebble-bed and the bottom of the top reflector (shown as 111 in Figure 1) and (ii) the helium gap between the side reflector and core barrel (shown as 189 in Figure 1). These regions are of course not really void but filled with helium at pressure. In the diffusion calculation directional dependent diffusion coefficients are used to represent the neutron streaming effects. A factor is multiplied to the diffusion coefficient for the R and Z direction, for (i) 0.10068 for R and 0.53660 for the Z direction and for (ii) 0.02149 and 0.66241 respectively. For the annulus use 42.5 cm and for the helium gap use 12.5 cm as the respective diffusion coefficients. The obtained results have indicated that the effect of using directional diffusion coefficients is small and only seen in local distributions around void regions.

Figure 1: Exercise 1 - PBMR Core Neutronics Model



	0	*10*	*41*	*73.6*	*80.55*	*92.05*	*100*	*117*	*134*	*151*	*168*	*185*	*192.95*	*204.45*	*211.4*	*225*	*243.6*	*260.6*	*275*	*287.5*	*292.5*
-200		10	31	32.6	6.95	11.5	7.95	17	17	17	17	17	7.95	11.5	6.95	13.6	18.6	17	14.4	12.5	5
-150	50	133	133	133	133	155	116	113	113	113	113	113	135	164	144	144	152	152	152	189	190
-100	50	133	133	133	133	155	116	113	113	113	113	113	135	164	144	144	152	152	152	189	190
-50	50	133	133	133	133	155	116	112	112	112	112	112	135	164	144	144	152	152	152	189	190
0	50	133	133	133	133	155	116	111	111	111	111	111	135	165	144	144	152	152	152	189	190
50	50	134	134	134	125	156	117	1	23	45	67	89	136	166	145	145	153	153	153	189	190
100	50	134	134	134	125	156	117	2	24	46	68	90	136	167	145	145	153	153	153	189	190
150	50	134	134	134	126	157	118	3	25	47	69	91	137	168	146	146	153	153	153	189	190
200	50	134	134	134	126	157	118	4	26	48	70	92	137	169	146	146	153	153	153	189	190
250	50	134	134	134	126	157	118	5	27	49	71	93	137	170	146	146	153	153	153	189	190
300	50	134	134	134	127	158	119	6	28	50	72	94	138	171	147	147	153	153	153	189	190
350	50	134	134	134	127	158	119	7	29	51	73	95	138	172	147	147	153	153	153	189	190
400	50	134	134	134	127	158	119	8	30	52	74	96	138	173	147	147	153	153	153	189	190
450	50	134	134	134	127	158	119	9	31	53	75	97	138	174	147	147	153	153	153	189	190
500	50	134	134	134	128	159	120	10	32	54	76	98	139	175	148	148	153	153	153	189	190
550	50	134	134	134	128	159	120	11	33	55	77	99	139	176	148	148	153	153	153	189	190
600	50	134	134	134	128	159	120	12	34	56	78	100	139	177	148	148	153	153	153	189	190
650	50	134	134	134	128	159	120	13	35	57	79	101	139	178	148	148	153	153	153	189	190
700	50	134	134	134	129	160	121	14	36	58	80	102	140	179	149	149	153	153	153	189	190
750	50	134	134	134	129	160	121	15	37	59	81	103	140	180	149	149	153	153	153	189	190
800	50	134	134	134	129	160	121	16	38	60	82	104	140	181	149	149	153	153	153	189	190
850	50	134	134	134	129	160	121	17	39	61	83	105	140	182	149	149	153	153	153	189	190
900	50	134	134	134	130	161	122	18	40	62	84	106	141	183	150	150	153	153	153	189	190
950	50	134	134	134	130	161	122	19	41	63	85	107	141	184	150	150	153	153	153	189	190
1000	50	134	134	134	130	161	122	20	42	64	86	108	141	185	150	150	153	153	153	189	190
1050	50	134	134	134	131	162	123	21	43	65	87	109	142	186	151	151	153	153	153	189	190
1100	50	134	134	134	131	162	123	22	44	66	88	110	142	187	151	151	153	153	153	189	190
1150	50	132	132	132	132	163	124	114	114	114	114	114	143	188	151	151	154	154	154	189	190
1200	50	132	132	132	132	163	124	115	115	115	115	115	143	188	151	151	154	154	154	189	190
1250	50	132	132	132	132	163	124	115	115	115	115	115	143	188	151	151	154	154	154	189	190

3. Description of Exercise 2

The Exercise 2 is defined as a thermal-hydraulic solution with given power / heat sources. The participants have to make use of the thermal hydraulic properties and model description provided in the benchmark specification. The participants are required to utilize the provided power / heat source density distribution as given in Table 2. The values correspond to core regions 1 – 110 as used in Exercise 1 (see Figure 1). The participants have to assume fresh fuel Zehner-Schlünder pebble bed effective thermal conductivities.

Participants are requested to calculate the temperatures distribution, outlet temperature, pressure drop over the core and heat loss to the constant temperature boundary. The calculation mesh is to be determined by each participant.

Eight participants from 9 organizations representing six countries have submitted their results for Exercise 2 as shown in Table 3. Most of the codes utilize different versions of THERMIX [3] with exception of MARS and WIMS.

Table 1: International Participation in Exercise 1

#	Organization	Country	Code
1	Delft University	Netherlands	DALTON
2	Delft University/Georgia Tech	Netherlands, USA	EVENT
3	KAERI	Korea	rz 2D FDM
4	KAERI	Korea	MASTER
5	KAIST	Korea	TOPS
6	PBMR	South Africa	TINTE
7	PSU	USA	NEM
8	INL	USA	PEBBED
9	INL	USA	NEM
10	Purdue University	USA	PARCS
11	Serco Assurance	UK	WIMS
12	NECSA	South Africa	MGRAC (OSCAR-4)
13	PBMR	South Africa	VSOP99/3
14	Stuttgart University-IKE	Germany	ZIRKUS
15	CEA/EDF	France	CRONOS2

4. Comparison and Analysis of Results

4.1 Exercise 1

The requested output includes global parameters such as k_{eff}, leakage from the core / fuel region and out of the system (neutronics domain). Two-dimensional maps, reported by the participants, contain relative power distribution and 2-group neutron flux distributions. This data was reduced by radially averaging for axial power distribution and axially averaging for radial distribution. Selected reduced results are presented below in Figures 2 through 5. Please note that in these comparisons the different sets of results are presented by the name of the utilized code. The reason for such representation is the fact that several participants have submitted multiple solutions obtained with different codes. The one-dimensional averaging smoothens the differences in the results obtained by different participants. Hence a good agreement is observed in the axial and the radial power and flux distributions. More differences were observed in the 2-D distribution comparisons of the results. Please note the differences in the axial power and fast flux distributions (Figures 2 and 4) in the top region of the core where the void region between the top of the pebble-bed and the bottom of the top reflector is located. These differences reflect the different modeling of neutron streaming in the void region in the participants' cdes as discussed in Section 2 of this paper.

Table 2: Heat Sources (W/cm^3) for Fuel Meshes

#	Region 1-22	Region 23-44	Region 45-66	Region 67-88	Region 89-110
1	2.570	2.040	1.753	1.529	1.371
2	4.320	3.449	2.968	2.590	2.328
3	6.266	5.113	4.512	4.080	3.841
4	8.221	6.911	6.337	6.123	6.517
5	9.721	8.353	7.806	7.716	8.390
6	10.491	9.155	8.612	8.541	9.234
7	10.547	9.330	8.808	8.732	9.350
8	10.075	9.022	8.542	8.458	8.967
9	9.275	8.398	7.970	7.881	8.280
10	8.318	7.600	7.227	7.138	7.441
11	7.304	6.729	6.411	6.325	6.546
12	6.315	5.860	5.592	5.512	5.669
13	5.400	5.041	4.817	4.744	4.854
14	4.581	4.298	4.112	4.046	4.122
15	3.859	3.636	3.482	3.425	3.475
16	3.232	3.056	2.929	2.879	2.912
17	2.690	2.552	2.448	2.404	2.425
18	2.222	2.113	2.029	1.992	2.004
19	1.815	1.730	1.662	1.631	1.638
20	1.457	1.391	1.336	1.311	1.314
21	1.136	1.087	1.045	1.024	1.023
22	0.872	0.855	0.827	0.799	0.775
Volumes of each region (all 22 axial regions the same height) given for the five rows					
	5.795E+05	6.703E+05	7.611E+05	8.518E+05	9.426E+05

4.2 Exercise 2

The requested output for Exercise includes integral parameters such as inlet / outlet pressure, inlet / outlet temperatures, total helium mass flow rate, average fuel temperature, average moderator temperature, and average helium temperature. In addition profiles (24 radial x 36 axial meshes) must be used to represent all the appropriate (2-D) results. These 2-D results contain temperatures such as fuel (Doppler), moderator (graphite), coolant (helium), pebble surface, and maximum fuel as well as pressure differences, and mass flow rate maps (separated in radial and axial directions).

In addition local (detail) results are also requested including pebble-bed effective thermal conductivity (from Zehner-Schlünder for example), fuel sphere surface temperatures, and temperature profiles within fuel spheres. Participants reported data according to the templates provided by the benchmark team. Comparison of single-value results was conducted using statistical methodology – see Figure 7. The 2-D data was reduced by radially-averaging for axial distributions and axially-averaging for radial distributions for a better graphical representation. Selected results are shown in Figures 6, 8 and 9. Agreement was observed in the radially-averaged axial data between the codes.

Differences were more pronounced in the axially-averaged radial data. In the actual 2-D distributions more pronounced deviations can be observed. The observed differences could be attributed to user-related modeling differences and interpretation of some submitted parameters.

Table 3: International Participation in Exercise 2

#	Organization	Country	Code
1	PBMR	South Africa	VSOP99/3
2	PBMR	South Africa	TINTE
3	Stuttgart University-IKE	Germany	THERMIX-KONVEK
4	PSU/INL	USA.	THERMIX-DIREKT
5	KAERI	Korea	MARS
6	Delft University/Georgia Tech	Netherlands, USA	THERMIX
7	Purdue University	USA	THERMIX-DIREKT
8	Serco Assurance	UK	WIMS

Figure 2: Comparison of Core Average Axial Power Distribution

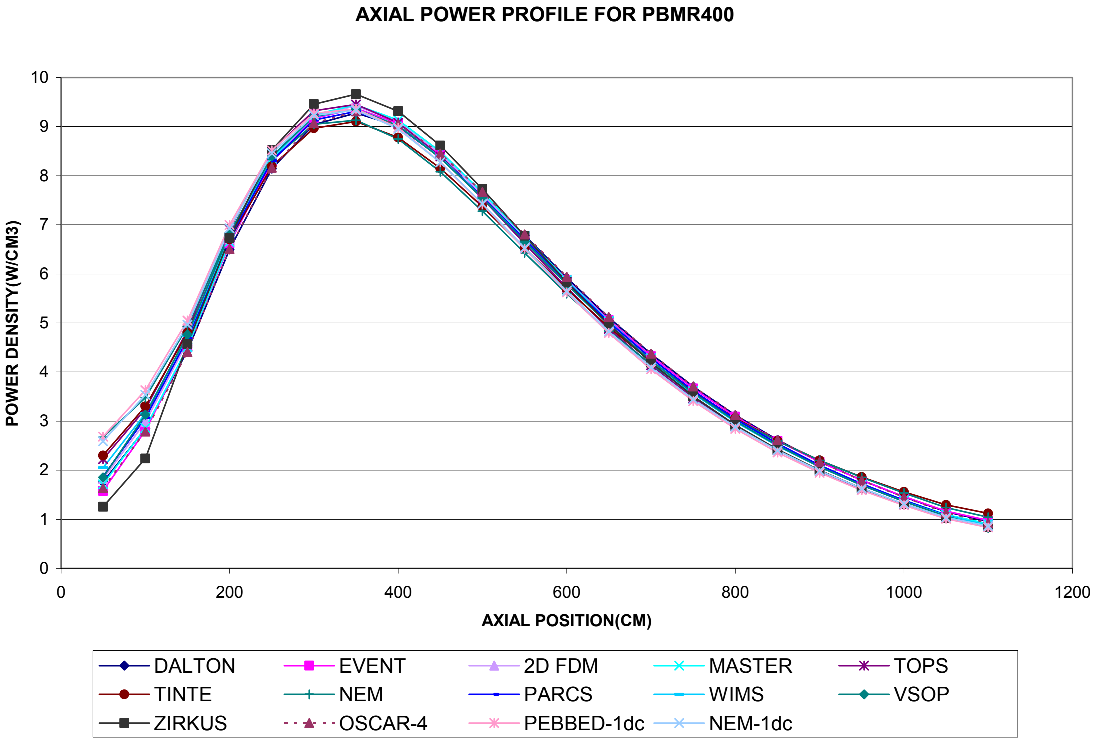


Figure 3: Comparison of Core Average Radial Power Distribution

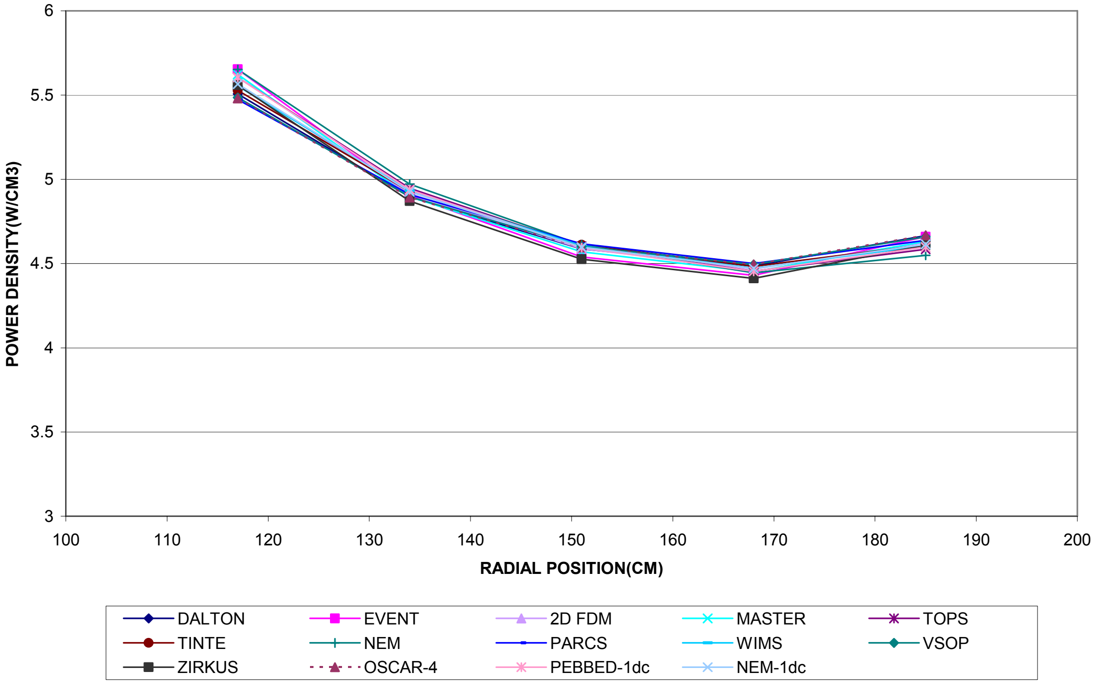


Figure 4: Comparison of Core Average Axial Fast Flux Distribution

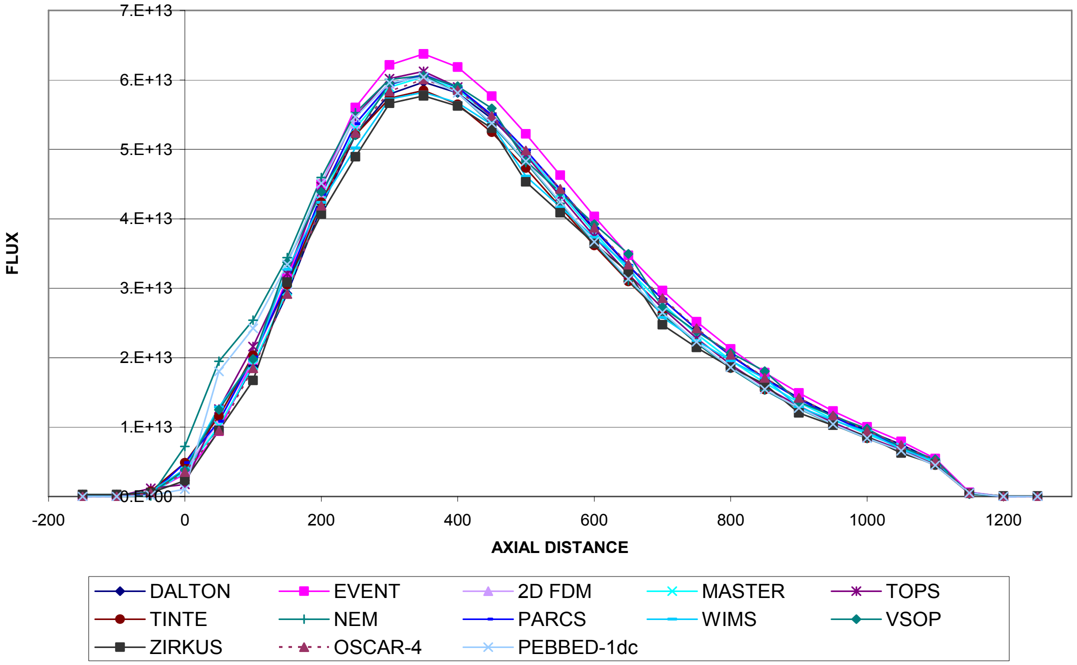


Figure 5: Comparison of Core Average Radial Fast Flux Distribution

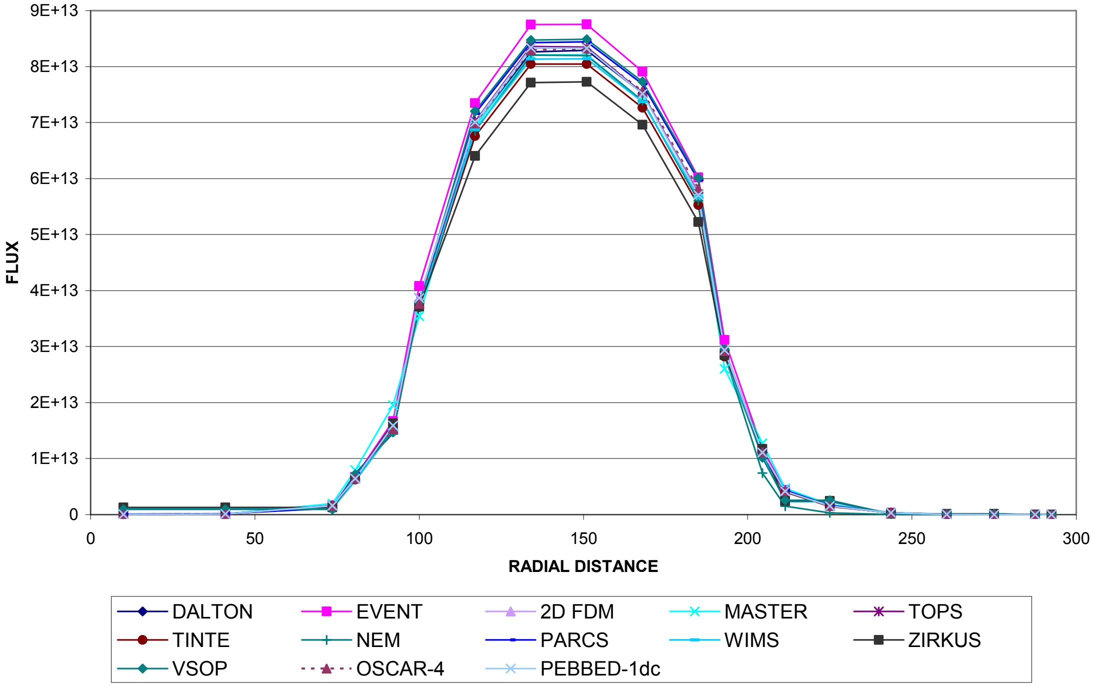


Figure 6: Comparison of Average Axial Coolant Temperature Distribution

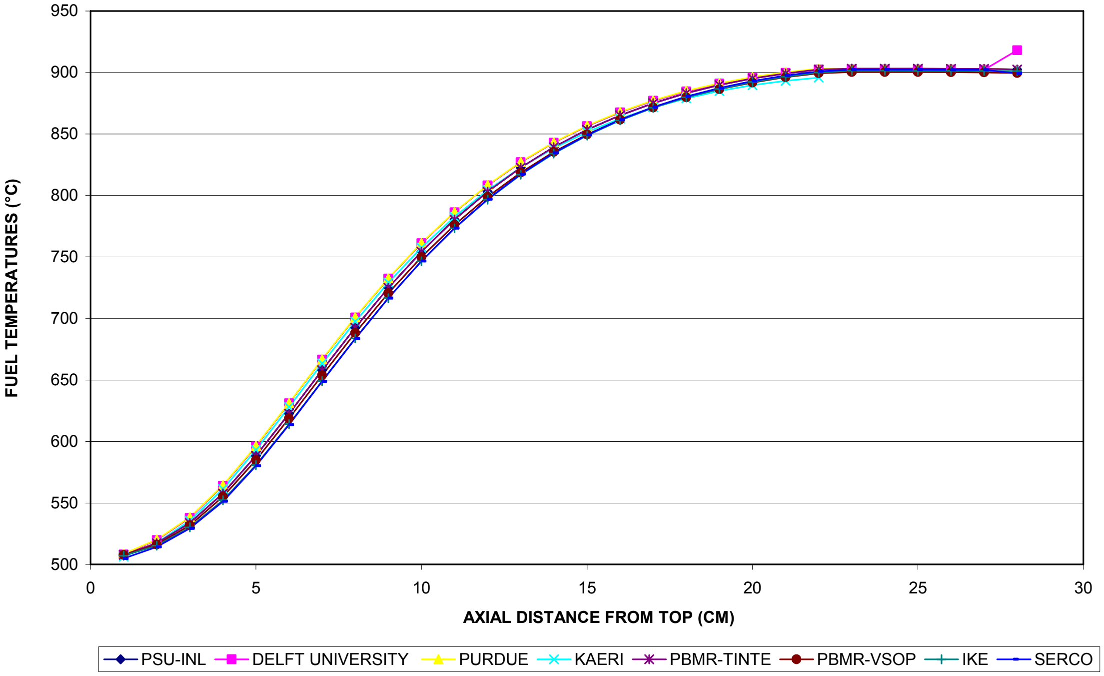


Figure 7: Comparison of Average Moderator Temperature

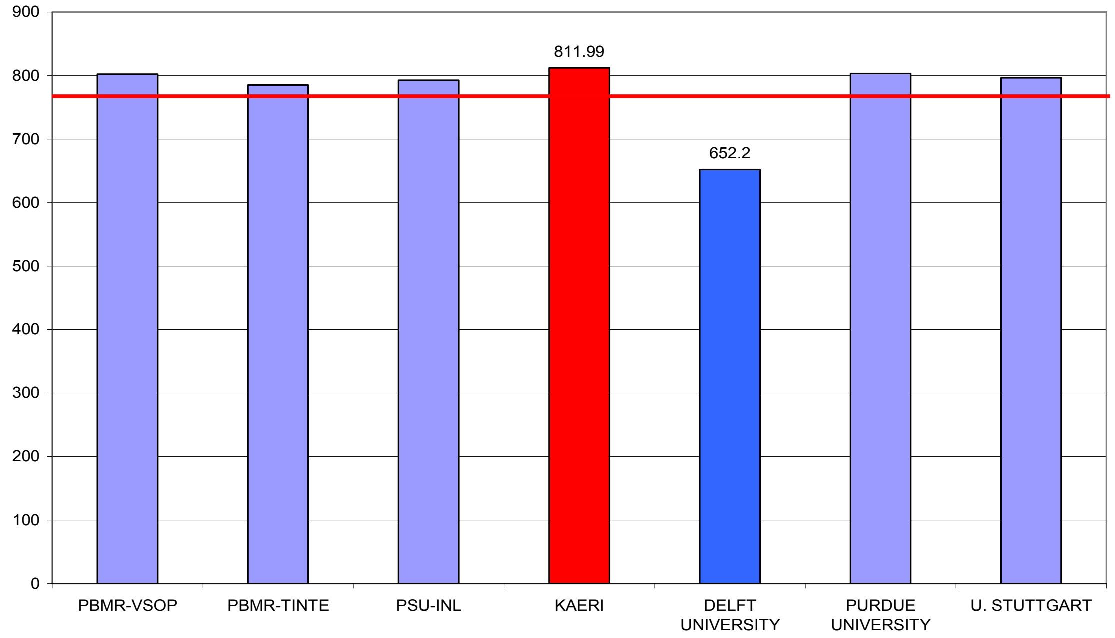


Figure 8: Comparison of Core Average Radial Fuel Temperature Distribution

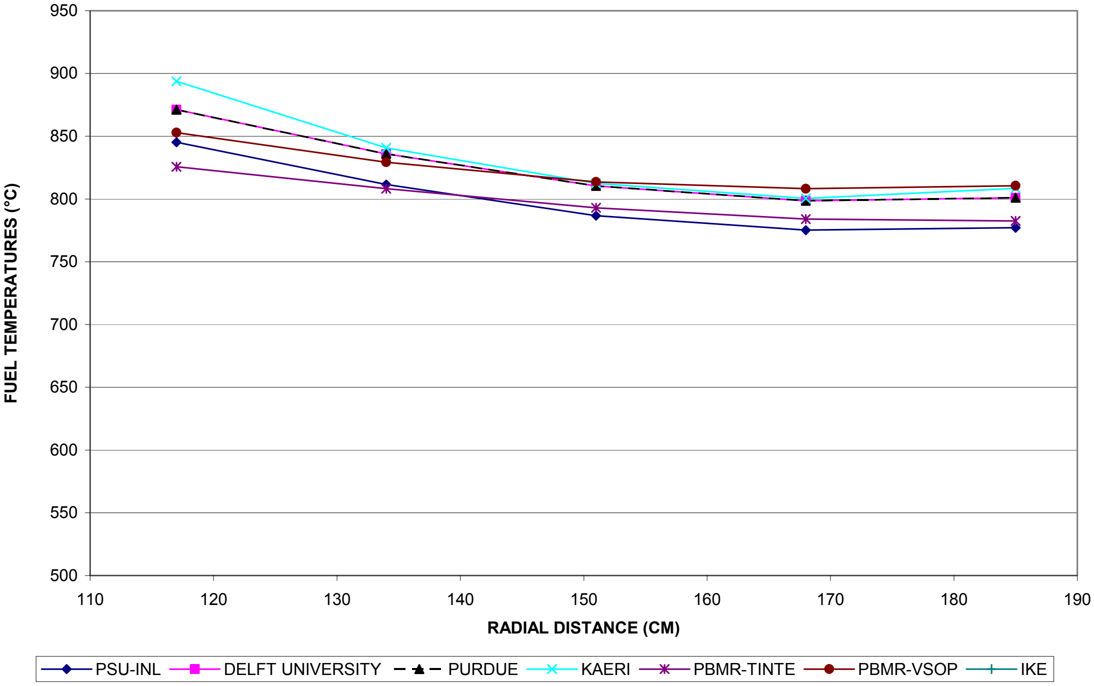
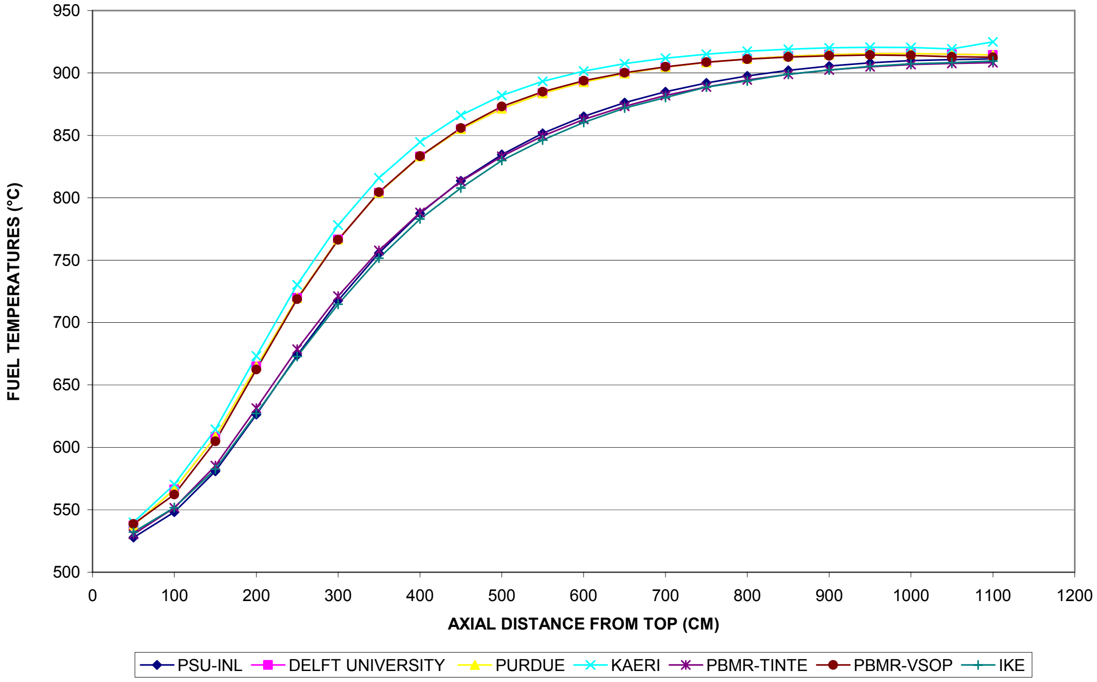


Figure 9: Comparison of Core Average Axial Fuel Temperature Distribution



5. Conclusion and Outlook

Based on the comparative analysis performed on the results submitted for Exercises 1 and 2 of the OECD PBMR-400 benchmark it can be concluded that there is a fair agreement in the modeling of the PBMR by the participating codes in these exercises. The difference in the actual parameters could be attributed to the different methods used by the codes, different interpretations of some submitted parameters by the participants, and still user-related modeling differences.

The comparison of results from different codes allows for an assessment of the sensitivity of a result to the method employed and can thus help focus development efforts on the most critical areas. The two first exercises also allow for removing of user-related modeling errors and prepare core neutronics and thermal-hydraulics models of the different codes for the rest of the exercises in the benchmark.

References

1) F. Reitsma, et al, “ PBMR-400 Coupled Neutronics/Thermal-Hydraulics Transient Benchmark . Volume 1 – Specifications”, NEA/NSC/DOC (2005)
2) F. Reitsma, K. Ivanov, T. Downar, H. de Haas, H.D. Gougar, ”The OECD/NEA/NSC PBMR Coupled Neutronics/Thermal Hydraulics Transient Benchmark: The PBMR-400 Core Design,” (To be published) Proceedings of PHYSOR 2006, Vancouver, BC, Canada, September 10-14, 2006.
3) H. J. Rütten, K. A. Haas, ‘V.S.O.P. (99/3) – Input Description’, Internal document, Institut für Sicherheitsforschung und Reaktortechnik (ISR), Forschungszentrum Jülich, 2003.
4) S. Struth., “THERMIX-DIREKT – A Computer Programme for non-steady, two-dimensional simulation of thermo-hydraulic transients,” Kernforschunsanslage Jülich, JÜL-1702, March 1999.