



**PBMR COUPLED NEUTRONICS/THERMAL  
HYDRAULICS TRANSIENT BENCHMARK  
THE PBMR-400 CORE DESIGN**



Prepared by PBMR-400  
Benchmark Chairman  
Frederik Reitsma

**Status and Feedback as on 25 January 2008**



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# Overview



- Background & Motivation
- The benchmark problem
- Meetings and participation
- Most important outcomes
- Conclusions & Future activities



# Background & Motivation



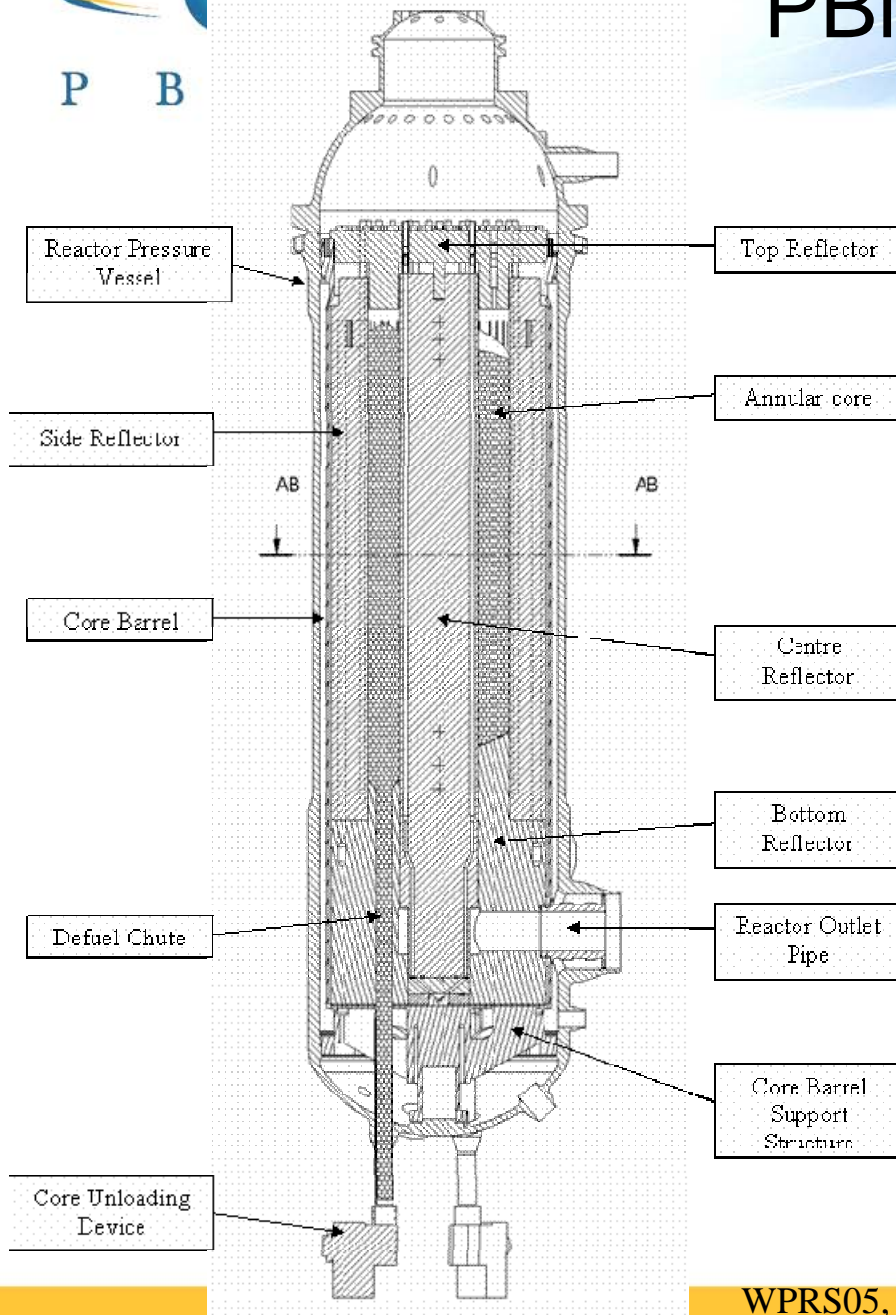
- A need for code-to-code benchmarking
  - Efforts to V&V legacy codes (VSOP, TINTE, RZKIND, ZIRKUS, THERMIX etc)
  - Unique design of PBMR with dynamic central column
  - IAEA CRP5 to be finalised in 2008 – limited focus on pebble-bed transients (steady-state and transient results of HTR-10 show large differences, general behaviour ok)
- This scope of the benchmark exercise 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
  - specific focus on transient events through a set of multi-dimensional computational test problems.
- In addition the benchmark exercise has the following objectives:
  - Establish a standard benchmark for coupled codes (neutronics/thermal-hydraulics) for PBMR design.
  - Code to code comparison using a common cross section library – important for Verification and Validation.
  - Obtain a detailed understanding of the events and the processes.
  - Benefit from different approaches, understanding limitations and approximations.
  - Organize special session at conference/special issue of publication (good exposure)
    - Special session held at PHYSOR-2006
    - Special session planned at PHYSOR2008 (~9 extended abstracts submitted)

# PBMR core design



## Main Characteristics:

- annular core of 3.7 m
- 'fixed central reflector' of 2 m,
- an effective cylindrical core height of 11 m,
- a graphite side reflector of ~90 cm,
- 24 partial length control rod positions in the side reflector as the reactivity control system (RCS)
- eight Small Absorber Sphere (SAS) systems positioned in the fixed central reflector as the Reserve Shutdown System (RSS)
  - filled with 1 cm diameter absorber spheres containing B4C when required,
- three fuel loading positions and three fuel unloading tubes
- core contains ~ 452,000 fuel spheres
- uranium loading is 9 g per fuel-sphere
- U235 enrichment at 9.6 wt%.





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# Benchmark Core layout - neutronics



	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	310	328	462	463	
-235	10	31	32.6	6.95	11.5	7.95	17	17	17	17	17	17	7.95	11.5	6.95	13.6	18.6	17	14.4	12.5	5	17.5	18	134	1	
-200	35	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP	TP
-150	50	CC	CC	CC	CC	RSS	CC	TR	TR	TR	TR	TR	SR	RCS	SR	SR	SR	SR	SR	SR	He	CB	He	RPV	Air	RCCS
-100	50	CC	CC	CC	CC	RSS	CC	TR	TR	TR	TR	TR	SR	RCS	SR	SR	SR	SR	SR	SR	He	CB	He	RPV	Air	RCCS
-50	50	CC	CC	CC	CC	RSS	CC	TR	TR	TR	TR	TR	SR	RCS	SR	SR	SR	SR	SR	SR	He	CB	He	RPV	Air	RCCS
0	50	CC	CC	CC	CC	RSS	CC	V	V	V	V	V	SR	RCS	SR	SR	SR	SR	SR	SR	He	CB	He	RPV	Air	RCCS
50	50	CC	CC	CC	CC	RSS	CC	F	F	F	F	F	IP	RCS	IP	IP	IP	RC	RC	SR	He	CB	He	RPV	Air	RCCS
100	50	CC	CC	CC	CC	RSS	CC	F	F	F	F	F	SR	RCS	SR	SR	SR	RC	RC	SR	He	CB	He	RPV	Air	RCCS
150	50	CC	CC	CC	CC	RSS	CC	F	F	F	F	F	SR	RCS	SR	SR	SR	RC	RC	SR	He	CB	He	RPV	Air	RCCS
200	50	CC	CC	CC	CC	RSS	CC	F	F	F	F	F	SR	RCS	SR	SR	SR	RC	RC	SR	He	CB	He	RPV	Air	RCCS
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350	50	CC	CC	CC	CC	RSS	CC	F	F	F	F	F	SR	RCS	SR	SR	SR	RC	RC	SR	He	CB	He	RPV	Air	RCCS
400	50	CC	CC	CC	CC	RSS	CC	F	F	F	F	F	SR	RCS	SR	SR	SR	RC	RC	SR	He	CB	He	RPV	Air	RCCS
450	50	CC	CC	CC	CC	RSS	CC	F	F	F	F	F	SR	RCS	SR	SR	SR	RC	RC	SR	He	CB	He	RPV	Air	RCCS
500	50	CC	CC	CC	CC	RSS	CC	F	F	F	F	F	SR	RCS	SR	SR	SR	RC	RC	SR	He	CB	He	RPV	Air	RCCS
550	50	CC	CC	CC	CC	RSS	CC	F	F	F	F	F	SR	RCS	SR	SR	SR	RC	RC	SR	He	CB	He	RPV	Air	RCCS
600	50	CC	CC	CC	CC	RSS	CC	F	F	F	F	F	SR	RCS	SR	SR	SR	RC	RC	SR	He	CB	He	RPV	Air	RCCS
650	50	CC	CC	CC	CC	RSS	CC	F	F	F	F	F	SR	RCS	SR	SR	SR	RC	RC	SR	He	CB	He	RPV	Air	RCCS
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850	50	CC	CC	CC	CC	RSS	CC	F	F	F	F	F	SR	RCS	SR	SR	SR	RC	RC	SR	He	CB	He	RPV	Air	RCCS
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950	50	CC	CC	CC	CC	RSS	CC	F	F	F	F	F	SR	RCS	SR	SR	SR	RC	RC	SR	He	CB	He	RPV	Air	RCCS
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1050	50	CC	CC	CC	CC	RSS	CC	F	F	F	F	F	SR	RCS	SR	SR	SR	RC	RC	SR	He	CB	He	RPV	Air	RCCS
1100	50	CC	CC	CC	CC	RSS	CC	F	F	F	F	F	SR	RCS	SR	SR	SR	RC	RC	SR	He	CB	He	RPV	Air	RCCS
1150	50	CC	CC	CC	CC	RSS	CC	BR	BR	BR	BR	BR	SR	RCS	SR	SR	SR	RC	RC	SR	He	CB	He	RPV	Air	RCCS
1200	50	CC	CC	CC	CC	RSS	CC	BR	BR	BR	BR	BR	SR	RCS	SR	SR	SR	RC	RC	SR	He	CB	He	RPV	Air	RCCS
1250	50	CC	CC	CC	CC	RSS	CC	BR	BR	BR	BR	BR	SR	RCS	SR	SR	SR	RC	RC	SR	He	CB	He	RPV	Air	RCCS
1300	50	CC	CC	CC	CC	CC	CC	BR	BR	BR	BR	BR	SR	SR	SR	SR	SR	IP	IP	SR	He	CB	He	RPV	Air	RCCS
1350	50	CC	CC	CC	CC	CC	CC	BR	BR	BR	BR	BR	SR	SR	SR	SR	SR	SR	SR	SR	He	CB	He	RPV	Air	RCCS
1400	50	CC	CC	CC	CC	CC	CC	OP	OP	OP	OP	OP	SR	SR	SR	SR	SR	SR	SR	SR	He	CB	He	RPV	Air	RCCS
1450	50	CC	CC	CC	CC	CC	CC	BR	BR	BR	BR	BR	SR	SR	SR	SR	SR	SR	SR	SR	He	CB	He	RPV	Air	RCCS
1500	50	CC	CC	CC	CC	CC	CC	BR	BR	BR	BR	BR	SR	SR	SR	SR	SR	SR	SR	SR	He	CB	He	RPV	Air	RCCS
1535	35	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP	BP



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# Benchmark Core layout – Thermal Hydraulics / Material definition



	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	310	328	462	463			
-235	10	31	32.6	6.95	11.5	7.95	17	17	17	17	17	17	7.95	11.5	6.95	13.6	18.6	17	14.4	12.5	5	17.5	18	134	1			
-200	35	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	11	12	13	19			
-150	50	5	5	5	5	5	5	3	3	3	3	3	4	4	4	4	4	4	4	4	9	10	11	12	13	19		
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150	50	5	5	5	5	5	5	1	1	1	1	1	4	4	4	4	4	4	4	4	15	4	9	10	11	12	13	19
200	50	5	5	5	5	5	5	1	1	1	1	1	4	4	4	4	4	4	4	4	15	4	9	10	11	12	13	19
250	50	5	5	5	5	5	5	1	1	1	1	1	4	4	4	4	4	4	4	4	15	4	9	10	11	12	13	19
300	50	5	5	5	5	5	5	1	1	1	1	1	4	4	4	4	4	4	4	4	15	4	9	10	11	12	13	19
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400	50	5	5	5	5	5	5	1	1	1	1	1	4	4	4	4	4	4	4	4	15	4	9	10	11	12	13	19
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500	50	5	5	5	5	5	5	1	1	1	1	1	4	4	4	4	4	4	4	4	15	4	9	10	11	12	13	19
550	50	5	5	5	5	5	5	1	1	1	1	1	4	4	4	4	4	4	4	4	15	4	9	10	11	12	13	19
600	50	5	5	5	5	5	5	1	1	1	1	1	4	4	4	4	4	4	4	4	15	4	9	10	11	12	13	19
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1400	50	5	5	5	5	5	5	18	18	18	18	18	4	4	4	4	4	4	4	4	9	10	11	12	13	19		
1450	50	5	5	5	5	5	5	6	6	6	6	6	4	4	4	4	4	4	4	4	9	10	11	12	13	19		
1500	50	5	5	5	5	5	5	6	6	6	6	6	4	4	4	4	4	4	4	4	9	10	11	12	13	19		
1535	35	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	11	12	13	19		



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# Benchmark assumptions I



- Rules followed
  - limit further approximations to a minimum
  - preserve all important characteristics
  - ensures representative results from the benchmark
- Simplifications
  - the core design is essentially two-dimensional (r,z)
    - flattening of the pebble bed's upper surface
    - removal of the bottom cone and de-fuel channel - flat bottom reflector
    - fuel flow channels assumed to be parallel and at equal speed
    - control rods are modelled as a cylindrical skirt (also referred to as a grey curtain) with a given B-10 concentration
  - only one of the transient cases, the single control rod ejection event, requires a three-dimensional model (allow more participants); boron concentration for the specific mesh are defined
  - Thermal hydraulics
    - simplified coolant flow (main engineered flow paths)
    - no reflector cooling or leakage paths defined
    - all heat sources (from fission) are deposited locally
    - simplified material thermal properties - constant values or specific correlations are employed.



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# Benchmark assumptions II



- Cross section libraries supplied
  - Same approach used in LWR / VVER transient benchmarks
  - Linear interpolation routines supplied
  - 2-group macroscopic cross section as function of 5 state parameters
    - fuel and moderator temperatures,
    - xenon concentration,
    - fast and thermal leakages (buckling terms)
- Decay heat
  - values provided as determined from the DIN 25485 standard
  - decay heat is supplied in a form of a lookup table with (log-log) linear interpolation similar to the cross sections
  - Assume decay heat distribution based on power profile at time of the start of the event (steady state solution)



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# Test Cases



- Steady state cases
  - Exercise 1: Neutronics Solution with Fixed Cross Sections
  - Exercise 2: Thermal Hydraulic solution with given power / heat sources
  - Exercise 3: Combined neutronics thermal hydraulics calculation – starting condition for the transients
- Transient cases
  - Exercise 1: DLOFC without SCRAM
  - Exercise 2 : DLOFC with SCRAM
  - Exercise 3 : PLOFC with SCRAM
  - Exercise 4 : 100-40-100 Load Follow
  - Exercise 5 : Reactivity Insertions by CRW and CRE
  - Exercise 6 : Cold Helium Inlet



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# Activity summary



- **PBMRT1: 16-17 June 2005**
  - 26 participants from 12 countries and 20 organizations
  - Benchmark definition and introduction
  - (NEA/NSC/DOC(2005)3; NEA/NSC/DOC(2005)13)
- **PBMRT1.5: Ad-hoc meeting at M&C2005, Avignon**
  - Lunchtime meeting 13 September 2005, 20 participants from 9 countries
- **PBMRT2: 26-27 January 2006**
  - 25 participants from 7 countries and 16 organizations
  - Results from Steady-State cases 1 & 2 compared
  - Cross section library generation problems with MICROX-2, alternative proposed
  - (NEA/NSC/DOC(2005)32; NEA/NSC/DOC(2006)29)
- **Physor-2006: 14 September 2006, Vancouver, Canada**
  - Special session on OECD PBMR400 Benchmark
  - 5 presentations focussed on the benchmark and other related papers in other sessions
  - Focus on Steady state results and codes / methods employed
- **PBMRT3: 1-2 February 2007**
  - 20 participants from 8 countries and 14 organizations
  - Finalisation of Steady-state comparisons for Case 1&2
  - Detailed comparison of Steady state Case 3 (with updated library)
  - First results for transient cases
  - Finalization of specification (published on web in June 2007)
  - (NEA/NSC/DOC(2006)30 and NEA/NSC/DOC(2007)11)



# Activity summary



- PBMRT4: 21 – 25 January 2008
  - 18 participants from 8 countries and 11 organizations
  - PART I - DIREKT workshop
    - Code background
    - Steady-state and Transient Test cases studied (PBMR 265 MW core design)
    - OECD PBMR 400MW Test case 2 created
    - Interest could lead to wider application of code and cooperation
  - PART 2 – OECD Benchmark Analysis
    - Feedback on developments and analysis from participants
    - Updated Steady-state comparisons and discussions
    - Detailed transient case comparisons
    - (NEA/NSC/DOC(2007)24) and summary to be published end of February



# PHYSOR2008 Special Session Planned



- Combined papers on Benchmark Status:
  - **The OECD/NEA/NSC PBMR400 MW coupled neutronics thermal hydraulics transient benchmark – Definition and Status.**, Frederik Reitsma, Kostadin Ivanov, and Enrico Sartori
  - **Comparison and Analysis of Results of the OECD PBMR Coupled Neutronics/Thermal Hydraulics Transient Benchmark**, James Han, Kostadin Ivanov, Frederik Reitsma, E. Sartori  
(These two papers to be combined on request of the organizers)
- Other submissions:
  - **DORT-TD/THERMIX solutions for the OECD/NEA/NSC PBMR400 MW coupled neutronics thermal hydraulics transient benchmark.**, Bismark Tyobeka, Andreas Pautz, Kostadin Ivanov
  - **Application of Time-Dependent Neutron Transport Theory to High-Temperature Reactors of Pebble Bed Type**, Andreas Pautz, Bismark Tyobeka, Kostadin Ivanov
  - **Coupled neutronics / thermal hydraulics calculations for High Temperature Reactors with the DALTON - THERMIX code system**, B. Boer, D. Lathouwers , M. Ding , J.L. Kloosterman
  - **Cross Section Representation options for HTR Transient Analysis Tested on the OECD PBMR 400MW Transient Benchmark**, Frederik Reitsma, Ivor Clifford, Gerhard Strydom
  - **A QUASI-REGRESSION METHOD FOR AUTOMATED CROSS-SECTION PARAMETERIZATION: PBMR BENCHMARK EXAMPLE**, Pavel M. Bokov, Rian Prinsloo, Djordje I. Tomasević, Frederik Reitsma
  - **SPECTRAL ZONES SELECTION METHODOLOGY FOR PEBBLE BED REACTORS**, Ramatsemela Mphahlele, Abderrafi Ougouag, Hans Gougar, Kostadin Ivanov
  - **DLOFC TRANSIENT ANALYSIS FOR PBMR WITH NEM/ THERMIXNEM-THERMIX**, P.T. Mkhabela, J. Hana K. Ivanov
  - Others moved from other sessions (Paper on PARCS)
  - Final confirmation of paper acceptance only 31 January 2008



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## Conclusions & Future work



- Benchmark definition is final and no changes will be made
- Successful workshops well attended with very stimulating discussions
- Wide variety of codes and methods are applied
- Decision to publish only one report (and not a separate specification)
  
- Next and final workshop planned for September 2008, PHYSOR 2008
  
- Major deadlines
  - Finalisation of results and submissions (30 April 2008)
  - Final date for comparisons (15 June 2008)
  - Drafted report for discussion at meeting (15 August 2008)
  - Final meeting (14 September 2008)
  - Report submitted to OECD / NEA (Dec 2008/ Jan 2009)
  - Published report (March / April 2009)
  
- A special Journal issue containing all the detailed submissions of the OECD PBMR 400MW Transient Benchmark Exercise will be pursued in 2009 (as a final detailed summary of all the related work)

