

# Monte Carlo Benchmark Calculations for 400MW<sub>TH</sub> PBMR CORE

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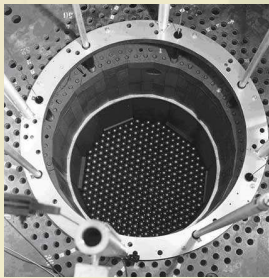
## Background and Goal

- ♣ Pebble-bed and other VHTR designs are in vogue in connection with hydrogen production.
- ♣ In Korea, a computational code system is under development for the VHTR core analysis.
- ♣ It needs to validate a computer code for VHTR core analysis which will be developed in future.
- ♣ Monte Carlo analysis of the VHTR core is useful and thus necessary for the code benchmark.

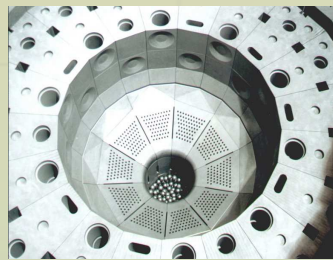


- ♣ Monte Carlo Analysis of Pebble-type VHTR core (Computation Code: MCNP5)

Previous Study



HTR-PROTEUS (Swiss)  
- Zero Power Reactor



HTR-10 (China)  
- Thermal Power Reactor

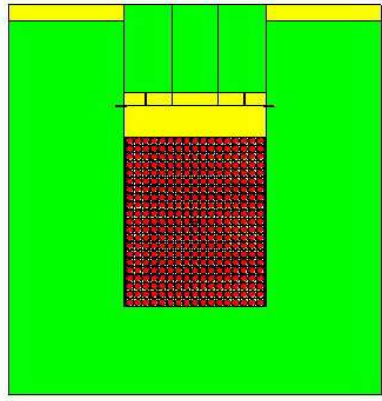


This Study

PBMR (South Africa)  
- Commercial Reactor

## Previous Study

### HTR-PROTEUS (Swiss)



<MCNP Modeling Result>

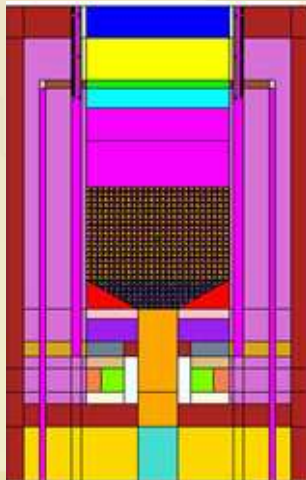
Criticality

TRISO Homogeneity Effect

Control Rod Worth

Shutdown Rod Worth

### HTR-10 (China)



<MCNP Modeling Result>

IAEA CRP Benchmark Problem

Initial Critical Height

Temperature Effect

Control Rod Worth

# Previous Study

## HTR-10 Benchmark Problem 1

- B1: **The height** of critical core above the conus region is expected to be determined under the helium atmosphere and at **20 °C without any control rod insertion.**

Critical Height [cm]	100	110	120	130	140	150	160	170	180
K-eff	0.91014± 0.00059	0.94899± 0.00068	<b>0.98436±</b> <b>0.00068</b>	<b>1.01641±0</b> <b>.00060</b>	1.04182± 0.00068	1.06844± 0.00063	1.08687± 0.00066	1.10920± 0.00069	1.12640± 0.00062
Fuel Ball No.	7963.7	8598.3	<b>9236.7</b>	<b>10216.0</b>	11065.4	11657.8	12385.0	13418.9	14137.8
Fuel Ball Ratio	0.58	0.57	<b>0.56</b>	<b>0.57</b>	0.58	0.57	0.56	0.57	0.57
Moderator Ball No.	5787.5	6508.1	<b>7223.3</b>	<b>7654.6</b>	8155.9	8947.7	9552.1	9960.4	10577.3
Moderator Ball Ratio	0.42	0.43	<b>0.44</b>	<b>0.43</b>	0.42	0.43	0.44	0.43	0.43
Total Balls No.	13751.3	15106.4	<b>16460.0</b>	<b>17870.6</b>	19221.3	20605.5	21937.1	23379.4	24715.1
VSOP Packing Fraction (INET)	<b>125.804</b>	0.611	<b>0.610</b>	<b>0.611</b>	0.610	0.611	0.609	<b>17267</b> 0.611	<b>0.610</b>
<i>=&gt; Interpolate Critical Height = 124.88cm</i>									
MCNP4A (INET)	126.116	-	-	-	-	-	17109	-	-
MCNP4B Experiment	Critical Height [cm] 128.0	K-eff 0.99980 ± 0.00090	Fuel Ball No. 9627	Fuel Ball Ratio 0.57	Mod. Ball No. 7263	Mod. Ball Ratio 0.43	Total Ball No. 16906	Packing Fraction 0.61	
<b>This Work (MCNP5)</b>	<b>124.88</b>	<b>0.99933 ±</b> <b>0.00061</b>	<b>9822</b>	<b>0.57</b>	<b>7323</b>	<b>0.43</b>	<b>17145</b>	<b>0.61</b>	

# Previous Study

## HTR-10 Benchmark Problem 2

- B2: Effective multiplication factor (k-eff) is to be determined for the full core (5m<sup>3</sup>) under He atmosphere and at temperatures of (a) 20 °C (B21), (b) 120 °C (B22), and (c) 250 °C (B23) without any control rod insertion.

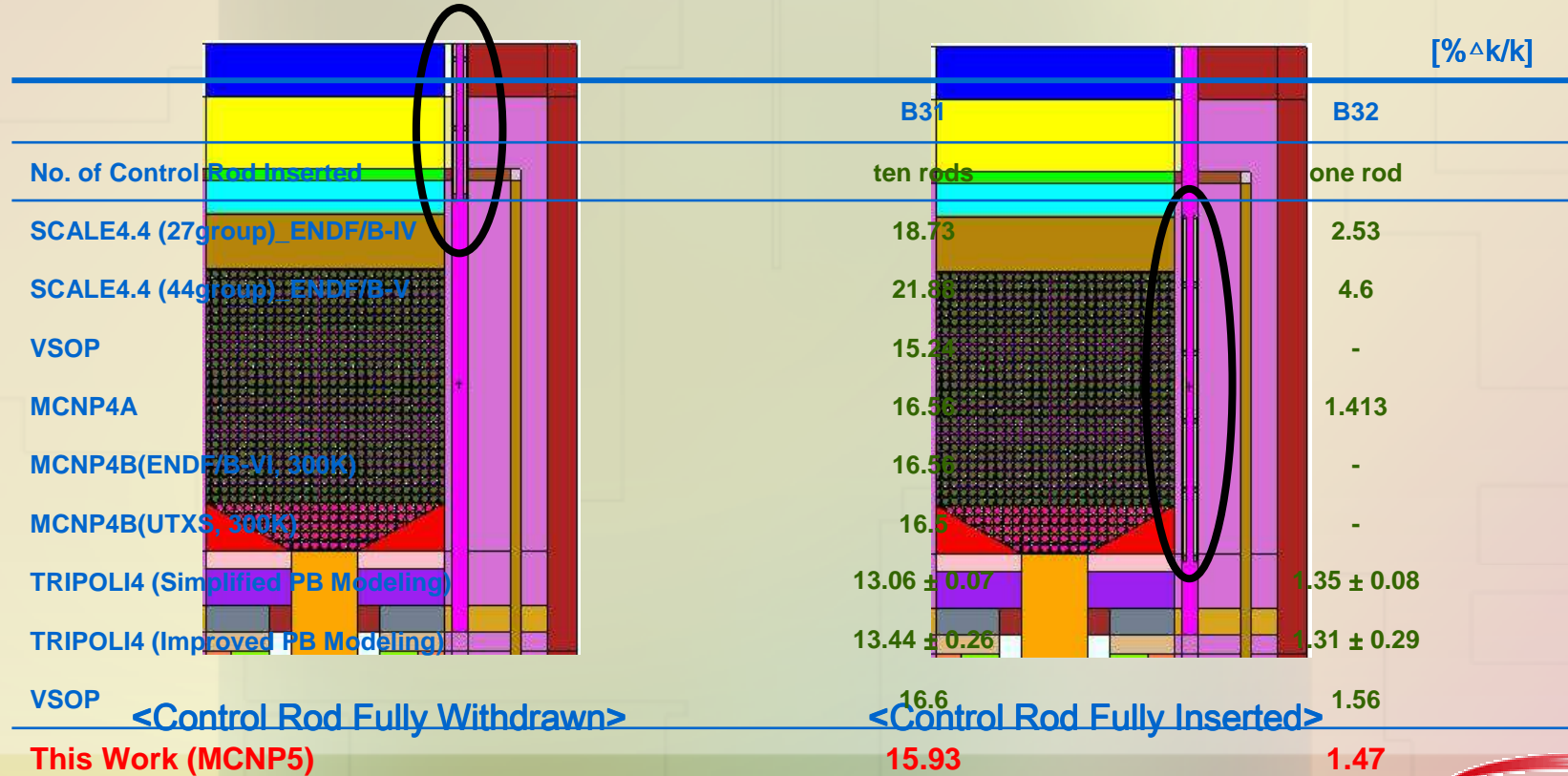
	B21		B22		B23	
Temperature (°C)	20		120		250	
SCALE4.4 (27group)_ENDF/B-IV	1.0941±0.0008		1.0802±0.0006		1.0671±0.0007	
VSOP	1.119747		1.110435		1.095961	
SCALE4.4 (44group)_ENDF/B-V	1.0809±0.0007		1.0380±0.0006		1.0035±0.0006	
VSOP P(T)	1.119747	-7.49E-05	1.110435	-9.15E-05	1.095961	
WIMS/D4	1.2193	1.1197	1.1983	1.1104	1.1748	1.0956
WIMS/D4 P(T)	1.1197		1.1104		1.0956	
SRAC	1.1381		1.1149		1.0844	
VSOP-RBMR	1.12976±0.00086		1.11956		-	1.10469
MCNP4B(ENDF/B-VI, 300K)	1.13185±0.00087	-7.16E-05		-9.25E-05		
MCNP4B(UTXS, 300K)	1.1322		1.1279		1.12452	
MCNP4B(UTXS, 293.15K, polynomial fit)	1.13725	1.12607±0.00063	1.12404	1.11439±0.00065	1.10699	1.10079±0.00062
VSOP (2-d geometry)	1.12665		1.1331		1.09588	
VSOP (3-d geometry) P(T)	1.12665	-9.31E-05	1.1331	-8.53E-05	1.09588	
VSOP-RBMR	1.12861		1.11956		1.10469	
P(T) = (k <sub>1</sub> -k <sub>2</sub> )/((k <sub>1</sub> *k <sub>2</sub> )*(T <sub>1</sub> -T <sub>2</sub> ))						
<b>This Work (MCNP5)</b>		<b>1.12607±0.00063</b>		<b>1.11439±0.00065</b>		<b>1.10079±0.00062</b>

\* Cross-section : ENDF/B-VI Cross-section Library

# Previous Study

## HTR-10 Benchmark Problem 3

- B3: This problem requires the calculation reactivity worth of (a) **ten fully inserted control rods (B31)** and (b) **one fully inserted control (B32)** under the helium atmosphere and the temperature of 20 °C for full core.



# Previous Study

## HTR-10 Benchmark Problem 4

- B4: Calculation of the **reactivity worth** of the ten **fully inserted control rods (B41)** under helium atmosphere and core temperature of 20°C for a loading height of 126cm, and the **differential worth of one control rod (B42)**, with the other rods in the withdrawn position).

♣ B41

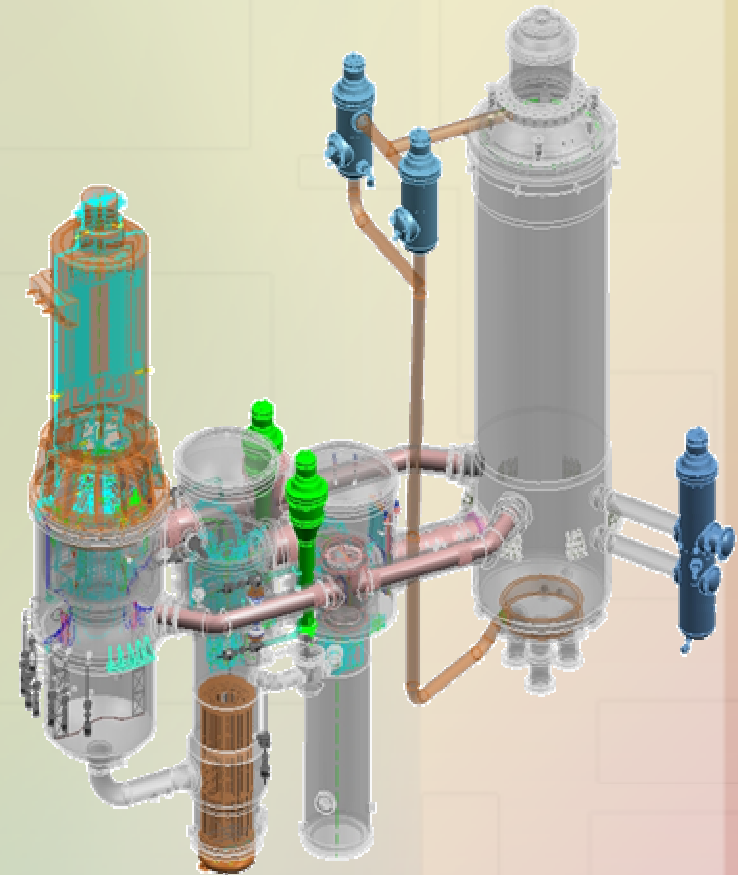
♣ B42

		Reactivity Worth [%Δk/k]							
									[%Δk/k]
Axial Position [cm]	VSOP	230.318	279.018	282.618	331.318	334.918	383.618	394.2	18.27
VSOP	MCNP	0.26	0.61	0.65	1.27	1.30	1.61	1.62	19.36
SCALE4.4 (27Group)_ENDF/B-IV	SCALE4.4 (27Group)_ENDF/B-IV	0.49	0.97	1.01	1.68	1.82	1.96	2.09	20.02
SCALE4.4 (44Group)_ENDF/B-V	SCALE4.4 (44Group)_ENDF/B-V	2.42	3.03	3.16	3.90	3.98	4.13	4.19	23.65
TRIPOLI4 (Simplified PB Modeling)	TRIPOLI4 (Simplified PB Modeling)	0.28	0.68	0.73	1.26	1.38	1.48	1.52	13.66
VSOP-CITATION	TRIPOLI4 (Improved PB Modeling)	0.42	0.94	1.00	1.68	1.72	1.97	1.97	13.80
<b>This Work (MCNP5)</b>	VSOP-CITATION	<b>0.33</b>	<b>0.90</b>	<b>0.95</b>	<b>1.48</b>	<b>1.56</b>	<b>1.65</b>	<b>1.73</b>	<b>20.55</b>
<b>This Work (MCNP5)</b>									<b>18.71</b>

# ■ PBMR Description

## Operating Characteristics of the PBMR

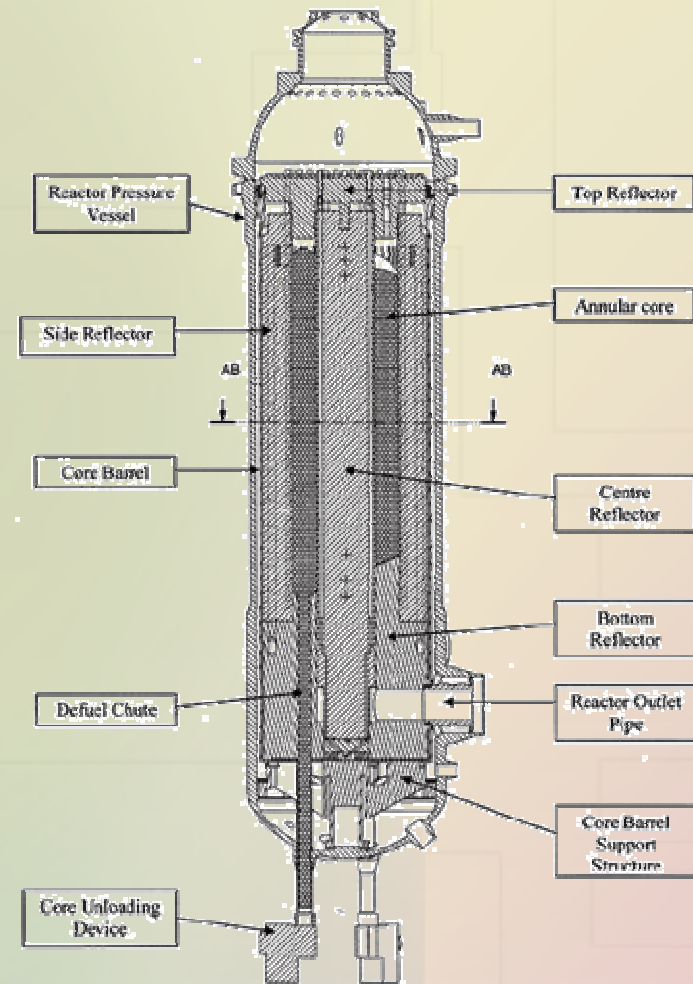
- ♣ Core Thermal Power: 400MWt
- ♣ Primary Coolant: Helium
- ♣ Primary Coolant Pressure: 9MPa
- ♣ Moderator: Graphite
- ♣ Core Outlet Temperature: 900°C
- ♣ Core Inlet Temperature: 503°C
- ♣ No. of RSS (Reserve Shutdown System)  
: 8
- ♣ No. of Control Rod Channels : 24



# ■ PBMR Description

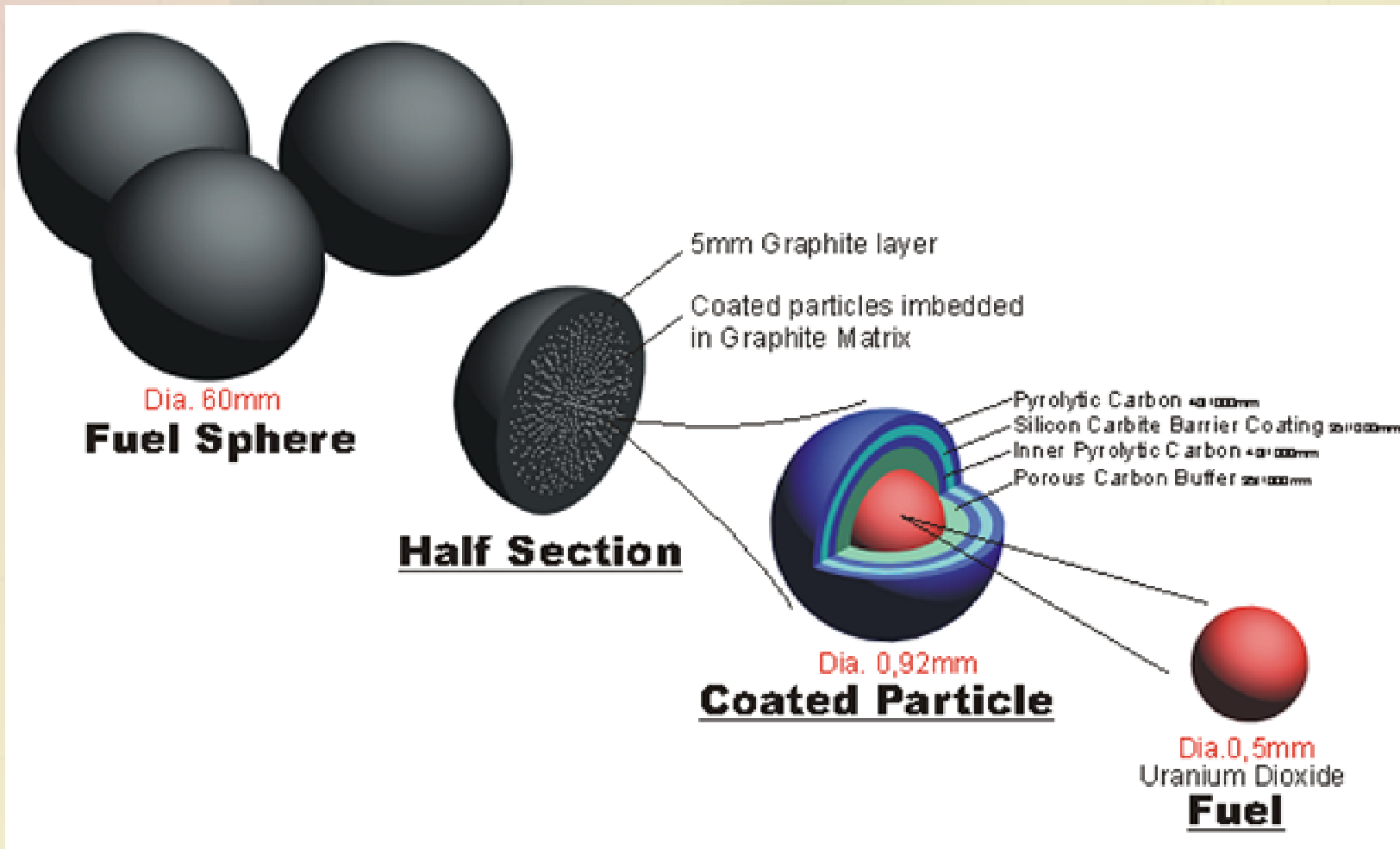
## Neutronics Model Parameters

- ♣ Core Outer Dia.: 3.7m
- ♣ Fuel Annular Thickness: 0.85m
- ♣ Central Reflector Dia.: 2m
- ♣ Avg. Core Height: 11m
- ♣ Total No. of Pebbles: 451,600
- ♣ Reflector Thickness at Top: 135cm
- ♣ Reflector Thickness at Bottom: 261cm



# ■ PBMR Description

## Structure of Fuel Pebble

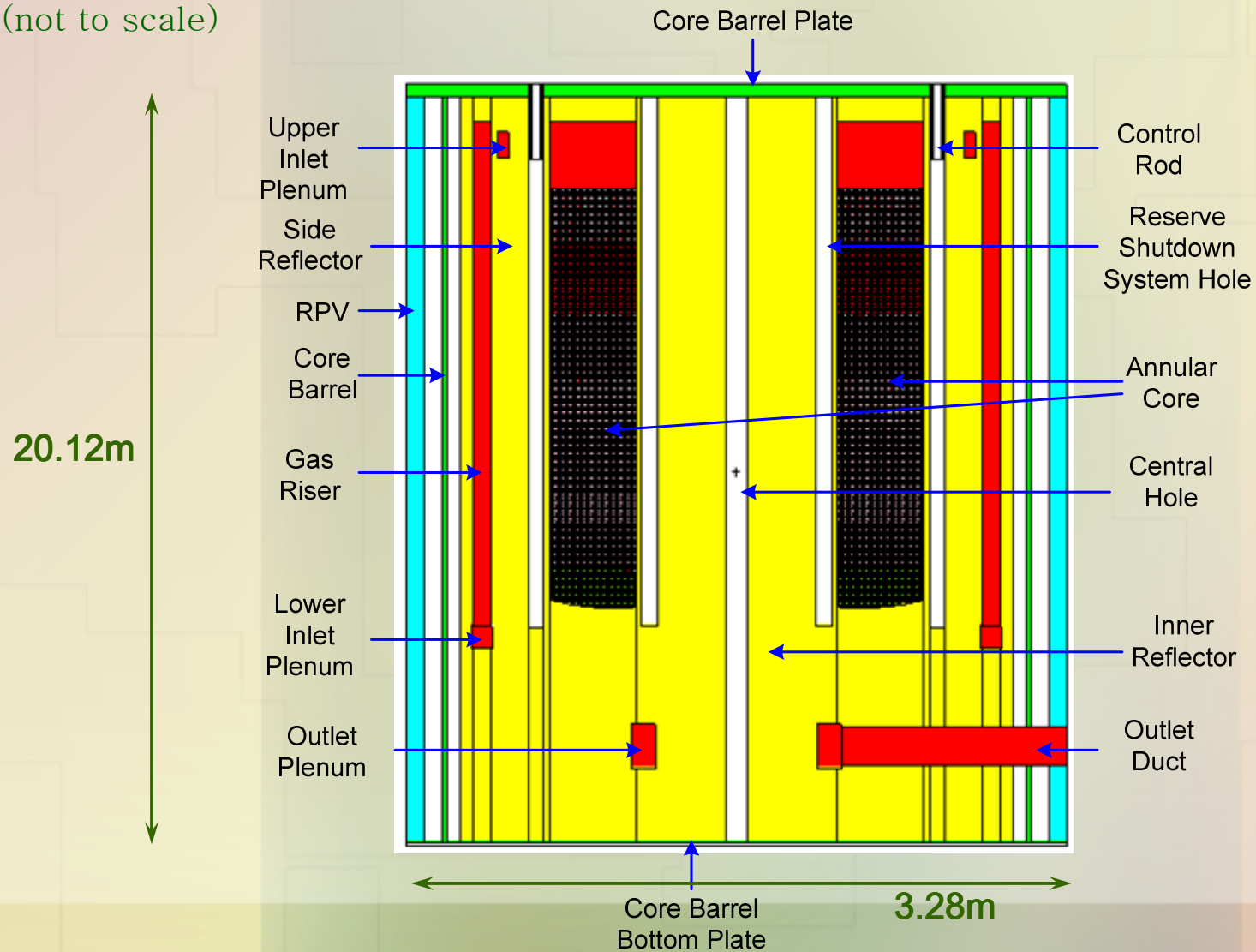


# MCNP Modeling Result for PBMR 1

( Whole Facility > Core > Pebble )

## Vertical View

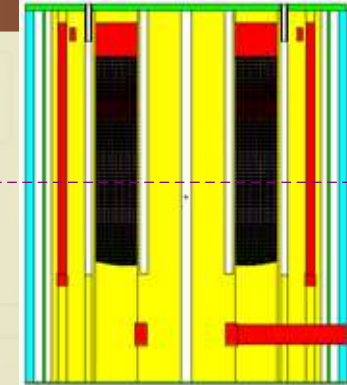
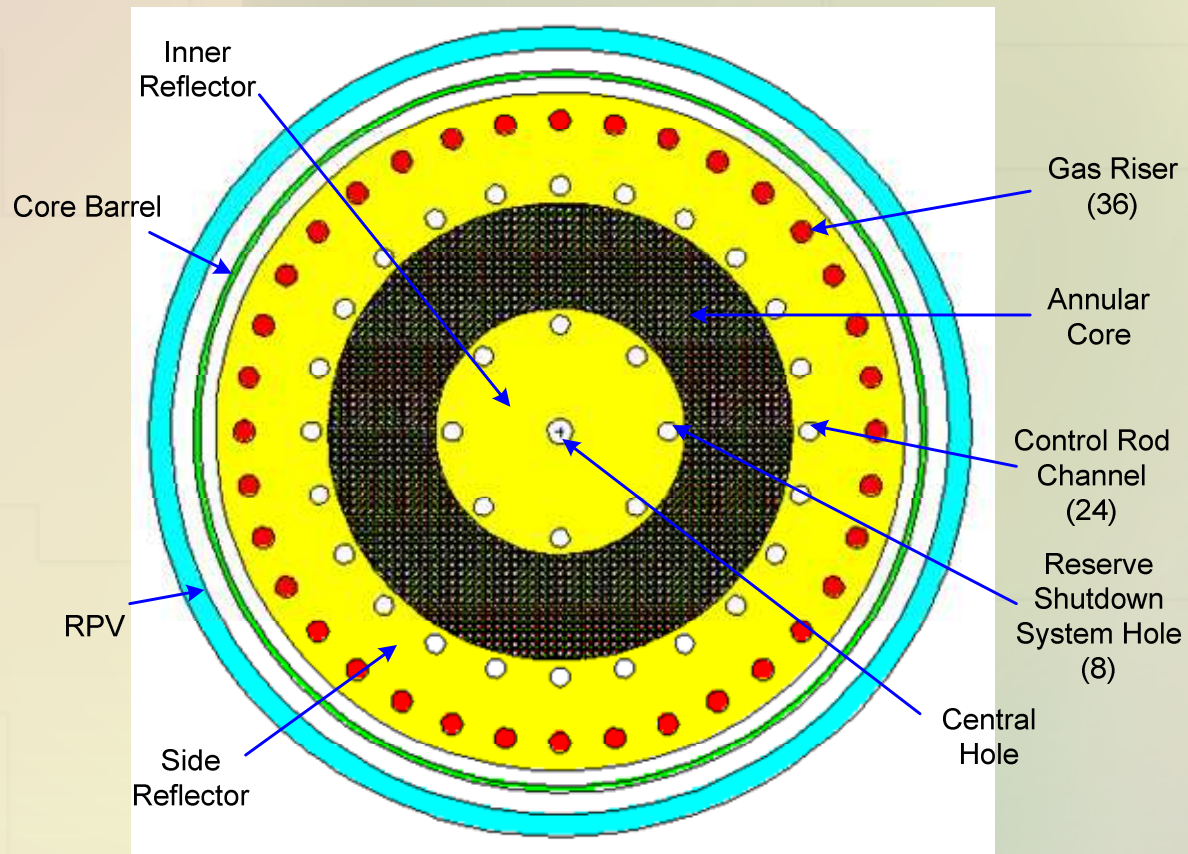
(not to scale)



# MCNP Modeling Result for PBMR 1

( Whole Facility > Core > Pebble )

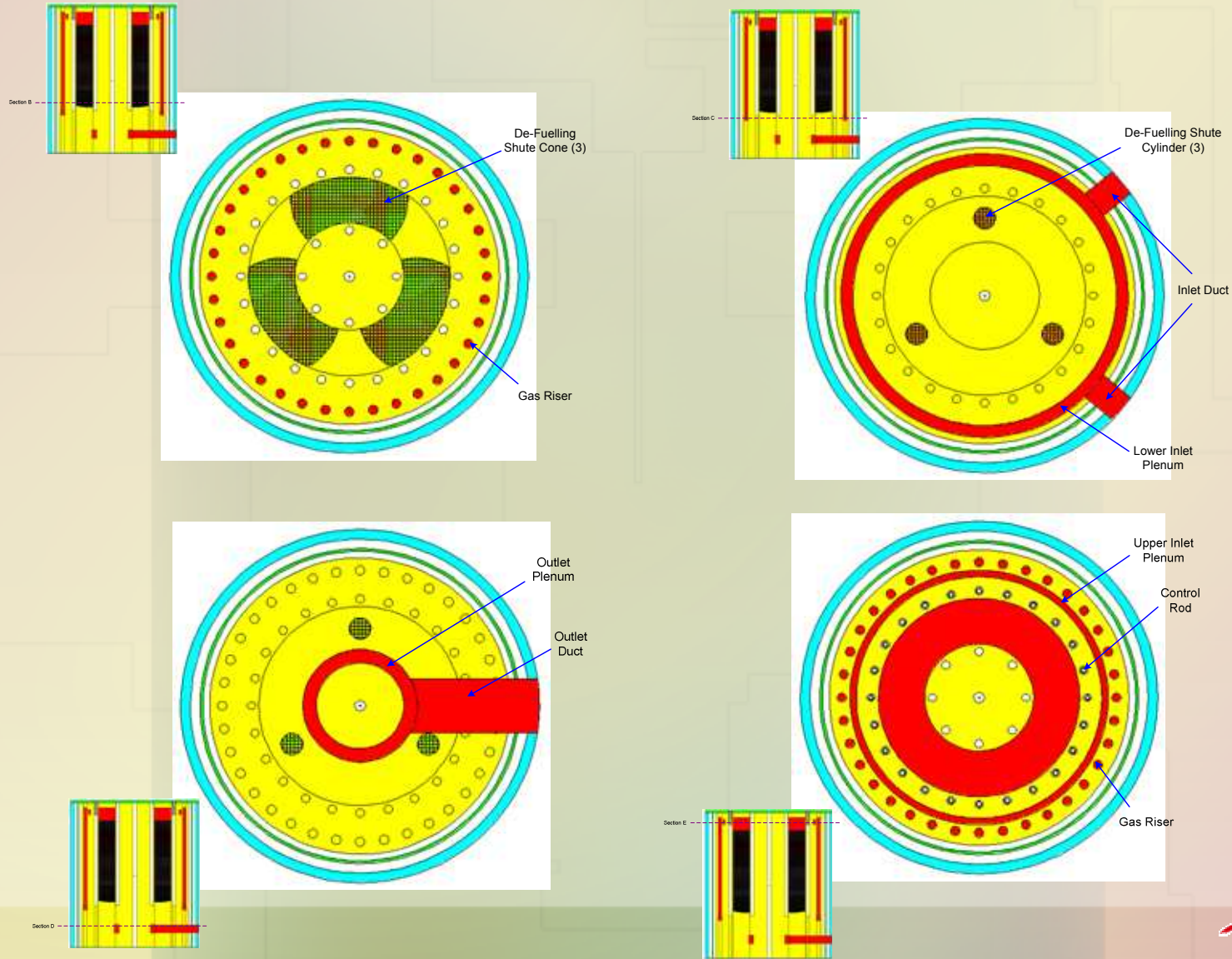
## Horizontal View



# MCNP Modeling Result for PBMR 1

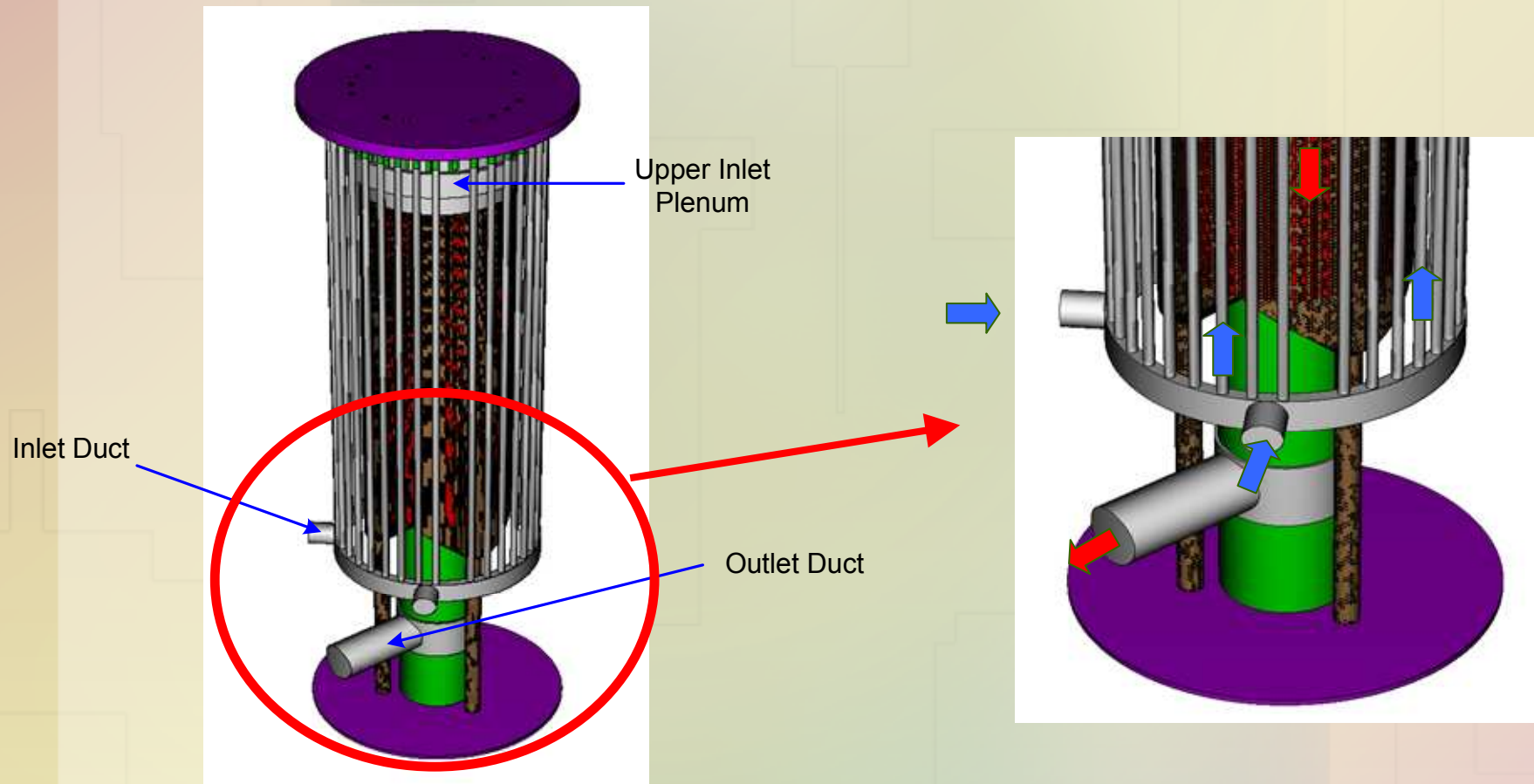
( Whole Facility > Core > Pebble )

## Horizontal View



# MCNP Modeling Result for PBMR 1

( Whole Facility > Core > Pebble )



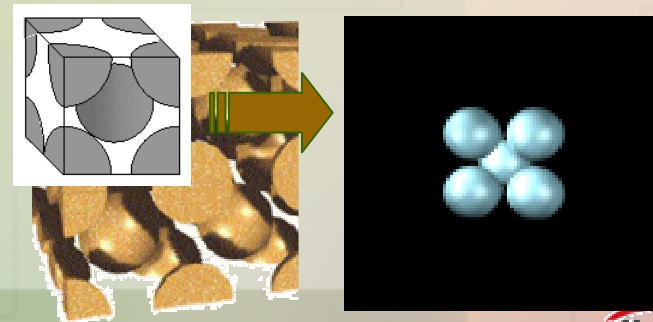
## Core Modeling

### ♣ Annular Core Region

- ▷ Fuel and Moderator pebbles are randomly packed (Packing Fraction = 0.61).
- ▷ It is not possible to exactly describe the feature to be randomly packed using Monte Carlo code or any other codes.
  - > Assumed to be a specified lattice model
- ▷ Several choices of lattice are possible.
  - Simple Cubic, BCC(body-centered cubic), FCC(face-centered cubic), HCP(hexagonal closed packed)
- ▷ The BCC lattice was found to work well for the loose packing typically encountered in pebble-bed reactor cores.



BCC Lattice Modeling



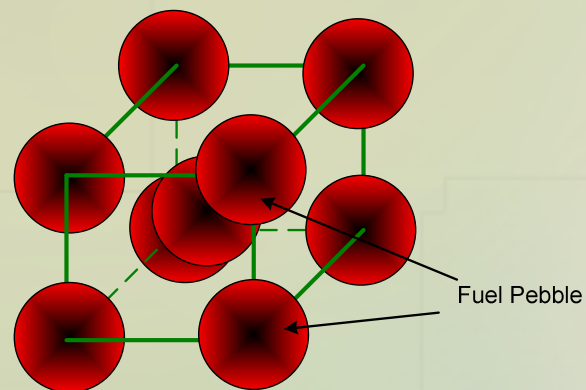
# MCNP Modeling Result for PBMR 2

( Whole Facility > Core > Pebble > )

## Core Modeling

### ♣ Benchmark Problem Case F-1

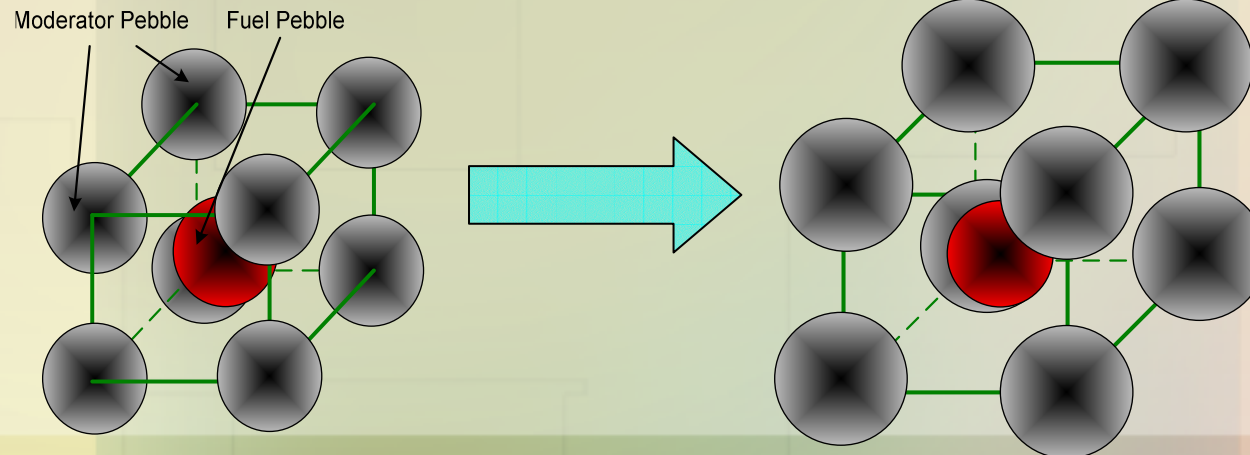
- ▷ Fuel Pebble Only
- ▷ Calculation of BCC Lattice Pitch to Maintain the Packing Fraction of 0.61 within One BCC Unit Cell  
-> Pitch = 7.18cm



## Core Modeling

### ♣ Benchmark Problem Case F-2

- ▷ Fuel Pebble : Moderator Pebble = 1:2
- ▷ Increase the Radius of Moderator Pebble to fit the specified F/M ratio of 1:2
  - > Radius of Moderator Pebble Increased: 3cm → 3.780cm
- ▷ Calculation of BCC Lattice Pitch Reproduced to Maintain the Packing Fraction of 0.61 within One BCC Unit Cell
  - > Pitch Reproduced: 7.18cm -> 8.22 cm



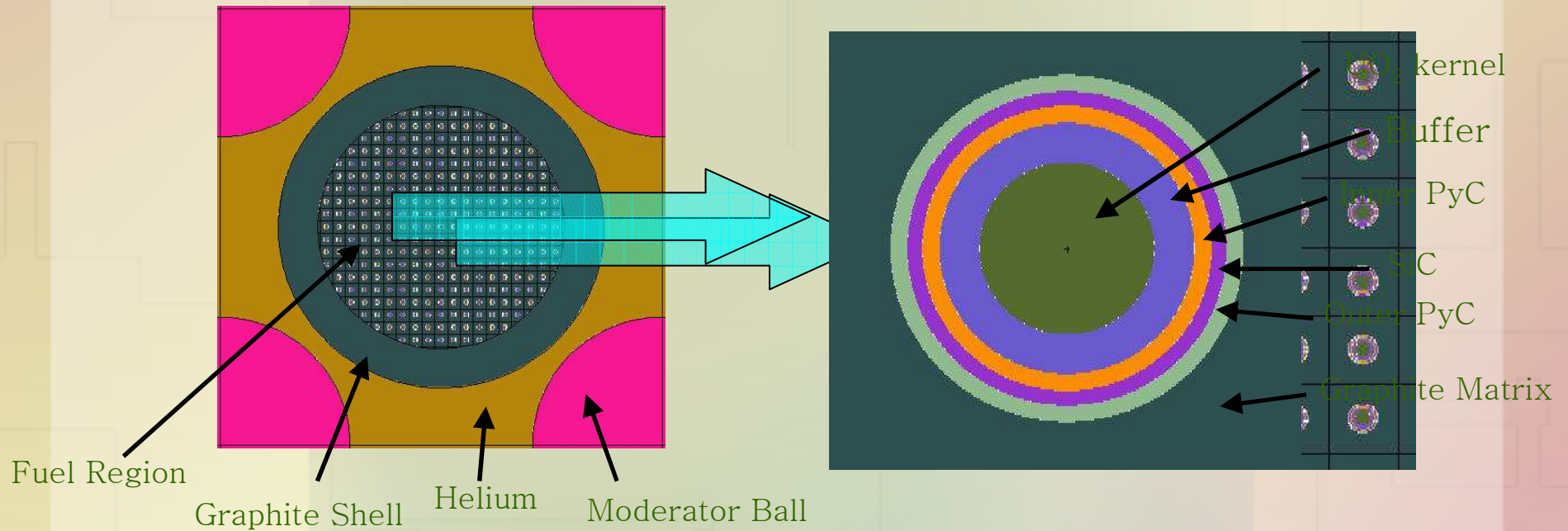
# MCNP Modeling Result for PBMR 3

( Whole Facility > Core > Pebble )

## Fuel Pebble Modeling

- ♣ Graphite shell in outer region
- ♣ Inner region (fuel region) contains about 15,000 TRISOs

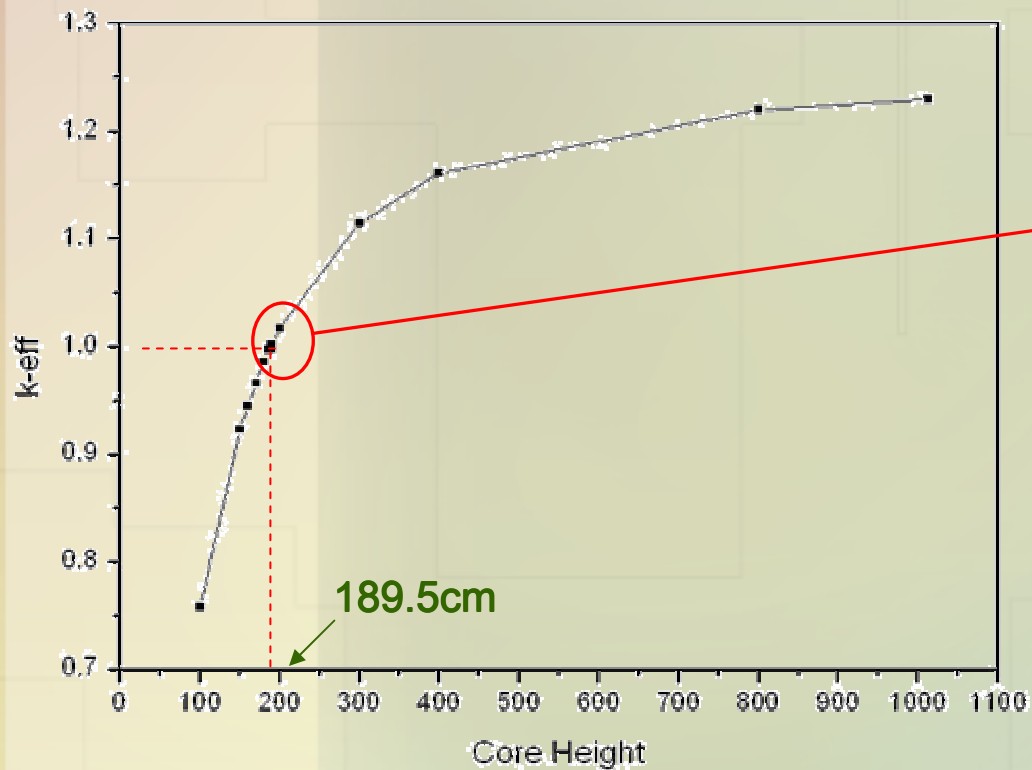
- ♣ Fuel region is divided into a cubic lattice.
- ♣ All of 5 concentric shells of TRISO were modeled
- ♣ Calculation of TRISO pitch to conserve the fuel quantity in the fuel region  $\rightarrow 0.1635$  cm



# Previous Study Results for PBMR

## The Height of Initial Critical Core

- ♣ Calculation for the height of initial critical core for the state without any control rod insertion



- ♣ Initial critical at the core height of 189.5cm

- ♣ No. of Total Pebbles= 77772

- No. of Fuel Pebbles= 39282

- No. of Mod. Pebbles= 38490

c.f) HTR-10 (China)

- No. of Total Pebbles= 17226

- No. of Fuel Pebbles= 9901

- No. of Mod. Pebbles= 7325

# Previous Study Results for PBMR

## Control Rod Worth Calculation

- ♣ Calculation of reactivity differences for full core (core height=10.12m) when Bank 1, Bank 2, and both Bank 1 and Bank 2 were fully inserted, respectively.
- ♣ Consist of 24 active control elements divided into two groups of 12
- ♣ Bank 1: Positioned in the upper half of the core, when fully inserted.
- ♣ Bank 2: Positioned in the lower half of the core, when fully inserted.

	State	Reactivity Difference [pcm]
Bank 1	Bank 1 Fully Inserted	3889
Bank 2	Bank 2 Fully Inserted	9695
Bank 1 and 2	Both Bank 1 and 2 Fully Inserted	13581



The reactivity difference for Bank 2 is more sensitive than those for Bank 1.

# ■ Benchmark Problem

- ❖ IAEA CRP-5(Coordinated Research Project) neutronics and thermal-hydraulics benchmark problem
  - ▷ Proposed for the testing of existing methods for HTGRs to analyze the neutronics and thermal-hydraulic behavior for the design and safety evaluations of the PBMR.

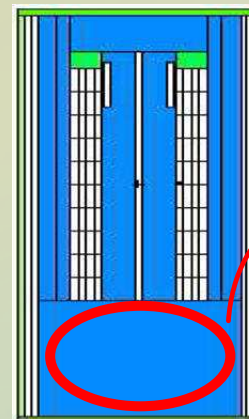
- ❖ Steady State Calculations
- ❖ Number density can be used for homogeneous material or volume weighted and applied to heterogeneous fuel specifications. -> Heterogeneous
- ❖ Cold conditions (300K) is employed for all materials.
- ❖ Use of own cross sections
  - ▷ ENDF/B-VI cross-section library
  - ▷ Graphite material: sab2002 thermal cross-section
- ❖ No control rods inserted (totally extracted)
- ❖ Case F-1
  - : The core is filled with fresh core fuel.
- ❖ Case F-2
  - : Employ a homogeneous mixture of 33.3% first core fuel and 66.6% graphite spheres.

# ■ Calculation Result

- ♣ Computation Code: MCNP5 Code
- ♣ Computation Time: About 3 Hours on 49 Parallel Linux Clustering System
- ♣ Benchmark Problem
  - ▷ Case F-1: Only Fresh Fuel
  - ▷ Case F-2: First Core Loading (F/M Ratio of 1:2)

	$k_{eff}$	
	Case F-1	Case F-2
MCNP4b (Turkey, Hacettepe Univ.)	1.2781	1.1533
MCNP5 (This Study)	1.2795± 0.00052	1.1401± 0.00055
$K_{eff}$ Difference	141 pcm	1315pcm

- 3 Bottom Cone Regions and De-Fueling Chutes
  - ▶ MCNP4b Calculation: Assumed as the Surface Flattened
  - ▶ This Study: Modeled Explicitly



<MCNP4b>



<This Study>

## ■ Summary and Expectation

- ♣ Monte Carlo calculations for benchmark problem proposed by IAEA CRP5 for 400MW<sub>th</sub> PBMR core
- ♣ Contributes and utilizes directly in the establishment of benchmark problems to develop deterministic neutronics analysis tools and methods, which lagged behind the state of the art compared to other reactor technologies, to design and analyze PBMR.
- ♣ Provides the basic data for pebble-type VHTR core analysis.
- ♣ This study would be utilized in the validation of a deterministic computer code for VHTR core analysis which will be developed in near future in Korea.