IAEA GT-MHR Benchmark Calculations using the HELIOS/MASTER Code Package

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Abstract

In this paper, the performance of the HELIOS/MASTER code package has been evaluated through the IAEA GT-MHR (Gas Turbine-Modular Helium Reactor) benchmark calculations with plutonium fuel. The proposed benchmark problems include five different cell models, two block models and six different core models. The computational results of the HELIOS and MASTER codes were compared with those of the MCNP code and other groups. The RPT method was used to remove a double heterogeneity in a fuel compact. The multiplication factors for the cell, block and core calculations agree well with those of the MCNP calculations. The multiplication factors and the radial and axial power distributions for the core calculations are very consistent with those of MCNP. From results above, it can be concluded that the HELIOS/MASTER 2-step procedure is available for the prismatic VHTR physics analysis.

KEYWORDS: GT-MHR, HELIOS/MASTER, MCNP, VHTR Physic Analysis

1. Introduction

The latest research associated with the very high temperature gas-cooled reactor (VHTR) is focused on the verification of a system performance and safety under operating conditions for the VHTRs. As a part of those, an international gas-cooled reactor program initiated by IAEA is going on. The key objectives of this program are the validation of analytical computer codes and the evaluation of benchmark models for the projected and actual VHTRs. [1] New reactor physics analysis procedure for the prismatic VHTR is under development by adopting the conventional two-step procedure. [2] In this procedure, a few group constants are generated through the transport lattice calculations using the HELIOS [3] code, and the core physics analysis is performed by the 3-dimensional nodal diffusion code MASTER [4].

We evaluated the performance of the HELIOS/MASTER code package through the benchmark calculations related to the GT-MHR to dispose weapon-grade plutonium. [1] We also established the MCNP models as a reference for the benchmark problems, and compared our computational results with those performed by other groups.

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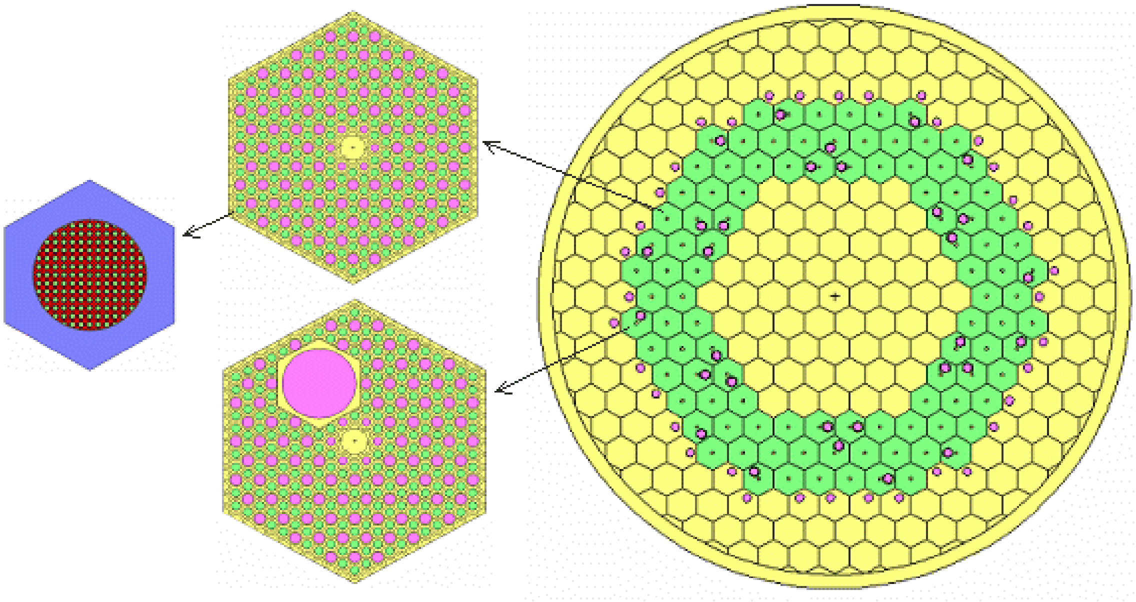
2. Benchmark Problems and Methods

2.1 Description of the GT-MHR Core

The GT-MHR core shown in Figure 1 is constructed as an active core with radial, internal and axial reflectors. The active core is made of 102 columns of 800 cm height consisting of 10 hexahedral prismatic fuel blocks with a 36 cm pitch stacked axially. In the 30 columns, there is eccentrically a 13 cm diameter hole for control rods or a reserve shutdown system (RSS). The reflectors are the graphite block which is similar to the shape of the fuel block. The height of the radial and internal reflector is 1060 cm. The 36 radial reflector columns contiguous with the core have a hole to accommodate the control rods.

Figure 1: MCNP model for the GT-MHR core.



2.2 Benchmark Problems

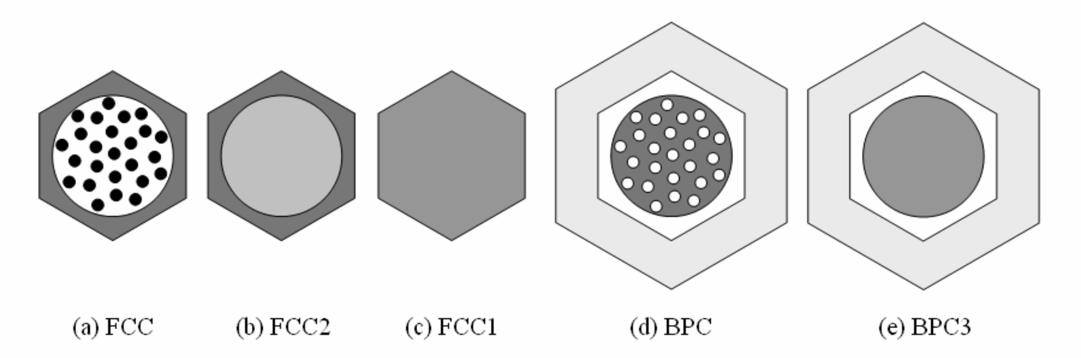
Benchmark problems include fuel compact cell models, burnable poison cell models and six different core models.

The fuel compact cell models include FCC, FCC2 and FCC1 as shown in Figure 2 (a), (b) and (c). FCC is made of the internal zone of fuel kernels ($PuO_{1.7}$) with a four-layer coating randomly dispersed in the graphite matrix and the external zone of the graphite block. The packing fraction of TRISO in the graphite matrix is 0.12978. FCC2 and FCC1 are to homogenize the TRISO and graphite matrix, and all the materials, respectively.

The burnable poison cell models include BPC and BPC3 as shown in Figure 2 (d) and (e). BPC consists of the internal zone of Er_2O_3 particulates (packing fraction: 0.08636) randomly dispersed in the graphite matrix, the intermediate zone of the graphite block and the external zone of the homogeneous mixture including the fuel, graphite block and helium. BPC3 is to homogenize the internal zone of the BPC.

The core calculation models as shown in Figure 1 are divided into six variants according to the axial arrangement of two different fuel blocks (FB1 and FB2) with four different fuel burnups.

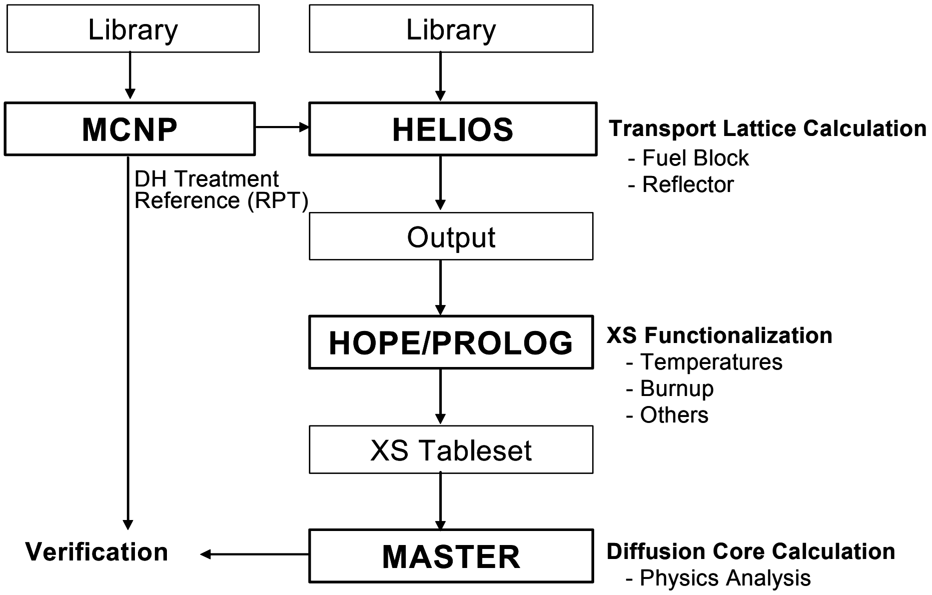
Figure 2: Schematic presentation of pin cell models.



2.3 Procedure for VHTR Physics Analysis

Figure 3 shows the flow chart of HELIOS/MASTER code package for the prismatic VHTR physics analysis developed by KAERI. At first, a double heterogeneity in a fuel compact is removed through the reactivity-equivalent physical transformation (RPT) [5] from the MCNP reference calculations. And then HELIOS performs a transport lattice calculation to generate a few group cross sections for each fuel block and reflectors. HOPE and PROLOG process the HELIOS output to generate the functionalized cross section tableset. MASTER carries out a nodal diffusion calculation for the VHTR cores.

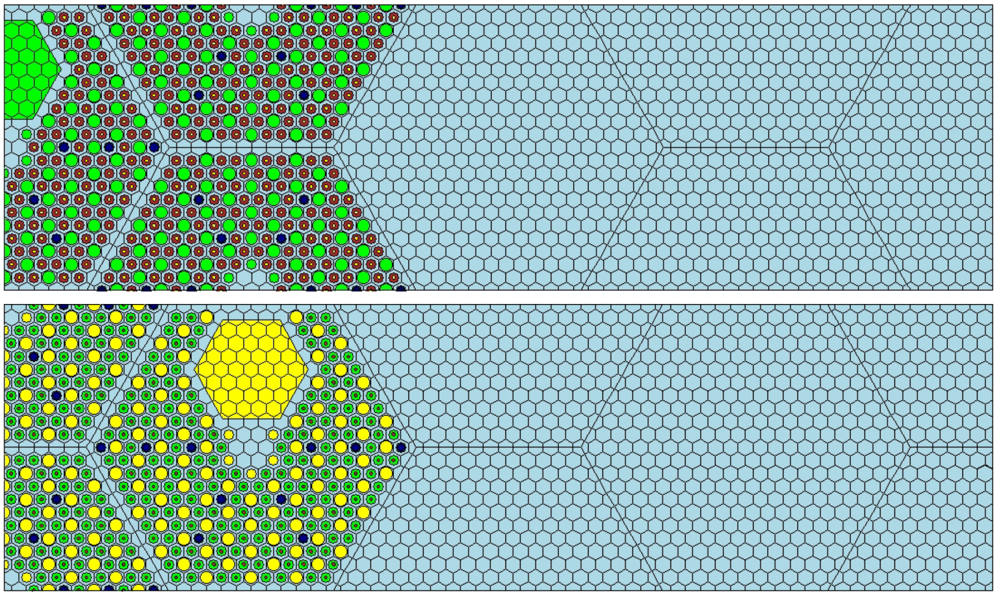
Figure 3: HELIOS/MASTER code package.



Our physics analysis procedure [2] is as follows:

1. Decide the optimal number of micro energy groups and the energy group boundaries for the GT-MHR core to cover the spectral change according to the location, temperature and burnup by 1-D core models,
2. Verify the outcome of the procedure by performing 1-D diffusion calculations. Reflector cross section are edited from the HELIOS 1-D output and adjusted by the discontinuity factors from the simplified equivalence theory,
3. Calculate the block cross section from a HELIOS mini core calculation with all the reflecting boundary condition as shown in Figure 4,
4. Perform the GT-MHR core calculations with the reflector cross section obtained in the procedure 2 and the block cross section in the procedure 3.

Figure 4: The HELIOS mini core model



3. Computational Results

3.1 Cell Calculations

Cell calculations were performed at four different constant temperatures of 300, 600, 900 and 1200 K. Since HELIOS can not treat the double heterogeneous problem in FCC and BPC, the RPT method has been employed to transform it into a single heterogeneous one. The effective radius of a mixture of the fuel kernels and graphite matrix is estimated to conserve all the neutronic parameters including the eigenvalue and reaction rates compared to the reference MCNP results. The calculational results for the cell models are compared with those of the MCNP calculations and Ref. [1]. As shown in Table 1, the multiplication factors of HELIOS agree well with those of MCNP and Ref. [1] within the maximum error of 450 pcm for the cell problems.

Table 2 shows the multiplication factors for the FCC and BPC3 calculations as a function of burnup at 1200 K. The maximum difference of the multiplication factors between the HELIOS results and Ref. [1] is about 830 pcm. The depleted particle number densities of erbium in BPC3 are compared with those of Ref. [1] to be very consistent with each other.

Additionally, calculations for two different fuel blocks (FB1 and FB2) were conducted under the same temperature conditions as used in the cell calculations. As shown in Table 1, the HELIOS results agree well with the MCNP results within the maximum error of 470 pcm.

Table 1: Comparison of the multiplication factors.

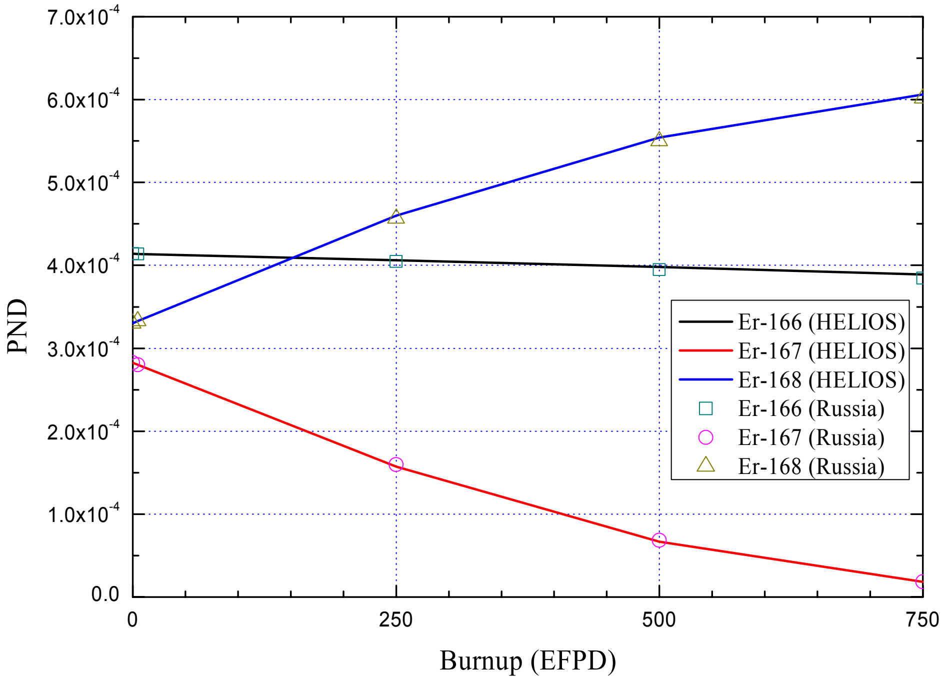
Type	Code	Temp. (K)			
		300	600	900	1200
FCC	MCNP	1.53724	1.51178	1.48077	1.46147
	HELIOS	70	-205	-89	0
	Russia	188	114	576	142
	France	3	-12	238	-22
FCC2	MCNP	1.45129	1.42794	1.40025	1.38158
	HELIOS	393	60	107	257
	Russia	388	242	322	200
	France	-190	-179	33	-251
FCC1	MCNP	1.43615	1.41408	1.38643	1.36845
	HELIOS	427	45	114	254
	Russia	167	6	108	-29
	France	-153	-174	71	-233
BPC	MCNP	1.22262	1.19209	1.16494	1.14949
	HELIOS	-143	445	196	0
BPC3	MCNP	1.19175	1.16097	1.13349	1.11797
	HELIOS	-384	160	1	-265
	Russia				512
	France	-592			-553
FB1	MCNP	1.27618	1.24919	1.21143	1.19002
	HELIOS	-58	-469	-98	-80
FB2	MCNP	1.34339	1.31400	1.27557	1.25274
	HELIOS	60	-256	64	116

□ MCNP standard deviation < 0.00060

Table 2: Comparison of the multiplication factors at different burnup steps.

Type	Code	Burnup (EFPD)				
		0	5	250	500	750
FCC	HELIOS	1.46147	1.43924	1.30269	1.23075	1.17141
	Russia	142	13	-123	-368	-832
	France	-22	-21	-337	-528	-728
BPC3	HELIOS	1.11797	1.10499	1.07033	1.10751	1.14106
	Russia	512	554	-256	-608	-748
	France	-553	-543	-415	-205	11

Figure 5: Comparison of the particle number densities of Erbium at different burnup steps.



3.2 Core Calculations

The GT-MHR core was slightly modified to be 1/6 symmetric, and the HELIOS/MASTER calculations were performed for this core at four different constant temperatures of 300, 600, 900 and 1200 K. As shown in Table 3, the multiplication factors of MASTER results agree well with those of MCNP within the maximum error of 780 pcm. Fig. 6 and Fig. 7 show the radial and axial power distributions of MCNP and MASTER for the symmetric core model with burnable poison at 1200 K. The radial power distributions of MASTER are estimated to be about a 2 % relative error, and the axial power distributions of MASTER are very consistent with those of MCNP.

The HELIOS.MASTER calculations were performed for the unmodified variant cores at three different constant temperatures of 300, 600 and 900 K. As shown in Table 4, the multiplication factors of the HELIOS/MASTER procedure agree very well with the MCNP results within the maximum error of 330 pcm.

Table 3: Comparison of the multiplication factors for the symmetric cores.

Type	Code	Temp. (K)			
		300	600	900	1200
with BP	MCNP	1.45672	1.43383	1.40328	1.38700
	MASTER	-687	-781	-525	-560
w/o BP	MCNP	1.51490	1.49188	1.46528	1.45129
	MASTER	-612	-668	-491	-466

□ MCNP standard deviation < 0.00026

Figure 6: Comparison of the radial power distribution for the symmetric cores.

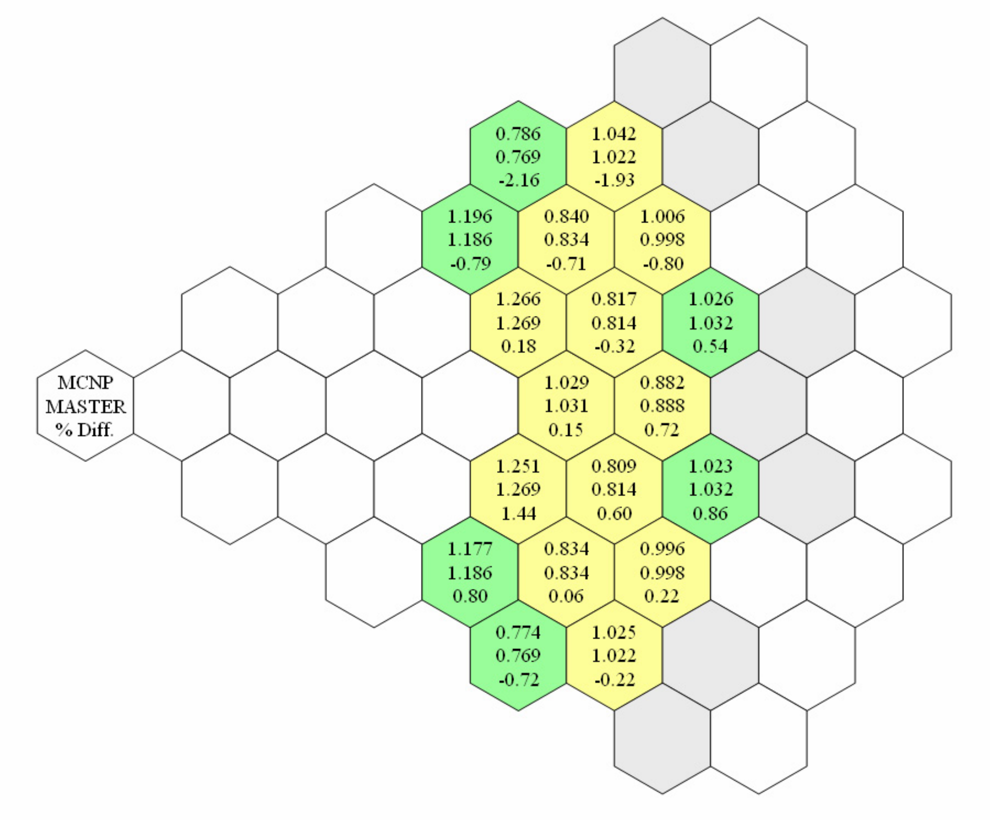


Figure 7: Comparison of the axial power distribution for the symmetric cores.

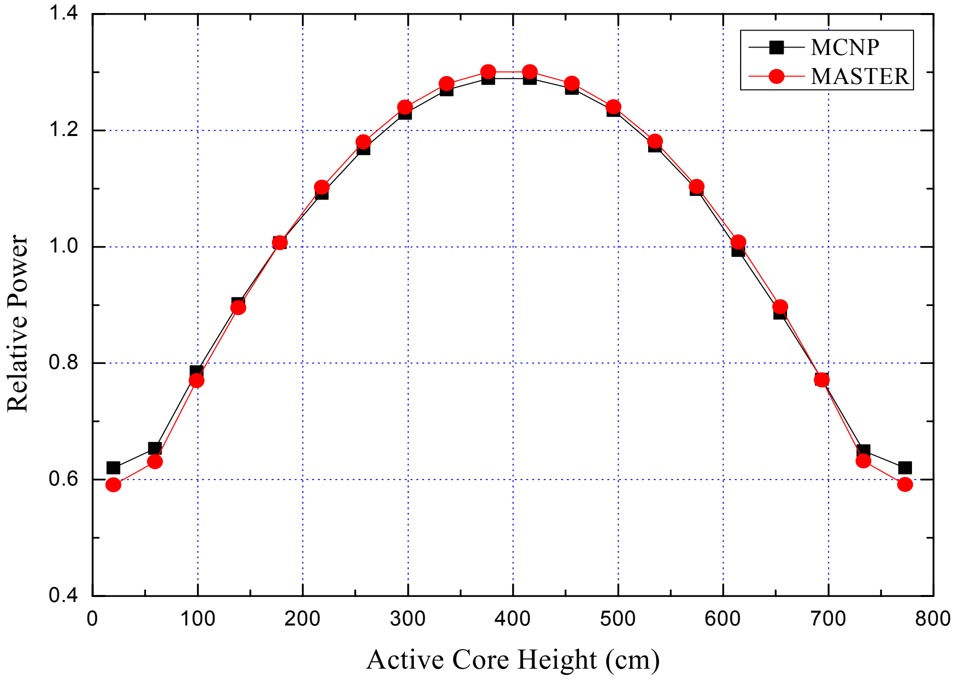


Table 4: Comparison of the multiplication factors for six variants core models.

Type	Code	Temp. (K)		
		300	600	900
Varinat-1	MCNP	1.18487	1.18659	1.17630
	MASTER	126	-247	-238
Varinat-2	MCNP	1.11045	1.12598	1.12871
	MASTER	304	-82	-230
Varinat-3	MCNP	1.19266	1.19088	1.17874
	MASTER	80	-239	-245
Varinat-4	MCNP	1.13342	1.14591	1.14484
	MASTER	114	-253	-303
Varinat-5	MCNP	1.16326	1.16916	1.16155
	MASTER	123	-275	-243
Varinat-6	MCNP	1.09269	1.11491	1.12356
	MASTER	331	-75	-320

□ MCNP standard deviation < 0.00050

4. Conclusion

The GT-MHR Benchmark calculations were performed using the Monte Carlo code MCNP and the HELIOS/MASTER code package adopting the 2-step procedure. Computational results show that the multiplication factors and power distribution of the HELIOS/MASTER calculations are very consistent with those of the MCNP calculations and Ref. [1]. The spectral effect due to the changes of the block location, temperature and burnup, and the burnable poison positioning could be covered by the energy group optimization and the mini core model. Reflector cross sections could be reasonably generated by using a simple 1-D core model with a simplified equivalence theory.

This procedure was proven to be well applicable to the prismatic core with uranium fuel where the neutron spectra are quite different from those of the GT-MHR with plutonium fuel. [2] Our newly developed HELIOS/MASTER 2-step procedure can be used in the physics analysis for any type of the prismatic VHTR cores.

Acknowledgements

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References

1) M. Methnani et al., "Evaluation of High Temperature Gas Cooled Reactor Performance,"

IAEA-TECDOC-TBD, International Atomic Energy Agency (2005).
2) Kang-Seog Kim et al., "Development of Two-step Procedure for the VHTR physics analysis," PHYSOR2006, Vancouver, Canada (2006).
3) R. J. Stamml'er et al., "HELIOS Methods," Studsvik Scandpower (1998).
4) B. O. Cho, et al., "MASTER-2.0 : Multi-purpose Analyzer for Static and Transient Effects of Reactors," KAERI/TR-1211/99 (1999).
5) Y. H. Kim, et al., "Reactivity-Equivalent Physical Transformation for Elimination of Double Heterogeneity," Trans. Am. Nucl. Soc., 93, 959-960 (2005).