Development of Two-Step Procedure for the Prismatic VHTR Physics Analysis

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Abstract

Two-step procedure using the HELIOS/MASTER code system has been developed for the prismatic VHTR physics analysis. Double heterogeneity effect due to the random distribution of the particulate fuel was considered by using the recently developed reactivity-equivalent physical transformation (RPT) method. At the stage of a group constant generation, a strong spectral effect of the graphite moderated reactor core could be covered by both an optimization of the number of energy groups and boundaries, and a mini core model instead of a single block model. A new procedure to generate a reflector cross section has been developed to conserve a neutron leakage from the fuel region by using a simplified equivalence theory.

A well-known two-step core analysis procedure has been established, where HELIOS is used for the transport lattice calculation and MASTER for the 3-D diffusion nodal core calculation. The applicability of our code system was tested against several core benchmark problems. The results of these benchmark tests show that our code system is very accurate and practical for the prismatic VHTR physics analysis.

KEYWORDS: HELIOS, MASTER, Double Heterogeneity, VHTR, Two-step Procedure, Equivalence Theory

1. Introduction

New nuclear design procedure is under development for a reactor physics analysis of the very high temperature gas-cooled reactor (VHTR). The conventional two-step procedure developed for the commercial pressurized water reactors (PWR) is adopted as a standard procedure for the prismatic VHTR reactor physics analysis. The neutronic characteristics of the VHTR core are quite different from the PWR one in many aspects. VHTR employs a graphite moderator which results in a long neutron diffusion length. A particulate fuel with multi-coating layers, called TRISO, is employed to achieve a high fuel performance and fission gas confinement, which is randomly dispersed in a graphite matrix. This causes a so-called double heterogeneity problem in the lattice calculation which requires a special treatment. Neutron spectra change according to a change of the local position, temperature and burnup, and the burnable poison loading. The conventional two-step procedure should be modified to be appropriate for the VHTR neutronic characteristics. We employed the HELIOS[1] code for the transport lattice calculation to generate a few group constants, and the MASTER[2] code for the 3-D core calculation to perform the

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reactor physics analysis.

Since it is very difficult and complicated to develop an appropriate procedure by using a 3-dimensional model, we developed a simplified 1-dimensional model to show most of the VHTR core characteristics. Using this simple 1-D core model and the equivalence theory, the number of energy groups and group energy boundaries were optimized to minimize the spectral effect, and the effective reflector cross sections were generated. Since some of the spectral effects could not be covered due to a burnable poison loading, we established a new procedure to generate a few group constants from a mini core model instead of a single block model. This procedure has been verified through a comparison of the calculation results of the 2-step procedure with those of MCNP[3] for the modified prismatic NGNP[4] core.

2. Methods

2.1 Two-step Procedure

The HELIOS/MASTER code package originally developed for the PWR physics analysis as shown in Figure 1 has been modified for the VHTR physics analysis. In this conventional 2-step procedure, the transport lattice calculations are performed by the HELIOS code to generate a few group constants through a flux volume weighting, and group constants are tabularized as a function of the temperatures and burnup by using the HOPE and PROLOG codes, and then the core physics analysis is performed by the MASTER code.

Figure 1: Flow Chart of the HELIOS/MASTER Code System

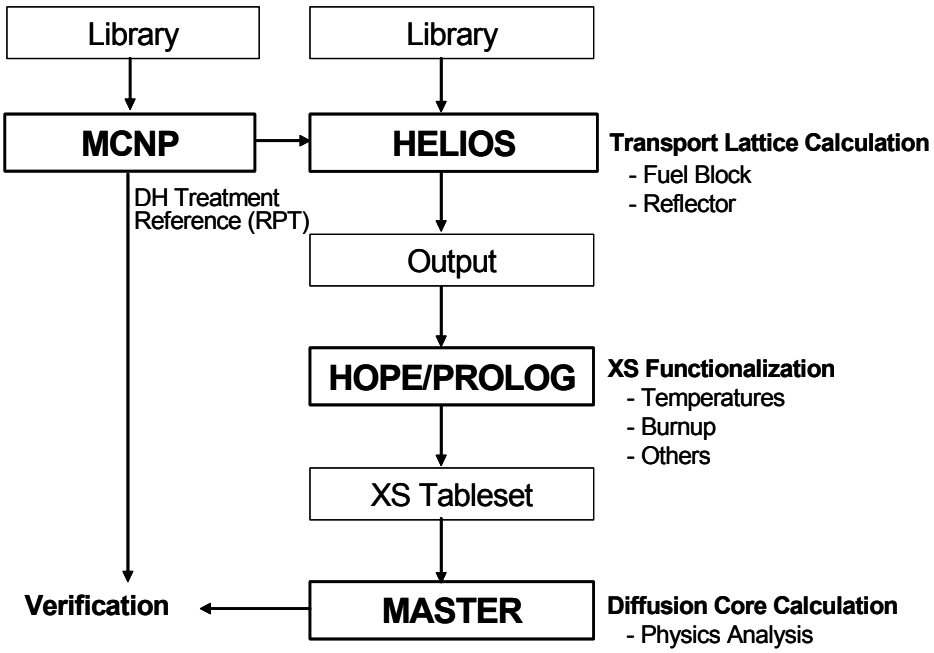


Figure 2: Simple 1-D Core Model

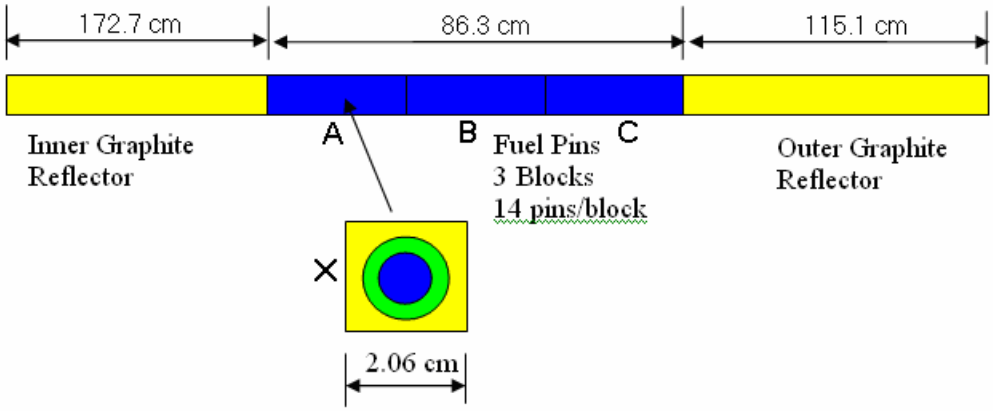
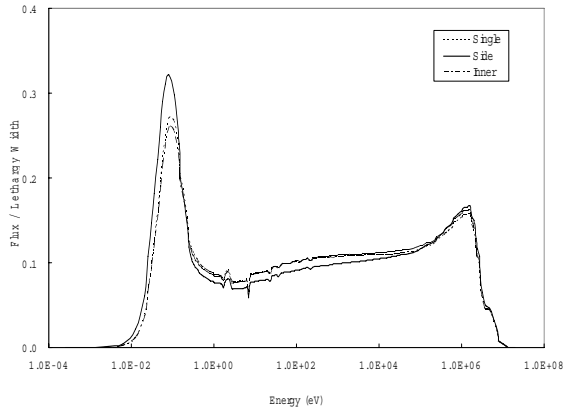
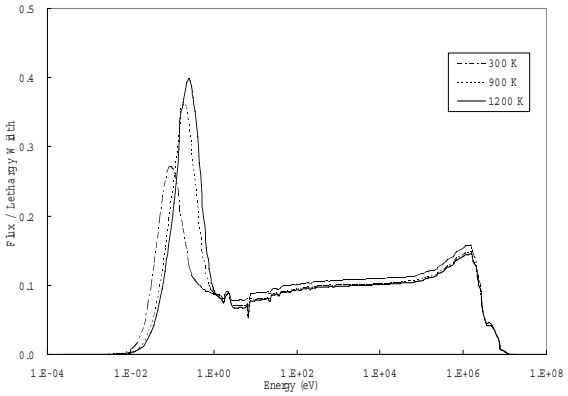


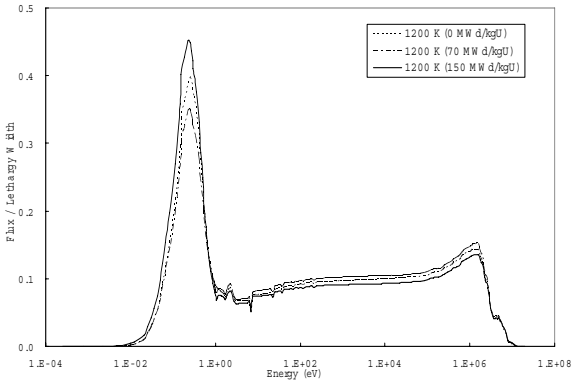
Figure 3: Characteristics of the VHTR spectra



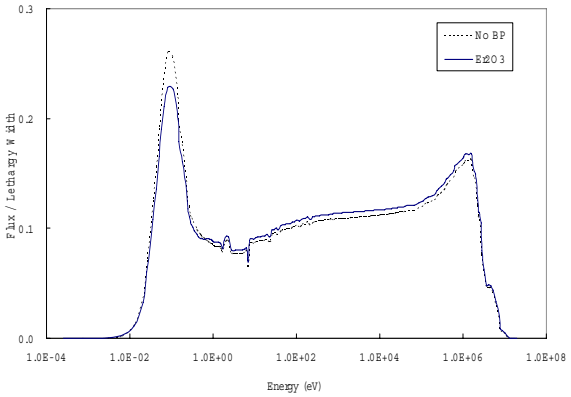
(a) Location



(b) Temperature



(c) Burnup

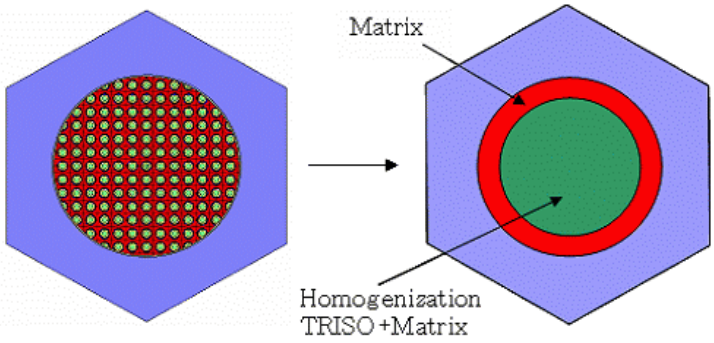


(d) Burnable Poison

We established a simple 1-D VHTR core as shown in Figure 2 to observe the characteristics of

the neutron spectra, which included inner and outer reflectors and the fuel region. Figure 3 shows the characteristics of the neutron spectra in the VHTR core with uranium fuel according to a change of the fuel location, temperature and burnup, and a burnable poison loading. Neutron spectra were obtained from the simple core and single pin HELIOS calculations by using a 190 group library. Spectral effect of the VHTR core is more severe than that of the PWR core, which makes an application of the typical 2-step procedure very difficult when applying it to the VHTR physics analysis. One of the key characteristics in the 2-step procedure is that the spectral effect can be covered in the lattice calculation. The old physics analysis procedure applied to the pebble and prismatic VHTR cores as used in the VSOP code package adopts an iterative method to cover the spectral effect. Therefore, we have to overcome a strong spectral effect to establish the 2-step procedure successfully. At the stage of a group constant generation, this strong spectral effect of the graphite moderated reactor core could be overcome by both an optimization of the number of energy groups and boundaries, and a mini core model instead of a single block model.

Figure 4: The RPT homogenization method



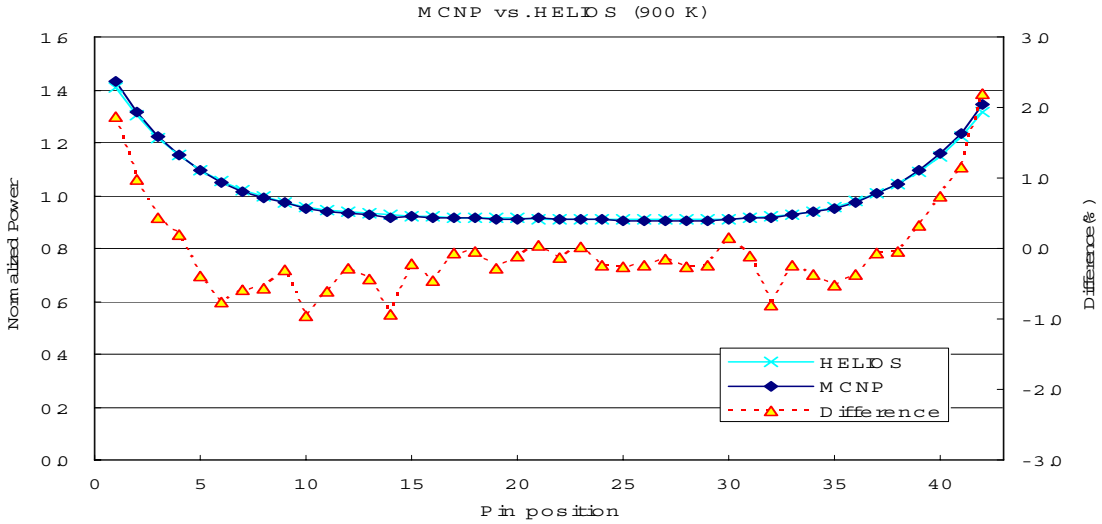
2.2 HELIOS Applicability to the VHTR Analysis

In a VHTR a particulate fuel with multi-coating layers, called TRISO, is employed to achieve a high fuel performance and fission gas confinement, which is randomly dispersed in a graphite matrix. This causes a so-called double heterogeneity problem in the lattice calculation which requires a special treatment. However, most of the conventional transport lattice codes including HELIOS do not include this capability, and the double heterogeneity effects due to the particulate fuel form are not treated appropriately. A new method was recently developed to capture the double heterogeneity effects accurately without modeling the fuel particle explicitly. This indirect method is called the reactivity-equivalent physical transformation (RPT) procedure [5], which ensures the conventional lattice codes are applicable to the analysis of VHTR fuel elements. In the RPT procedure, the self-shielding effect of randomly distributed fuel particles is determined by representing a fuel region by an equivalent cell of two homogeneous zones. The concept of the RPT procedure is depicted in Figure 4 for a single pin cell problem. The fuel particles are moved into a smaller inner zone and homogenized with a graphite matrix by a simple volume weighting. The reduced radius of the new homogeneous fuel zone is determined such that the resulting neutron multiplication factor is equal to the reference solution. The reference solution can be obtained by either a high-fidelity deterministic code or a Monte Carlo method.

Various sample calculations have been performed to assess the overall capability of HELIOS with its 190 group library for the VHTR core, which includes pin cells, blocks and a simple 1-dimensional core including the inner and outer graphite reflectors and the fuel blocks as shown in Figure 2. The results of the HELIOS calculations were compared with those of the MCNP calculations. Figure 5 shows the comparison of the HELIOS multiplication factors and the pin power distributions with the MCNP results for a simple 1-D core. The multiplication factors are very consistent to within a maximum error of 174 pcm. The pin power distributions of the HELIOS calculations at the various temperatures agree well with those of the MCNP calculations to within a maximum error of 2.2%.

Figure 5: Comparison of k_{eff} and Pin Powers for a Simple 1-D Core

Temp. (K)	Multiplication Factor		Δρ Difference (pcm)
	MCNP	HELIOS	
300	1.43721±0.00048	1.43363	174
600	1.40820±0.00040	1.40577	123
900	1.38186±0.00043	1.38020	87



2.3 Energy Group Boundary and Reflector Cross Sections

In order to determine the number of energy groups and their boundaries to cover a spectral effect, the variations of the neutron spectra due to a change of the fuel position, temperature and burnup should be considered. A few group absorption and ν*fission macroscopic cross sections and neutron spectra are extracted from the HELIOS output for blocks A, B and C of the 1-D core model and a single block model (X) in Figure 2. Group boundaries are adjusted to minimize the differences of the group cross sections and the infinite multiplication factors ($k_{inf.}$), where $k_{inf.}$ for a block is calculated by using the regional cross sections and the spectrum of X, and the core k_{eff} is obtained by using the regional cross sections and spectra of A, B and C. This optimization process is repeated for a specified temperature and burnup by changing the number of energy

groups, and then the pre-determined number of energy groups and boundaries are applied to the other temperatures and burnup points. Finally, macro group cross sections are obtained from the single block and simple 1-D HELIOS transport calculations, and then 1-D diffusion calculations are performed to make sure this procedure reasonable by comparing the multiplication factors and the pin power distributions. As shown in Figure 6, results show that the optimized number of groups is 8 by which the maximum reactivity and pin power difference are 215 pcm and 0.5%, respectively. In this procedure, 1-D diffusion calculations employing a finite difference method (FDM) are performed by using the homogeneous cross sections obtained from the HELIOS models. Region-wise discontinuity factors were determined through the simplified equivalence theory[6] by using the interface currents and region-wise cross sections. Discontinuity factor (f_G) is defined as follows:

$$f_G = \frac{\phi_{G,s}^{het}}{\phi_{G,s}^{hom}} \tag{1}$$

where $\phi_{G,s}^{het}$ is a surface flux extracted from the HELIOS calculation, and $\phi_{G,s}^{hom}$ is a surface flux extracted from the FDM calculation. Two different discontinuity factors can be obtained at the left and right surfaces for each region. One discontinuity factor can also be determined for each region using a simplified equivalence theory approach as shown in Figure 7. Various sensitivity calculations showed that since discontinuity factors between the fuel blocks were close to 1.0, they could be neglected as only those between the fuel and the reflector should be considered. The reflector cross sections are adjusted by the discontinuity factors, which can be used as a reflector cross section in the VHTR core analysis.

Figure 6: Comparison of the Multiplication Factors and the Pin Powers

Temp. (K)	Multiplication Factor			Block Power Diff.(%)
	HELIOS	FDM	Diff. (pcm)	
300	1.43489	1.43933	-215	-0.2
600	1.40756	1.41171	-209	-0.3
900	1.38255	1.38605	-183	-0.5
1200	1.36580	1.36427	82	0.4

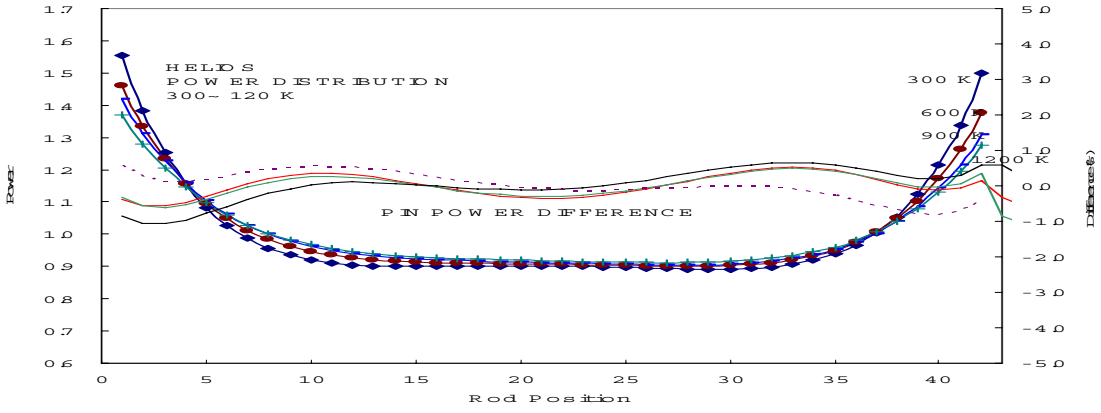


Figure 7: Region-wise discontinuity factors

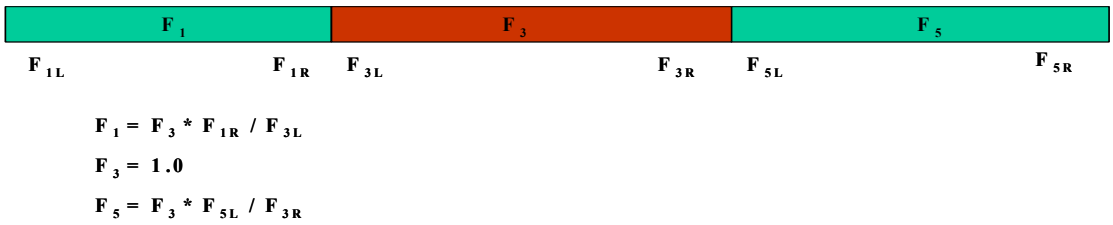
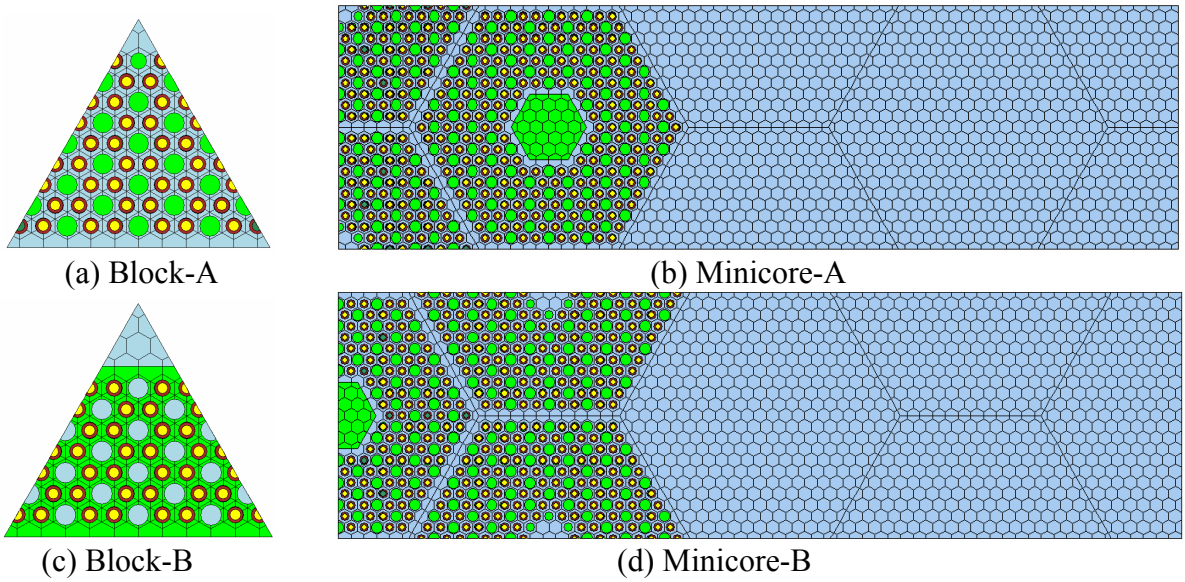


Figure 8: The HELIOS Models to generate few group cross sections



Since the implementation of the burnable poisons and the control rods will change the neutron spectra, this may cause an inaccurate prediction. Therefore, we tried two different approaches for generating the effective block cross sections. The first one was to generate the block cross sections by a HELIOS calculation for a single block, and the second one by a HELIOS calculation for a mini core.

3. Benchmark Calculation

The HELIOS/MASTER code package was applied to the physics analysis of the prismatic NGNP core developed by Idaho National Laboratory. Since the NGNP core is asymmetric, this was modified to be 1/6 symmetric. The reference solutions were obtained through the MCNP calculation by adopting the RPT method. A few group cross sections for blocks were obtained by two different models as shown in Figure 8. The first one was to generate the block cross sections by a HELIOS calculation for a single block (Case A), and the second one by a HELIOS calculation for a mini core (Case B). Reflector cross sections were obtained from the simple 1-D core model with a simplified equivalence theory.

Table 1: Comparison of the multiplication factors for the simplified NGNP core

Burnable Poison	Temp. (K)	Reactivity Difference (pcm)		
		MCNP*	MASTER [Case A]	MASTER [Case B]
No	300	1.42671	179	-170
	600	1.40045	189	-125
	900	1.37714	83	-150
Er2O3 (6 /block)	300	1.20107	255	-52
	600	1.14972	22	-83
	900	1.08220	-136	-153
Er2O3 (12 /block)	300	1.02538	113	395
	600	0.96401	-531	257
	900	0.88482	-1208	-91

* Standard Deviation < 0.00026

Figure 8: Comparison of the Radial Block Power Distribution

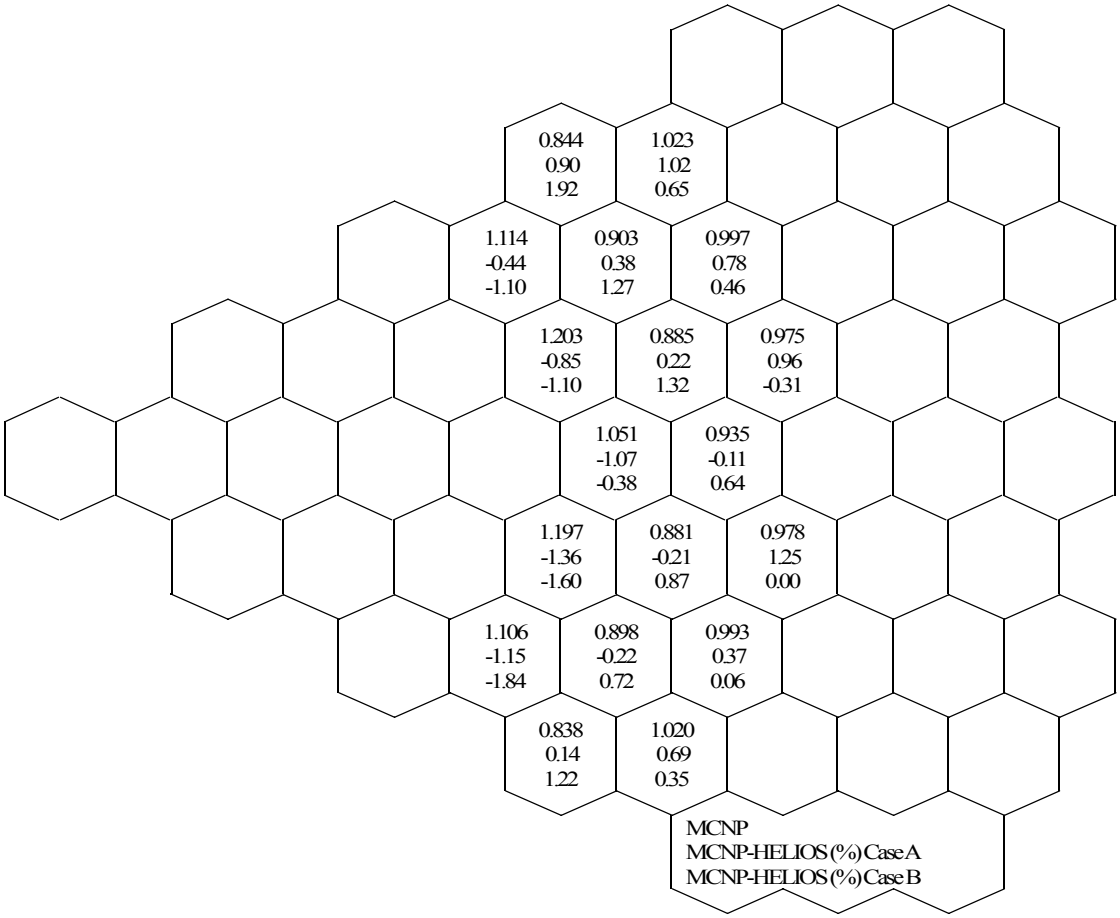
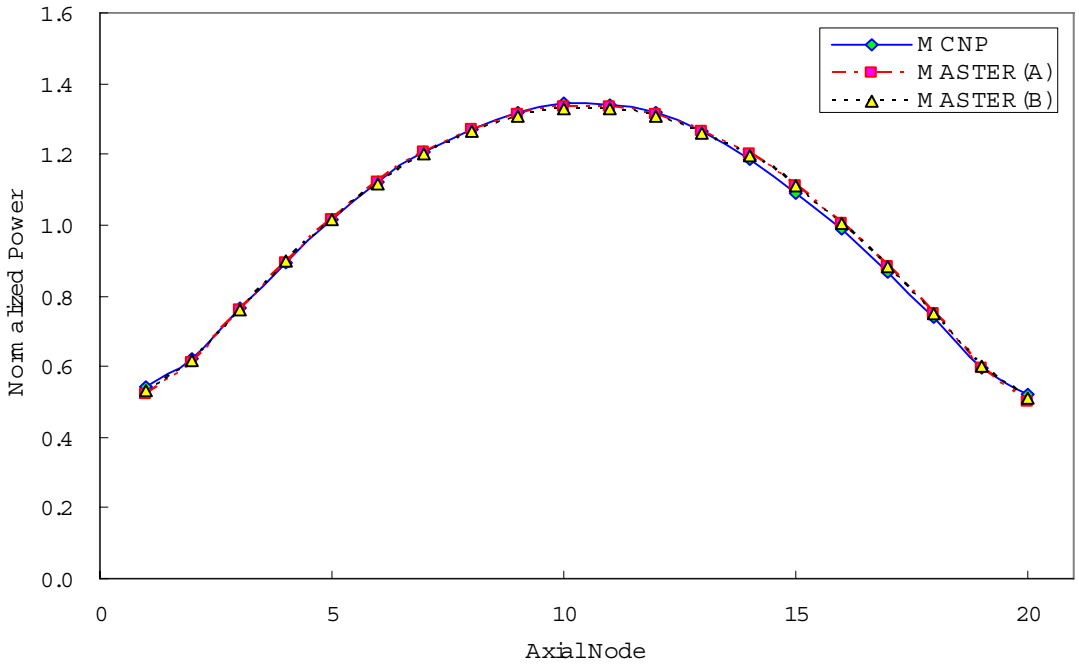


Figure 9: Comparison of the Axial Power Distribution (300 K, with Er_2O_3 rods)



Multiplication factors and power distributions of the HELIOS/MASTER package are compared with those of the MCNP as shown in Table 1 and Figures 8 and 9. In the case of the cores without any burnable poison rods and with 6 Er_2O_3 rods per block, the multiplication factors from Cases A and B are very consistent with those of MCNP to within a maximum error of 255 pcm. However, while the results of Case A for the core with 6 Er_2O_3 rods per block are not consistent with those of MCNP at the high temperatures, those of Case B are very consistent. This means that the spectral effect due to a burnable poison rod loading may not be covered by a single block model. Figure 9 shows the comparison of the radial power distributions of the HELIOS/MASTER procedure with those of MCNP at 300 K, where the maximum error is about 1.9%. As shown in Figure 9 the axial power distribution of the HELIOS/MASTER package is very consistent with that of MCNP.

4. Conclusion

We have developed a new 2-step procedure based on the HELIOS/MASTER package for a prismatic VHTR physics analysis. The strong spectral effects could be solved both by optimizing the number of energy groups and group boundaries, and by employing a mini core model instead of a single block one to generate a few group cross sections. And a new procedure to generate an effective reflector cross section has been developed by using a simple 1-D core model by adopting a simplified equivalence theory.

The results of the benchmark calculations for the modified NGNP core show that this 2-step procedure is working reasonable. This HELIOS/MASTER 2-step procedure can be applied to the

physics analysis of any type of the VHTR core with different neutron spectra. This procedure has been successfully applied to the GT-MHR core with a weapon grade plutonium fuel where the neutron spectra are much harder than those of the NGNP core.[7]

Acknowledgements

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