Development of the Optimization Procedure for the Number of Neutron Energy Groups and Boundaries in the VHTR Physics Analysis

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1. Introduction

A new nuclear design procedure based on the two-step procedure is under development for the reactor physics analysis of the very high temperature gas-cooled reactor (VHTR).[1] The MASTER[2] code was employed for the 3-D core calculation to perform the reactor physics analysis. The HELIOS[3] code was employed to generate the coarse (2~10) group cross sections by a flux-volume weighting through the transport lattice calculation with a fine (45~190) group library. In the typical 2-step procedure for a PWR, two-group structure has been used with the energy boundary of 0.625 eV or 1.855 eV. In a VHTR, since the spectral effects due to the changes of the neighboring material, temperature and burnup are very complicated, the coarse energy group structure should be optimized to consider the large spectral effects.

In this study we developed an optimization procedure and a program for the number of neutron energy groups and boundaries to be used in the VHTR physics analysis. This process is based on the simple mini core model and was applied to determine the optimal number of coarse energy groups and boundaries for the prismatic VHTR with uranium and weapon-grade plutonium fuels.

2. Methods and Results

2.1 Characteristics of the Neutron Spectra

A mini core model as shown in Figure 1 was developed to observe the characteristics of the neutron spectra for VHTR and to determine the optimal energy group structure. The mini core model includes 3 blocks including 14 pin cells where the hexagonal cell is converted into a square cell while preserving the graphite moderator volume.

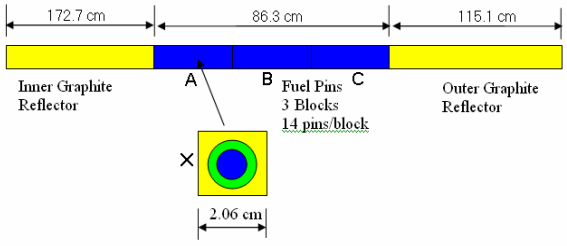
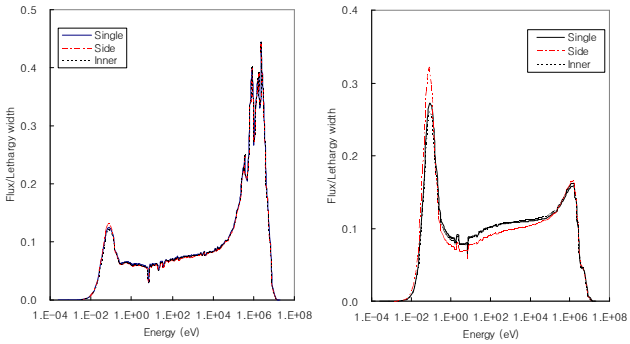


Figure 1. The VHTR mini core model

Figure 2 shows the neutron spectra with the various block locations for a PWR and a uranium fueled VHTR, respectively. Neutron diffusion lengths of the VHTR fuel and the graphite reflector are about 30 cm and 70 cm, respectively, which are 4 and 14 times as large as the PWR ones. Therefore, the environmental effect of the VHTR fuel and reflector is relatively large as shown in the figure, which makes it difficult to apply the 2-step method to the VHTR physics analysis.



(a) PWR (b) VHTR($UC_{0.5}O_{1.5}$)

Figure 2. Neutron spectra

2.2 Optimization Procedure

We have developed a procedure to determine the optimal group structure by using the HELIOS mini core models with a 190 group library. The optimization algorithm is as follows:

A. Perform the HELIOS mini core calculations using a 190 group library with the various temperatures, burnups and locations of the control rods or burnable poisons
B. Edit the scalar fluxes ($\phi_{g,i}$) and absorption ($\Sigma_{a,g,i}$) and ν*fission ($\nu\Sigma_{f,g,i}$) cross sections for the block regions
C. Collapse the energy groups by a flux weighting by increasing the number of groups one-by-one to be included in the starting macro energy group as follows:

$$\phi_{G_k,i} = \sum_{g=g_{k1}}^{g_{k2}} \phi_{g,i} \,, \tag{1}$$

$$\Sigma_{a,G_k,i} = \frac{\sum_{g=g_{k1}}^{g_{k2}} \Sigma_{a,g,i}\phi_{g,i}}{\phi_{G_k,i}}, \quad \nu\Sigma_{f,G_k,i} = \frac{\sum_{g=g_{k1}}^{g_{k2}} \nu\Sigma_{a,f,i}\phi_{g,i}}{\phi_{G_k,i}} \,. \tag{2}$$

D. Calculate the absorption ($R_{a,Gk,i}$) and ν*fission ($\nu R_{f,Gk,i}$) reaction rates for each block and each group, and the total absorption ($R_{a,i}$) and ν*fission ($\nu R_{f,i}$) reaction rates with the following equations:

$$R_{a,G_k,i} = \Sigma_{a,G_k,i}\phi_{G_k,i}, \quad R_{a,i} = \sum_{g=1}^{G}\Sigma_{a,g,i}\phi_{g,i}$$
$$\nu R_{f,G_k,i} = \nu\Sigma_{f,G_k,i}\phi_{G_k,i}, \quad \nu R_{f,i} = \sum_{g=1}^{G}\nu\Sigma_{f,g,i}\phi_{g,i} \quad . (3)$$

E. Replace the absorption or ν*fission cross sections according to the input specification, and calculate the absorption ($R'_{a,Gk,i}$) and ν*fission ($\nu R'_{f,Gk,i}$) reaction rates for each block with the following equations:

$$R'_{a,G_k,i} = \Sigma'_{a,G_k,i}\phi_{G_k,i}, \quad \nu R'_{f,G_k,i} = \nu\Sigma'_{f,G_k,i}\phi_{G_k,i}. \quad (4)$$

F. Calculate the fractional difference for the absorption and ν*fission reaction rates in *pcm* as follows:

$$\Delta R_{a,G_k,i} = \frac{R_{a,G_k,i} - R'_{a,G_k,i}}{R_{a,i}}, \Delta\nu R_{f,G_k,i} = \frac{\nu R_{f,G_k,i} - \nu R'_{f,G_k,i}}{\nu R_{f,i}}. \quad (5)$$

G. If the fractional difference for the absorption and ν*fission reaction rates in pcm are less than a certain criteria (eg. 150 pcm), go to procedure (c). If larger, then begin with the next macro group.

H. If all the macro groups are decided, calculate the infinite multiplication factors as follows:

$$k_{inf} = \frac{\sum_{g=1}^{G}\sum_{i=2}^{4}\nu\Sigma_{f,g}\phi_{g,i}}{\sum_{g=1}^{G}\sum_{i=2}^{4}\Sigma_{a,g}\phi_{g,i}}. \quad (6)$$

This Algorithm was implemented in the program called GRBOUND to determine the optimal energy group structure.

2.3 Sample Calculations

We applied the GRBOUND program to determine the optimal energy group structures for the prismatic NGNP[4] with a $UC_{0.5}O_{1.5}$ fuel and the GT-MHR[5] core with a $PuO_{1.7}$ fuel. Sixty HELIOS mini core calculations were performed for these two fuel types with various burnups, variations and temperatures as shown in Table 1. The optimal energy group structures were determined with the sixty HELIOS outputs by the GRBOUND program, which are shown in Table 2. Previously the number of energy groups and boundaries were determined manually for the prismatic NGNP. This result was compared with the GRBOUND result. While the maximum error of $k_{inf.}$ in the manual method was 127 *pcm*, the maximum one in the GRBOUND calculation was 61 *pcm*. The determined energy group structures were verified by the FDM diffusion calculations and by a comparison of the cross sections directly edited from different environments.

Table 1 Calculation cases

Case	$UC_{0.5}O_{1.5}$ fuel	$PuO_{1.7}$ fuel
Burnup	(1) 0.0 MWd/kgU (2) 70.0 MWd/kgU (3) 150.0 MWd/kgU	(1) 0 EFPD (2) 560 EFPD (3) 840 EFPD
Variation	(1) No control rod (2) Rod in block A (3) Rod in block B (4) Rod in block C (5) Rod in outer reflector	
Temperature	(1) 300 K (2) 600 K (3) 900 K (4) 1200 K	

Table 2 Energy group boundaries for NGNP and GT-MHR

$UC_{0.5}O_{1.5}$ fuel		$PuO_{1.7}$ fuel	
Group	Upper (eV)	Group	Upper (eV)
1	2.000000E+07	1	2.000000E+07
2	2.144498E+02	2	1.012999E+02
3	6.868019E+00	3	1.307904E+00
4	9.710043E-01	4	8.336811E-01
5	4.170395E-01	5	4.500015E-01
6	2.907404E-01	6	3.576701E-01
7	2.276891E-01	7	2.276891E-01
8	1.115699E-01	8	1.457206E-01
9	4.999990E-02	9	4.275520E-02
10	2.049193E-02	10	1.239596E-02

3. Conclusion

We developed a procedure and a program called GRBOUND to automatically determine the optimal energy group structure for the prismatic VHTR. The computation results showed that this procedure works effectively and efficiently. This procedure can be applied to other types of reactor cores to which the 2-step procedure can be applied.

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