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Homogenization of KMRR Hafnium Control Assembly for 3-D Diffusion Calculation

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3차원 중성자 확산계산을 위한 KMRR Hafnium 조정집합체 균질화에 대한 연구

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Abstract

The hafnium shroud is used to control the excess reactivity and power distribution in KMRR. The core analysis is performed by the diffusion code VENTURE using the 5 group macroscopic cross sections homogenized for an assembly. Investigated are the applicability of the diffusion calculation by homogenized cross sections to the analysis of control assembly which features unusual geometry such that hafnium shroud surrounds a multiplying medium inside. Comparative calculation is performed for the excess reactivity and power levels by the transport code TWOTRAN. The results show the acceptability of the difusion calculation by the homogenized cross sections without significant error.

요 약

KMRR은 잉여반응도 및 출력분포조절을 위하여 Hafnium관을 사용한다. 현재 노심해석은 핵연료집합체 단위로 균질화된 5군 군정수를 이용하여 중성자 확산코드인 VENTURE을 이용한다. Hafnium관내에 핵연료가 들어있는 특수한 조정집합체에 대해서도 이러한 균질화된 군정수를 사용한 중성자 확산계산이 적용될 수 있는가를 조사하였다. 비교계산은 중성자 수송코드인 TWOTRAN을 사용하여 잉여반응도 및 출력 준위에 대해 수행하였다. 계산결과 현재의 균질화된 군정수를 사용하는 중성자 확산계산이 큰 오차없이 적용할 수 있는 것으로 나타났다.

1. Introduction

The Korea Multipurpose Research Reactor (KMRR) has been designed for the versatile research activities and industrial applications[1]. The reactor core is classified into two parts; inner and outer core. The inner core consists of 23 sites of hexagonal zircaloy flow tubes and 8 sites of circular flow tubes on a uniform hexagonal pitch. The 36-element driver fuel assemblies may be placed in any of hexagonal flow tubes. The shutoff and control Hf-shroud designated as S and C in Fig. 1 are located at the top of circular flow tubes and inserted when required. The Hf shroud is composed of 4.5 mm thick natural hafnium and the compostion is listed in Table.1. The outer core consists of 8 circular flow tubes around the inner core. The 18-element fuel assembly or graphite block may be loaded in these

sites. These inner and outer core are embedded in the bulky D_2O reflector tank(diameter=2.0m).

Table 1 Characteritics of Hf Shroud

Isotope	Composition(w/o)
174	0.16
176	5.2
177	18.6
178	27.1
179	13.7
180	35.2
Density(g/cm^3)	: 13.3
Inner Diameter (cm)	: 6.876
Outer Diameter (cm)	: 7.776
Thickness (cm)	: 0.45

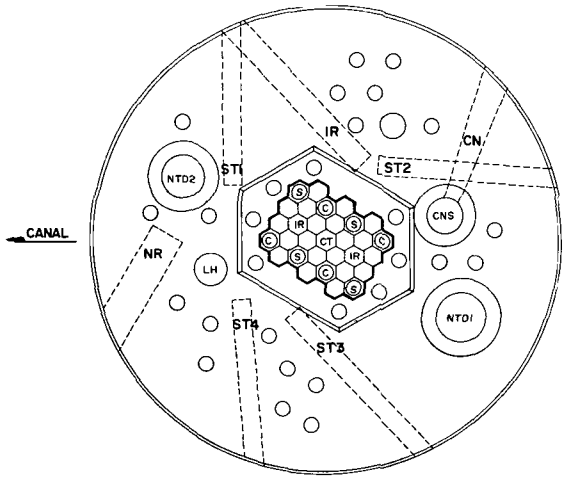


Figure 1. Plan View of KMRR Core.

The shutoff shrouds are fully withdrawn during normal operation and the control shrouds are regulated to control the excess reactivity and flux levels. Because 18-elment shim fuel assembly is loaded inside the Hf shroud, the conventional method which uses black boundary condition[2,3] can not be easily applied to this cotrol assembly. In this study, the reactivity worth of Hf shroud is evaluated by the transport calculation using the "thin region approach[4]" which represents the Hf shroud explicitly.

As mentioned above, the KMRR geometry is very complicated and hence shows strong heterogeneity. To take into accout the transport effect between fuel assemblies, the pin-by-pin fine mesh model is mostly desirable, but the irregular array of the fuel elements makes it very difficult to analyze the core characteristics using difusion theory grid model. Therefore the assembly homogenization procedure is needed prior to performing core calculation. This paper has an objective to verify the adequacy of the assembly homogenization for the control/shutoff assembly by comparing the results between heterogeneous and homogeneous treatment to the hafnium shroud. The homogenization and condensation of the lattice parameters for the region-of-interest were carried out using the system 'WIMS-KAERI'-'REGAV-K'. TWOTRAN based on transport theory and VENTURE based on diffusion theory are used to analyze the hafnium shroud discretely, and homogeneously, respectively.

2. Generation of Homogenized Parameters for Control Assembly

Two kinds of homogenized parameters are generated for the control assembly. One is the parameters homogenized to the equivalent radius of 4.2056 cm to be used in diffusion calculation for the core by the VENTURE, and the other is those homegenized for the region-of-interest in control assembly to be used in transport calculation for the core by the TWOTRAN. The detail procedures will be described in the next section.

In the control assembly, the neutronic behavior is affected by the neutron leakage from the surface and by the neutron spectrum of the adjacent fuel assemblies. With zero current boundary condition on the equivalent boundary of the control assembly, incoming neutrons from the surroundings and neutron absorption for the outer surface cannot be adequately counted, so a supercell model[8] is introduced for the generation of homgenized parameters. In the supercell the control assembly is surrounded by half of six driver fuel assemblies as shown in Fig.2. The equivalent radius of this supercell becomes 8.4111 cm.

The heterogeneous multigroup parameters are at first generated through the WIMS-KAERI for the super-

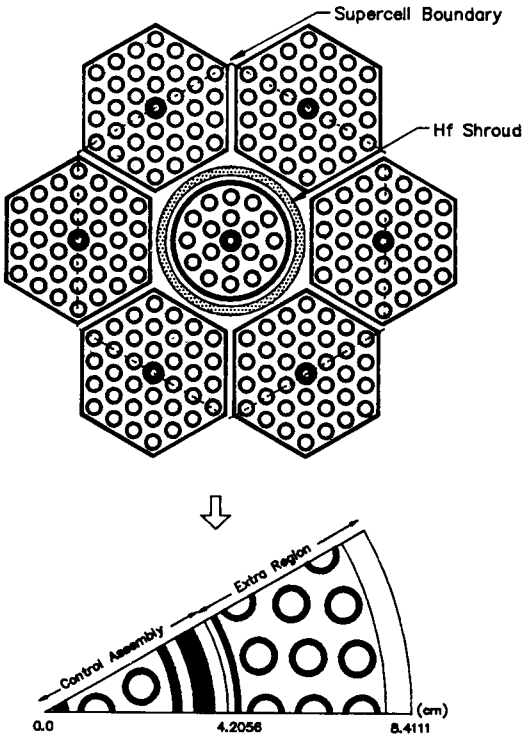


Figure 2. Supercell Modelling of Control Assembly

cell by the collision probability method(PIJ). The collision probability method is a well established theory for solving the abnormal lattice problems in reactor physics[9]. Though the WIMS-KAERI is constructed to use 69 energy group library, WIMSLIB, based on the U.K. Nuclear Data Library[10]. previous studies[11] have shown that 18 main transport group calculation is adequate for the fuelled and non-fuelled lattices of KMRR. The 18 and 5 group structures are listed in Table 2. In the 5-group structures, the first group refers to the fast neutron with energy approximately higher than 1 MeV. The second group represents the neutron with energy between fast and redsonance energy region. The third and fourth group indicate higher and lower resonance separately treated in WIMS-KAERT. 6.25 eV is the cutoff energh of the thermal neutron usually used in reactor physics.

2.1 Homogenization for Diffusion Core Calculation

Comparing a few group solution of a homogenized reactor representation with a multigroup reference solution of a heterogeneous reactor representation, the difficulty to define consistent homogenization procedure becomes obvious[12]. But the equivalence between these two representations may be postulated for certain integral values.

Table 2. Multigroup Structure

Multigroup	Energy Boundary	Few Group
1	10.0 MeV – 3.679 MeV	
2	3.679 MeV – 0.821 MeV	1
3	0.821 MeV –67.34 keV	
4	67.34 keV –15.03 keV	
5	15.03 keV – 9.118 keV	2
6	9.118 keV–48.052 eV	
7	48.052 eV–27.700 eV	
8	27.700 eV– 9.877 eV	
9	9.877 eV– 4.000 eV	3
10	4.000 eV– 1.071 eV	
11	1.071 eV– 0.996 eV	
12	0.996 eV– 0.625 eV	4
13	0.625 eV– 0.350 eV	
14	0.350 eV– 0.220 eV	
15	0.220 eV– 0.100 eV	
16	0.100 eV– 0.058 eV	
17	0.058 eV– 0.030 eV	
18	0.030 eV– 0.000 eV	5

The homogenization theory adopted in this study uses the conventional volume and flux weighting procedures. The integral reaction rates and the total leakage as known from the spectral calculation are related to each other according to the integral balance equation:

$$\frac{1}{V}\int \vec{J}_G \cdot d\vec{S} + (\Sigma_{aG} + \sum_{G'}\Sigma_{GG'})\,\phi_G = \sum_{G'}(\Sigma_{G'G} + \frac{X_G'}{K_{eff}}\nu\Sigma_{fG'})\,\phi_{G'} \quad (1)$$

where the notation has the conventinal meanings used in the reactor physics..

The postulate of homogenization, the conservation of the integral reaction rates and fluxes, leads to the statement that the flux and volume weighted cross sections should be conserved

$$\bar{\Sigma}_{\alpha i} = \frac{\int \Sigma_{\alpha G}(r)\,\phi_G(r)dv}{\int \phi_G(r)dv} \quad (2)$$

The integration over the considered region leads to a balance equations of following form:

$$\frac{1}{V}\int \vec{J}_G^{hom}\, d\vec{s} + (\Sigma_{aG}^{hom} + \sum_G \Sigma_{GG'}^{hom})\,\phi_G^{hom} = \sum_G (\Sigma_{G'G}^{hom} + \frac{X_G}{K_{eff}}\, \nu\Sigma_{fG}^{hom})\,\phi_G^{hom} \quad (3)$$

$$\Sigma_{aG}^{hom} = \frac{\int \Sigma_{aG}(r)\,\phi_G(r)dv}{\int \phi_G^{hom}(r)dv} \quad (4)$$

As in the conventional procedure these cross sections are introduced as spatially constant parameters in the few group equivalent representation:

$$\Sigma_{aG}^{hom} = \overline{\Sigma}_{aG} \quad (5)$$

The homogenization and energy condensation is performed through KAERI improved codes, REGAV-K and WIMPAK, respectively.

The leakage term is represented by the diffusion coefficient in diffusion calculation, the multigroup homogenized diffusion coefficient is defined[13] as

$$D_g^{hom} = \frac{1}{3\Sigma_{trg}^{hom}} \quad (6)$$

The condensation procedure used in WIMPAK is similar to those of WIMS[14] as

$$D_G^{hom} = \frac{\sum_g^c D_g^{hom}\,\phi_g^{hom}}{\sum_g^c \phi_g^{hom}} \quad (7)$$

1.2 Homogenization for Transport Core Calculation

The TWOTRAN code is used for the verification of homogenized cross sections of control assembly in diffusion core calculation. Because the rod-wise modeling is impossible in core calcuation, the supercell is modeled again in rectangular and few group structure.

Considering the coarse mesh model of KMRR[1], the rectangular model is determined as in Fig.3 through various modeling. The homogenization is performed for regions separately ; fuel region inside the Hf shroud (zone 1), Hf shroud only (zone 2), H_2O moderator outside the Hf shroud (zone 3) and extra fuel region (zone 4). The homogenization and energy condensation procedure is the same as previous section except the diffusion coefficient since this coefficient is not needed in transport calculation. Because the volume of fuel region and H_2O moderator is decreased and increased by 5.17% and 23.38%, respectively, in the rectangular model, the cross sections of these regions are corrected to produce the same reaction rates as those of WIMS supercell reference model by iterations. The reaction rates of each region in this supercell are compared with those of WIMS calculation in Table 3. The maximum error of reaction rates in this rectangular model is found to be 9.1% of group 5 absorption in zone 4. This model is to be adopted in reference core simulation for the analysis of control assembly.

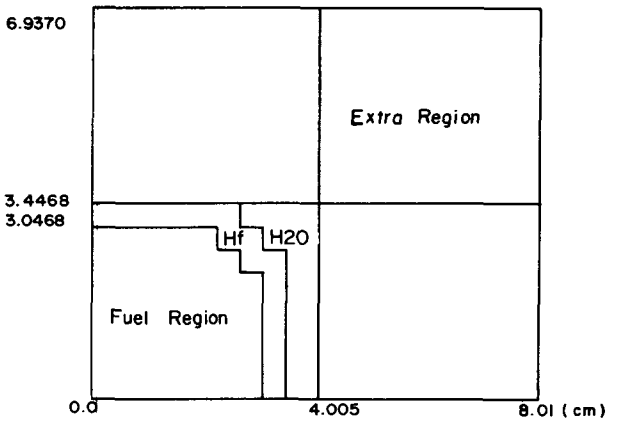


Figure 3. Reactangular Model of Supercell

The rectangular model of the supercell is analyzed for the effect of auxiliary parameters; extra region size, number of meshes and Sn order. The ratio of neutron production to absorption for the edit region is plotted according to the extra region size as shown in Fig.4. The number of meshes used for the rectangular model is compared in Fig.5. Since the TWOTRAN is designed to solve two-dimensional transport equation in multigroup discrete ordinate approximation, the calculation results may depend on Sn order. The rectangular model which uses S_4 order is compared with the result of different Sn order as shown in Fig.6. S_8 quadrature

Table 3 Comparison of Reaction Rate Ratio

Group	Reaction	Zone 1	Zone 2	Zone 3	Zone 4
1	Absorption	0.964	1.010	1.041	1.002
	Nu-fission	0.954	-	-	1.003
2	Absorption	0.990	0.976	***	1.014
	Nu-fission	0.987	-	-	1.007
3	Absorption	1.001	1.012	1.029	1.009
	Nu-fission	0.996	-	-	1.009
4	Absorption	0.984	0.997	1.034	1.007
	Nu-fission	0.989	-	-	1.007
5	Absorption	0.954	0.917	0.909	1.091
	Nu-fission	0.963	-	-	1.033

$$\text{Ratio} = \frac{\text{TWOTRAN Rectangular Model}}{\text{WIMS Supercell Model}}$$

*** The absolute value of reaction rate is too low to be compared in this table.

set is mostly preferable, but unacceptible computing requirement prohibits the use of it and hence S_4 is chosen as the reference set. Comparing to the converged values, the present model lies in the range of 2.5, 0.01 and 0.4% error bounday for the following effects;extra region size, number of meshes and Sn order, respectively.

3. Core Simulations and Results

The homogenized cross sections of the control assembly are assessed by the two-dimensional core si-

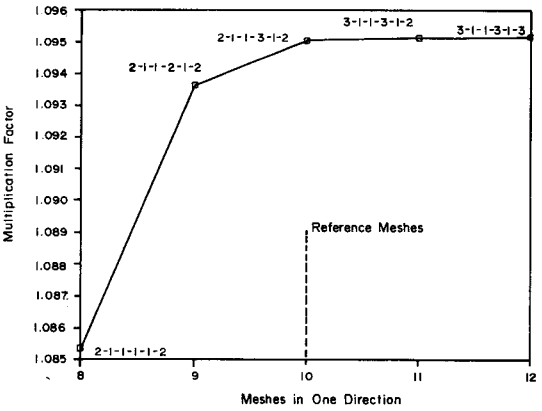


Figure 5. Effect of Meshes

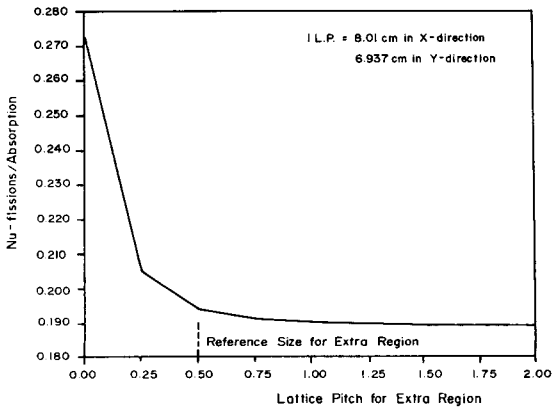


Figure 4. Effect of Extra Region Size

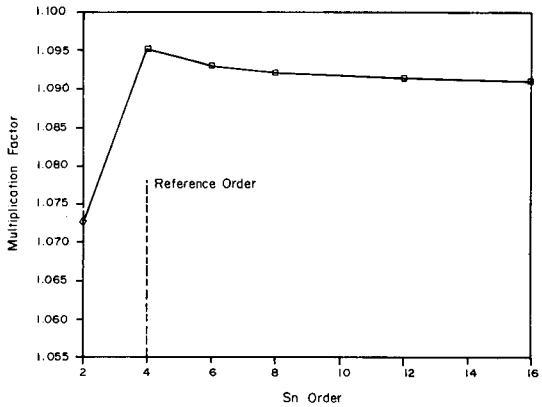


Figure 6. Effect of Sn Order

mulations; X-Y and R-Z calculation. The core calculation is performed at first by the TWOTRAN which uses the heterogenous Hf shroud model. The results of this simulation are compared with those of VENTURE calculation which uses the homogenized control assembly cross sections.

All the experimental facilities are excluded and fuels are assumed to be fresh. The reactor is analyzed in 1/4 core geometry as shown in Fig.7. The rectangular model of control assembly is adopted in core model. The core simulations are performed for 4 different cores ; core 1 has all Hf shroud out, core 2 has upper Hf shroud (CA) inserted, core 3 has lower Hf shroud(CB) inserted and core 4 has all Hf shrouds inserted. The results of transport and diffusion core calculation are shown in Table 4 and Fig.8. The assembly power distributions are summarized in Table 5 for the core 4 (refer Fig. 7) which shows the largest (0.66%) error in multiplication factor. Except the control assembly, the diffusion calculation yieds the maximum error of 10.0% in power distribution compared to transport calculation. Though the control assembly (CA) shows large error, the amount of power generated by this assembly corresponds to only 2.2% of reactor total power. This error may be due to the environmental D_2O moderator which has not been considered in the supercell model.

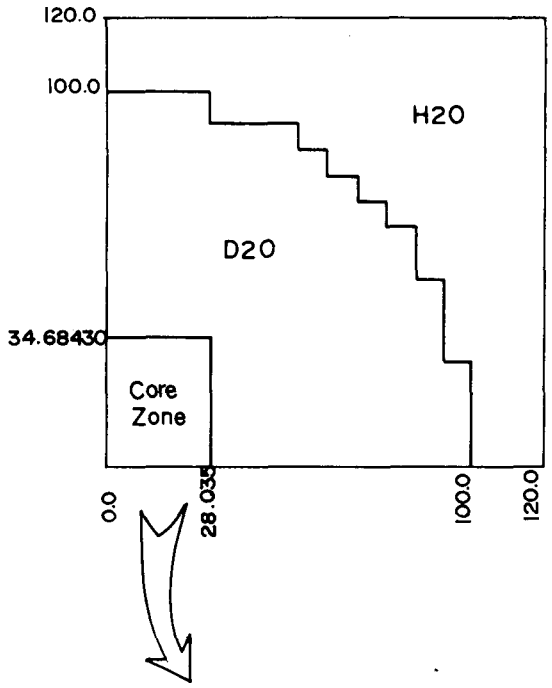
The core simulation is performed again in R-Z geometry to analyze the axial flux distribution. The reactor is simplified to cylindrical geometry. Because the Hf shroud cannot be modeled explicitly at its site, a sample Hf shroud is assumed to be inserted in the central thimble region. The cross sections of control assembly in tranport calculation is separately homogenized as in rectangular model without cross section corrections. The simulation is performed for 3 different cores; core 5 has Hf shroud out, core 6 has Hf shroud inserted by half and core 7 has Hf shroud fully inserted. The results of transport and diffusion calculation are shown in Table 6 and Fig.9. It can be concluded that the diffusion calculation produces conststent results as transport calculation.

Table 4 Results of 1/4 Core Calculation

Core	Transport		Diffusion		difference
	K	Hf-worth(mk)	K	Hf-worth(mk)	$\triangle \rho$ (mk)
Core 1	1.45713178	-	1.4529387	-	-
Core 2	1.30873278	77.82	1.3035476	78.88	1.06
Core 3	1.27483338	98.14	1.2745449	96.33	-1.81
Core 4	1.06381331	253.73	1.0707796	245.64	8.09

Table 5 Assembly Power Distributions

Assembly	Site	Transport Calculation(kw)	Diffusion Calculation (kw)	Difference (%)
Control	CA	2.38	3.29	38.2
Assembly	CB	2.72	2.67	-1.8
	D1	8.37	7.97	-4.8
	D2	7.34	7.76	5.7
	D3	21.82	19.63	-10.0
Driver	D4	15.28	14.86	-2.7
	D5	13.70	14.71	7.4
	D6	19.46	18.77	-3.5
Outer Core		15.28		9.2



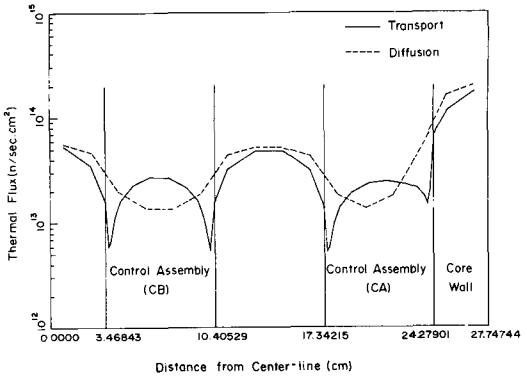


Figure 8. Thermal Flux Distribution through Control Assembly

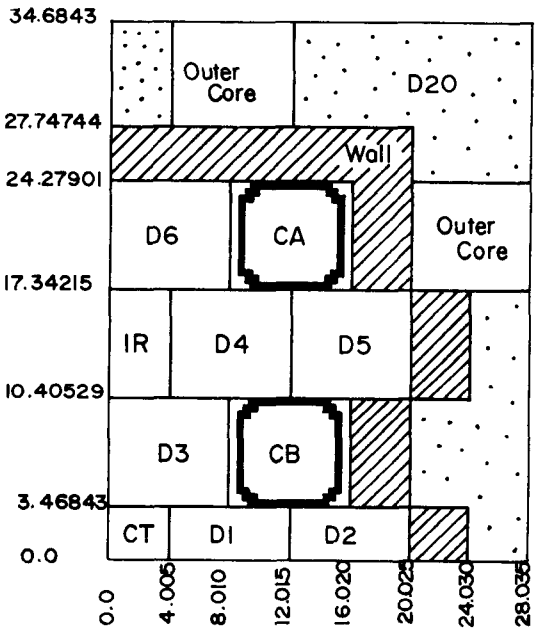


Figure 7. Horizontal 1/4 Core Model

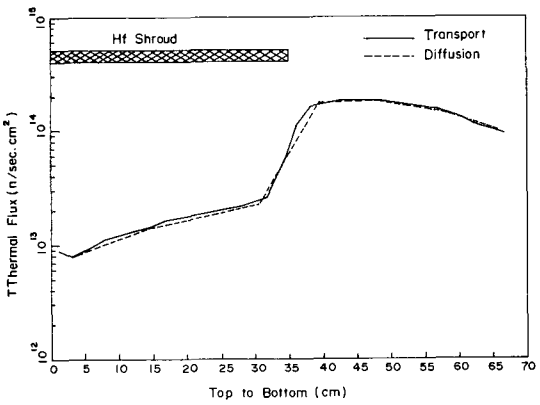


Figure 9. Axial Thermal Flux Distribution

Table 6 : Results of R-Z Core Calculation

Core	Transport		Diffusion		difference
	K	Hf-worth(mk)	K	Hf-worth(mk)	$\triangle \rho$ (mk)
Core 5	1.37737146		1.3736789	-	-
Core 6	1.34679096	16.49	1.3444445	15.83	-0.66
Core 7	1.31424161	34.88	1.3115308	34.50	-0.38

4. Conclusion

The homogenization procedure for the hafnium control assembly was evaluated by the diffusion calculation for the core. Unlike conventional control rod design, the control absorber bundle of KMRR features a unique geometry such that, when inserted, Hf shroud surrounds the circular flow tube in which 18 element fuel bundle or beryllium block occupies. Since Hf shroud faces the multiplying medium on both surfaces, single bundle homogenization is considered to be not appropriate. Therefore, a supercell model has been developed to account for the effect of surrounding multiplying medium. In this study, the homogenization procedure adopts a flux-volume weighting scheme. It has been shown that this scheme can produce the results which are fairly consistent with those of transport core simulation using discrete absorber representation in terms of the multiplication factor and flux distribution.

Because the control Hf shroud moves from the mid-plane to top of the core during normal operation, the reactivity worth of control Hf shroud can be evaluated by diffusion core simulations with good accuracy. Both the control and shutoff shrouds are inserted when reactor is tripped. The shutdown reactivity worth of the diffusion core simulation is estimated to be lower by 3.2% than that of transport simulation. Thus the prediction of control bundle worth by diffusion core calculation with homogenized cross sections is still considered to be within acceptable range.

Although the multiplication factor and flux levels show good agreement between the diffusion and transport core simulations, the production rates of control assembly still has some discrepancy between them. This problem is to be solved by some corrections in homogenization method in the future.

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