Verification of AEGIS/SCOPE2, a Next-Generation In-Core Fuel Management System

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Abstract

AEGIS/SCOPE2 is a next-generation code system for in-core fuel management of PWRs; AEGIS is a 2-D lattice code which treats heterogeneous geometry based on the MOC, while SCOPE2 is a highly efficient parallel code which performs multi-group nodal-transport calculations in 3-D pin-by-pin geometry. Cross sections for SCOPE2 calculations are provided by AEGIS. In this paper, a preliminary result of numerical performance by the AEGIS/SCOPE2 system is presented.

In assembly calculations, prediction results by AEGIS were compared with reference results by MVP, a continuous-energy Monte-Carlo code, for k_∞ and fission rate distributions within an assembly. Good agreement between the codes was observed. A preliminary result of burnup calculation is also presented with comparisons of k_∞ between AEGIS and MVP-burn, a burnup code coupled with MVP. AEGIS predicted k_∞ within $\pm 0.2\ \%\Delta k/k$ throughout burnup up to 60GWd/t compared to the reference.

An initial core of a commercial PWR at HZP was analyzed with AEGIS/SCOPE2 using nuclear data libraries including ENDF-B/VI rev.8, B/VII beta0 and JENDL-3.3. In this preliminary study, the criticality was a little underestimated, however assembly-wise power distribution was predicted in good accuracy.

KEYWORDS: AEGIS, SCOPE2, in-core fuel management, next-generation system, assembly calculation, burnup calculation, core calculation

1. Introduction

The SCOPE2 methodology that is the multi-group nodal SP3 transport calculation in 3-D pin-by-pin geometry[1] has been successfully adopted to in-core fuel management of commercial PWRs[2]. SCOPE2 gives good numerical performance to the current design of fuel assembly. The evolution of the fuel assembly, however, brings highly spatial

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heterogeneity of neutronics properties in the commercial LWRs. Furthermore, the concept of advanced fuel assemblies of Generation IV reactors are more complicated[3] and their neutronics properties will be more heterogeneous. In order to accurately compute such highly heterogeneous cores, AEGIS/SCOPE2, a core calculation system of next generation, is being developed by NEL and NFI in cooperation with Nagoya University.

The AEGIS code[4-6] is a 2-D multi-group lattice physics code based on the method of characteristics[7]. The effective cross sections are estimated by ultra-fine-group calculation[8]. The cross sections are collapsed into 9 groups using neutron spectra in assembly calculations to be used in SCOPE2 calculation. In order to minimize the error due to homogenization within a fuel cell for SCOPE2 calculations, the SPH method[9] is adopted.

SCOPE2 solves the multi-group nodal SP3 transport equations in 3-D pin-by-pin geometry. Although its computation load is considerably heavy, SCOPE2 achieves practical computation time by the use of efficient numerical algorithms and parallel computing; for example, a depletion calculation for reload core design can be finished within a few hours or less depending on the number of processors because of very good scalability.

Numerical performance of the next-generation in-core fuel management system depends on accuracy of effective cross sections generated by lattice physics code and that of core calculation code. In order to achieve good performance, therefore, it is very important for the both codes to give accurate numerical results at each stage. Thus a set of numerical verification of ASEGIS/SCOPE2 system was performed comparing with reference results by continuous-energy Monte-Carlo code and measurement data in an initial startup test of a commercial PWR.

In this paper, preliminary results of assembly calculations, a burnup calculation in cell geometry, core calculations are presented.

2. Verification

2.1 Assembly Calculation by AEGIS

Calculations were performed in assembly geometry with AEGIS for a variety of enrichments: 2.0, 3.5 and 4.1wt%. Effective cross sections in resolved resonance energy domain were treated by the ultra-fine energy group (32000 groups) structure for better accuracy while others are calculated based on the equivalent theorem and NR approximation. The ultra-fine group cross sections were collapsed in the 172-group structure with the neutron spectra obtained in AEGIS calculations within single cell geometry[8]. Then the multi-group cross sections were assigned into single assembly geometry to solve the neutron transport. After the collapse into the 9-group structure, cross sections for each cell are obtained. In AEGIS calculations, heterogeneity inside a 17x17-type assembly was accurately treated with its capability of flexible description of geometry.

Numerical results by AEGIS were compared with that by MVP, a continuous energy Monte-Carlo code developed by JAERI[10]. As a common nuclear data library for the both codes, the ENDF/B-VI rev.8 was adopted. In comparison of results between MVP and AEGIS with the identical nuclear data file, validity of AEGIS calculation was examined. The effect on change of nuclear data file was also examined with ENDF/B-VII beta0 and JENDL-3.3 within AEGIS calculations. Generation of the AELIB, a cross section library for AEGIS, is discussed in other paper[11].

Table 1 summarizes the results of k_∞ by MVP and AEGIS for each library. The results of AEGIS were obtained in calculations with 172-group structure. In the case of no-BPR(Burnable Poison Rod), the k_∞ predicted by AEGIS with ENDF/B-VI rev.8 (indicated as B6.r8 in Table 1) agreed well with that by MVP. This fact indicates that preparation of cross sections and neutron transport calculations are properly conducted in the code. For the cases when RCC is instead, slight bias approximately 0.35% Δk/k was observed. Difference in the worth of RCC between two codes, however, was approximately 160 pcm which is reasonably small for this calculation condition in terms of single assembly geometry.

Figure 1 is an example of comparisons on pin-wise fission rate distribution of the case that RCC was inserted in an assembly of 2.0wt% enrichment. It showed good agreement between MVP and AEGIS where the maximum error was approximately 0.5%. For other configurations with less heterogeneity, it showed very good agreement with smaller errors.

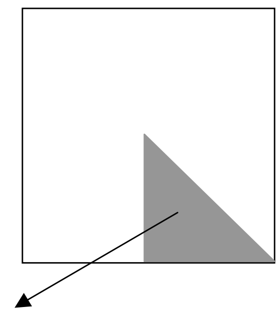
Table 1: Comparison of k_∞ in single assembly geometry.

U-235 Enrich.	BPR/RCC	Reference	AEGIS			
		MVP (B6.r8)	B6.r8 (Error)		B7.b0	J33
2.0%	None	0.97012	0.9695	0.07%	0.9718	0.9687
	12BPR		0.8709	-	0.8728	0.8701
	RCC	0.65487	0.6526	0.35%	0.6537	0.6517
3.5%	None	1.15880	1.1581	0.06%	1.1605	1.1573
	12BPR		1.0635	-	1.0656	1.0627
	16BPR		1.0357	-	1.0377	1.0349
	20BPR	1.00838	1.0074	0.10%	1.0093	1.0065
	24BPR		0.9814	-	0.9832	0.9805
	RCC		0.8234	-	0.8247	0.8225
4.1%	None	1.20572	1.2052	0.04%	1.2075	1.2052
	20BPR	1.05902	1.0582	0.07%	1.0601	1.0581
	24BPR		1.0325	-	1.0343	1.0323
	RCC		0.8707	-	0.8721	0.8704

BPR: Burnable Poison Rod   RCC: Rod Cluster Control

Figure 1: Comparisons of Fission Rate Distribution in an octant of an assembly (2wt% enrich, RCC-in Case, ENDF/B-VI rev.8 library)

IT								
1.058 1.060 -0.2	1.023 1.025 -0.2	--AEGIS --MVP --(AEGIS-MVP)/MVP						
0.913 0.915 -0.2	0.947 0.951 -0.5	0.919 0.922 -0.3						
RCC	0.855 0.855 0.0	0.845 0.846 -0.1	RCC					
0.843 0.841 0.2	0.897 0.898 -0.2	0.890 0.891 -0.2	0.820 0.818 0.3	0.841 0.841 0.0				
0.850 0.847 0.4	0.906 0.907 -0.1	0.900 0.900 0.0	0.825 0.820 0.6	0.819 0.816 0.3	RCC			
RCC	0.887 0.886 0.1	0.887 0.886 0.1	RCC	0.889 0.887 0.2	0.963 0.962 0.1	1.096 1.096 0.0		
0.955 0.956 0.0	1.006 1.008 -0.3	1.012 1.015 -0.3	0.974 0.976 -0.2	1.052 1.053 -0.1	1.124 1.123 0.1	1.198 1.196 0.1	1.259 1.257 0.2	
1.085 1.084 0.0	1.095 1.096 -0.1	1.103 1.104 -0.1	1.111 1.111 0.0	1.151 1.152 -0.1	1.201 1.201 0.0	1.255 1.254 0.1	1.301 1.298 0.2	1.335 1.333 0.1



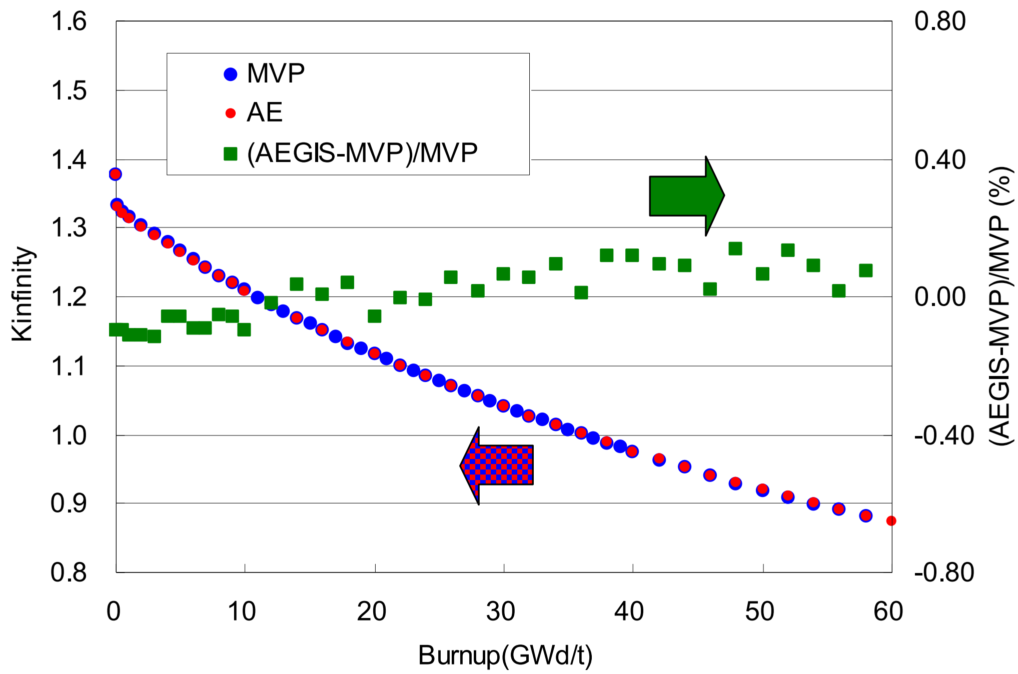
2.2 Burnup calculation by AEGIS

Accuracy of burnup calculation in AEGIS was also examined through comparison with MVP-burn, a burnup calculation code coupled with MVP. In order to perform very precise comparison between two codes, calculations were performed in pin cell geometry. A typical fuel cell of PWR with 4.1wt% enrichment of U-235 was selected for the examination. Burnup calculation up to 60GWd/t was conducted with a detail burnup chain with 221 nuclides. Note that the identical burnup chain and nuclear data library (ENDF/B-VI rev.8) were used in this examination for the both codes. In MVP-burn calculations, one million histories of neutron were tracked so that uncertainties on integral reaction rates of each nuclide can be negligible, which affects accuracy of burnup calculation. The predictor-corrector method was applied in calculations by both codes. In MVP-burn calculations, more burnup steps are introduced to retain good accuracy.

Figure 2 shows predicted k-infinity values by two codes and its difference. Note that the results by AEGIS are still preliminary. The difference was below 0.15%Δk/k throughout the burnup. The uncertainty on k_∞ by MVP at 0GWd/t and 58GWd/t were 0.03% Δk/k and 0.06%Δk/k, respectively. The effective uncertainty seemed approximately 0.1Δk/k, including the effects due to error propagation of number densities. Although a slight dependency of the difference on burnup was observed, therefore, the difference might has only small impact on prediction of core characteristics in actual applications of AEGIS.

For further study, examinations for dependency on enrichment and/or combination of fuel types will be conducted. Comparisons of burnup characteristics in larger geometry such as assembly geometry of PWR should be done in future study.

Figure 2: K-infinity versus burnup (4.1wt% enrichment UO2 pin cell)



2.2 Core Calculation by SCOPE2

Analysis of an initial core of 3-loop type PWR at the HZP (hot zero power) condition was performed using SCOPE2 with 9-group cross sections generated by AEGIS. In order to preserve reaction rates in heterogeneous calculation by AEGIS within the framework of pin-by-pin system with homogenization inside a cell, the SPH method was adopted. The SPH correction factors were calculated by an auxiliary code and used in SCOPE2 calculations.

As the first step of verification of the AEGIS/SCOPE2 system, the following strategies were chosen:

1. Cross sections from AEGIS and associated SPH factors are directly used in SCOPE2. No compile of cross sections and SPH factors are involved.

2. Cross sections are prepared under the measure conditions: critical boron concentration, fuel/moderator temperature and so on.

3. K-effective search without feedback is performed; No update is done for cross sections.

4. No depletion is considered.

5. Cross sections for baffle reflector and moderator are generated by CASMO-4.

Three sets of cross sections based on difference nuclear data files were prepared by AEGIS, namely ENDF/B-VI rev.8, ENDF/B-VII beta0 and JENDL-3.3. K-effective values by SCOPE2 were summarized in Table 3. As conditions in AEGIS and SCOPE2 calculations are normalized to the measured value, predicted k-effective should be unity. SCOPE2 slightly underestimated the criticality, ~0.2%Δk/k. Power distribution by SCOPE2 was also compared with measured map. Figure 3 shows the error of assembly-wise power distribution when ENDF/B-VII beta0 was utilized.

Table 2: Comparison of k-effective by SCOPE2 versus nuclear data source of AELIB, the library of AEGIS.

AELIB source	SCOPE2 K-effective
ENDF/B-VI rev.8	0.99400
ENDF/B-VII beta0	0.99656
JENDL-3.3	0.99387

Figure 3: Discrepancy of relative assembly-wise power at HZP condition between AEGIS/SCOPE2 and measured map (Library: ENDF-B/VII beta0, Unit: %)

-2.7	-3.2	-1.8	-1.9	0.8	0.9	2.8	3.1
-2.9	-1.7	-2.2	-0.9	-0.3	1.3	1.4	2.9
-1.7	-2.1	-0.2	-1.3	-0.4	-0.1	1.1	
-1.3	-0.3	-1.0	-0.5	-0.6	0.1	0.7	
0.8	-0.2	-0.5	-1.2	-0.1	0.2		
0.4	0.9	-0.2	-0.1	0.2			
2.6	1.2	0.7	0.6				
2.7	2.4						

RMS : 1.4 [%]

3. Conclusion

In order to accurately predict properties in highly heterogeneous systems, AEGIS/SCOPE2, a core calculation system of next generation, is being developed by NEL and NFI in cooperation with Nagoya University. Especially, AEGIS has been actively implemented by all the party with careful verification studies at each development stage, while SCOPE2 has been matured as a core calculation for production use. In this paper, its numerical performance was presented as a set of preliminary results in verifications at the very first stage.

In assembly calculations, the results by AEGIS aggraded with the reference by MVP, a continuous energy Monte-Carlo code. Therefore cross sections prepared by AEGIS were expected to be proper. A result of burnup calculation by AEGIS was also agreed well with the result by MVP-burn, a burnup code based on MVP. Future studies are expected to investigate accuracy of the models implemented in AEGIS.

In core calculations, prediction by SCOPE2 was satisfactory at this preliminary stage in comparisons with measured data. In this examination presented here does not include conditions, which is indispensable to in-core fuel management, such as feedback calculations, reconstruction of cross sections using tabulated data, and so on. Preparation of cross sections for baffle reflectors by AEGIS is also an important subject since accuracy on cross sections for baffles greatly affects the leakage from the core.

AEGIS/SCOPE2 is one of the most innovative systems for in-core fuel management of commercial PWRs. The accuracy and flexibility of the system will bring benefits to the aspects in design and operation.

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