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Establishment and Preliminary Verification of the nTRACER-RENUS Core Analysis System

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1. Introduction

Although direct whole core calculation becomes the current trend in the development of the reactor analysis methods, two-step core calculations are still necessary and preferred in the industrial applications because of the merit in calculation efficiency. In this regard, the nTRACER-RENUS core analysis system has been established at Seoul National University for the application of the direct whole core transport code nTRACER [1] to the two-step calculations in which the RENUS nodal code [2] is used for fast core calculation. Here nTRACER is used for group constant (GC) generation through the assembly lattice transport calculations and the whole core nTRACER calculation results can be used as the reference to evaluate the two-step calculation method based on the same multigroup cross section (XS) library data.

In order to resolve the conventional problem of estimating proper few-group constants to be used in the core calculation considering the surrounding effect in the core, the new leakage correction and peripheral assembly treatment method [3] are implemented in the nTARCER-RENUS calculation system. In order to generate the two-group condensed XSs or group constants (GC) properly functionalized as a function of state parameters including the leakage fraction, a utility code N2R (nTRACER-to-RENUS) was developed. It tabulates all kind of group constants consisting of microscopic XSs and assembly discontinuity factors (ADFs) as a function of burnup and thermo-hydraulic (T/H) parameters.

In this paper, the detailed procedure of generating and functionalizing the GCs is introduced and a preliminary verification of the nTRACER-RENUS system with N2R is performed by applying it to the analysis of an Advanced Power Reactor 1400 (APR1400) core by comparing the two-step solutions with the direct whole core solutions.

2. The nTRACER-RENUS system

Although nTRACER was originally developed for direct whole core transport calculation, it can also be used to generate assembly homogenized and group-condensed GCs using the assembly transport calculation results. Although the GC generation is straight-forward, elaborations are required in the functionalization of the GCs particularly over burnup. In the following the details of the GC generation and functionalization are given.

2.1 Generation of Group Constants

While the microscopic GCs are obtained by the usual flux-volume weighting scheme, the diffusion coefficients are obtained from the homogenized transport XS as follows:

$$\overline{\Sigma}_{tr,g} = \frac{\sum_i^V \Sigma_{tr,g,i}\phi_{g,i}V_i}{\sum_i^V \phi_{g,i}V_i} \rightarrow D_g = \frac{1}{3\overline{\Sigma}_{tr,g}} \rightarrow D_G = \frac{\sum_{g\in G} D_g\overline{\phi}_g}{\sum_{g\in G}\overline{\phi}_g} \quad (1)$$

where $\overline{\Sigma}_{tr,g}$ is the homogenized XS in fine group g, and D_G is the condensed diffusion coefficient in few group G.

Assembly Discontinuity Factors (ADF), which are defined as the ratio between the surface average flux and the average flux from the single assembly (SA) calculation, are obtained as follows[4]:

$$f_{ADF} \equiv \frac{\phi_{surf}}{\phi_{avg}} \quad (2)$$

2.2 Functionalization of Group Constants

N2R produces the isotope-wise microscopic XSs from the outputs of nTRACER and functionalizes those for the use in RENUS. The functionalization of XS for T/H feedback and depletion is based on Eq. (3) such that XSs are a function of burnup, boron concentration, fuel and moderator temperature and the density of moderator. Note that the derivative of moderator temperature includes the effect of moderator density change at a constant pressure condition, namely it is the total derivate. And the partial derivative for the moderator density effect for the non-reference pressure condition such as the LOCA condition is given additionally.

$$\begin{aligned}&\sigma(BU, ppm, T_f, T_m, \rho_m)\\&= \sigma(BU, ppm_0, T_{f0}, T_{m0}, \rho_{m0})\\&+\frac{\partial\sigma}{\partial ppm}(ppm - ppm_0) + \frac{\partial\sigma}{\partial\sqrt{T_f}}(\sqrt{T_f} - \sqrt{T_{f0}}) \quad (3)\\&+\frac{d\sigma}{dT_m}(T_m - T_{m0}) + \frac{\partial\sigma}{\partial\rho_m}(\rho_m - \rho_{T_m,P_0})\end{aligned}$$

Unlike other GC editing utility codes, N2R has the unique feature of automatically determining the burnup point in the functionalized GC table. This is an additional feature to using the user-defined burnup steps which was introduced to make sure that the GC interpolation error becomes less than the given criteria in terms of k_∞. With this feature, the GC set retains the desired accuracy with fewer depletion points. In the interpolation over burnup, N2R uses not only the piece-wise linear scheme, but also the second order Lagrange method which can be selected by the user.

Fig. 1 shows the result of the auto-selection scheme with the two interpolation methods. Out of a total of 61 burnup points given in the reference, the auto-selection function can generate the GC library having the interpolation error than 50 pcm error by only choosing 9 points with the second order Lagrange scheme or 11 points with the piece-wise linear interpolation scheme, which is only one sixth of the original library size. Although the second order Lagrange method has more accurate, the compression factors are almost the same as the piece-wise linear method. Thus, considering its simplicity, currently, the piece-wise linear method is set as the default.

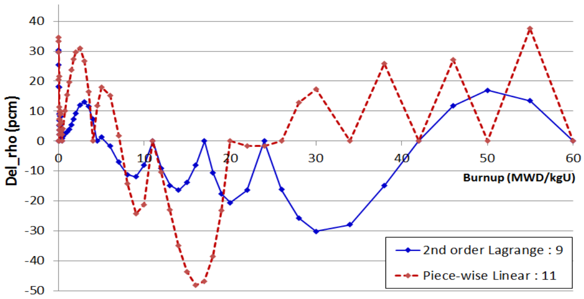

Fig. 1. Auto-selection scheme with the two interpolation methods

2.3 Reflector Group Constants

There are at least three types of the fuel-reflector configurations in a core. The I-type constitutes a two assembly size local problem while the L-type and corner type require 2-by-2 assembly size local problems. The discontinuity factors (DFs) of the reflector which affects the core radial power profile significantly are determined such that the nodal solution can preserve the reference heterogeneous solution in the local problem in which the GCs are generated. As there is only one degree of freedom for each interface between the fuel and reflector, the reflector DF(f^*) in the local problem is determined such that:

$$f^* = \frac{\phi_{surf}^{fuel}}{\phi_{surf}^{refl}} \qquad (4)$$

Where ϕ_{surf}^{refl} and ϕ_{surf}^{fuel} are the surface flux of the homogenized reflector and fuel assembly.

The ratio f^* is then multiplied by the ADF of the neighboring fuel assembly, which is obtained from SA calculation, in order to obtain the discontinuity f^{refl} between the fuel and reflector in the core calculation as:

$$f^{refl} = f_{ADF}^{fuel} f^* \qquad (5)$$

3. Preliminary Verification

An APR1400 fresh core is solved for the verification of the newly established nTRACER-RENUS system. The direct whole core transport solutions of nTRACER are used as the reference of each test case. The fixed uniform temperatures at the HFP core average condition are set to be the base conditions of the GC generation. Each branch case has four different variations, and can be used in the further detailed analysis. The base pressure condition is 15.514 MPa and the pressure variation for moderator density change is made from 10.0 MPa to 16.0 MPa. Table I summarizes the calculation condition of each branch state. There are one base condition and 16 branch conditions.

Table I: Base and branch conditions of GC generation

Case	*Boron (ppm)*	*Temp. of Fuel(℃)*	*Temp. of Mod.(℃)*	*Density of Mod.(g/cm³)*
Base	**1200**	**606.68**	**308.94**	**0.7072**
1	1	291.30	291.30	0.6938
2	300	450.00	300.00	0.6989
3	600	817.42	316.95	0.7037
4	900	1145.13	324.83	0.7083

The leakage effect on the GC are considered in three ways: the B1 method which considers amount of leakage in critical core, the Leakage Feedback Method (LFM) [3] which counts the actual leakage effect determined in the core calculation, and the additional Peripheral Assembly Treatment (PAT) [3] which employs a special treatment for the peripheral fuel assemblies.

3.1 Single Assembly

The single assembly infinite medium condition without any T/H feedback was used as the first state to verify the system. As the result, the k_∞'s of the nTRACER references and the nTRACER-RENUS results based on N2R matches exactly as it should be.

For the verification of the T/H feedback function of nTRACER-RENUS system with N2R, two kinds of 1D axial problem with a single assembly were performed. The one is the fixed power, boron variation case and the other is fixed boron, power variation case. The effective fuel temperature used in RENUS was obtained from a least square fitting to determine the optimized weighting factor between fuel center line and fuel surface temperature which resulted in 0.64.

Table II and Fig. 2 show the summarized RENUS results and its errors relative to the nTRACER reference. The inlet temperature of moderator at 100% power in two codes is same as 291.3 ℃ which is given, but outlet temperature of nTRACER and RENUS is different as 325.04 ℃ and 325.16 ℃ due to using different steam table. In the boron variation cases with fixed power, the largest reactivity error is -12 pcm and the power error is 1.58%. And in the power variation cases with fixed boron, the largest reactivity error is -45 pcm and power error is 1.47%.

Table II: Summary of 1D axial SA results(A0 type)

		nTRACER (reference)	k_∞	Δρ (pcm)	RMS* (%)
Boron (100%)	10 ppm	1.18809	1.18805	-3	1.58
	500 ppm	1.09018	1.09007	-9	0.96
	1200 ppm	0.97728	0.97717	-12	1.17
Power (500ppm)	HZP	1.09984	1.09929	-45	0.69
	25 %	1.09767	1.09723	-37	0.49
	75 %	1.09276	1.09261	-13	0.86
	100 %	1.09018	1.09007	-9	0.96
	150 %	1.08451	1.08456	4	1.47

* Assembly-wise power RMS

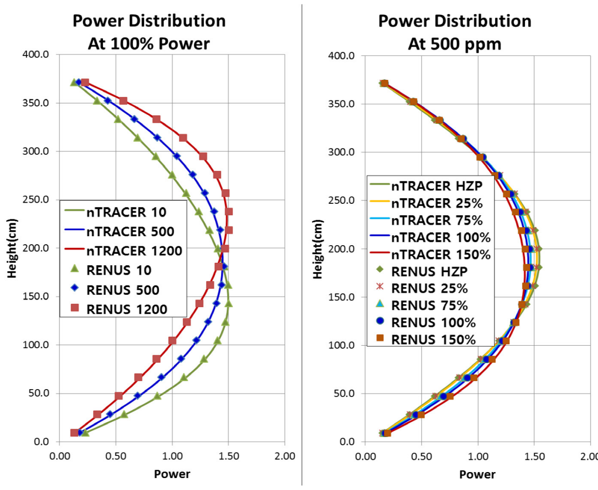

Fig. 2. Comparison of 1D axial power distributions

Next the depletion calculation for a 0D SA condition was performed to verify the burnup functionalization up to 30 MWD/kgHM. The number of selected depletion points was 38 and it appears that the intervals between the depletion points were determined differently according the burnup behavior.

Fig. 3. shows the results of the depletion calculation which show the difference between the nTRACER reference and the two-code system with N2R. Although the result has a slightly difference in the middle range due to the different depletion modules of nTRACER and RENUS, where are difference of depletion chain and matrix exponential solver for depletion calculation, the maximum difference is 97 pcm at 17 MWD/kgHM. This shows that the depletion calculation with the GCs generated from nTRACER can be performed by RENUS with sufficiently good accuracy.

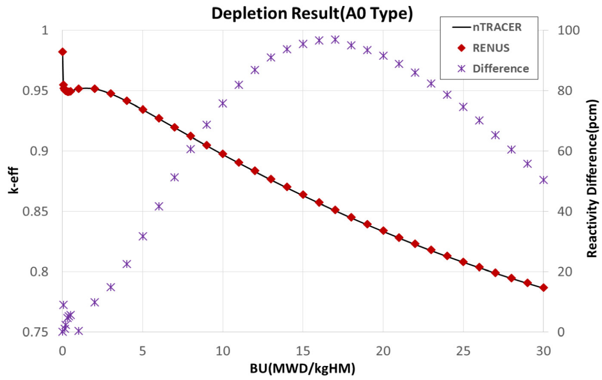

Fig. 3. Comparison of two depletion results and its difference

3.2 Checkerboard

Two assemblies from the APR1400 fresh core configuration are selected to have a large power difference between assemblies. Power sharing between assemblies in the nTRACER reference calculation is 1.13/0.87 at the HFP fixed uniform temperature condition and 1.14/0.86 at the HZP. Three sets of the GC libraries, the single assembly infinite medium GC, B1 critical corrected GC and LFM applied GC were used to perform the calculation.

Table III shows the summarized RENUS results and its errors relative to the nTRACER reference. The B1 leakage correction case seems to have a slightly better result than a single assembly infinite medium GC but it renders even worse reactivity results at the HZP condition. However, with the LFM, there is a remarkable accuracy improvement attainable by reflecting the proper leakage effect of leakage. Especially, at 2D HFP without T/H feedback case, the reactivity difference is only 9 pcm and its power sharing error is only 0.1%.

Table III: Summary of B3C0 checkerboard results

Case		*HZP(T/H on)*			*HFP(T/H off)*		
		k_{eff}	Δρ (pcm)	RMS (%)	k_{eff}	Δρ (pcm)	RMS (%)
2D	nTR	1.10142	-	-	1.09304	-	-
	SA	1.10254	92	0.86	1.09432	107	0.83
	B1	1.10009	-110	0.70	1.09184	-101	0.73
	LFM	1.10109	-27	0.11	1.09293	-9	0.10
3D	nTR	1.09747	-	-	1.08887	-	-
	SA	1.09858	92	0.85	1.09013	106	0.84
	B1	1.09611	-113	0.71	1.08765	-103	0.72
	LFM	1.09696	-42	0.25	1.08859	-24	0.24

At the 2D Checkerboard HFP condition with fixed uniform temperature, the depletion result was obtained as compared in Fig. 4. The maximum difference is 148 pcm at 22 MWD/kgHM. Fig. 5 shows the power sharing variation and its relative error obtained in a checkerboard depletion. As depletion goes on, the power sharing approaches each other and its error reduces as well. At the last burnup step, the power sharing error is only 0.07%/-0.07%.

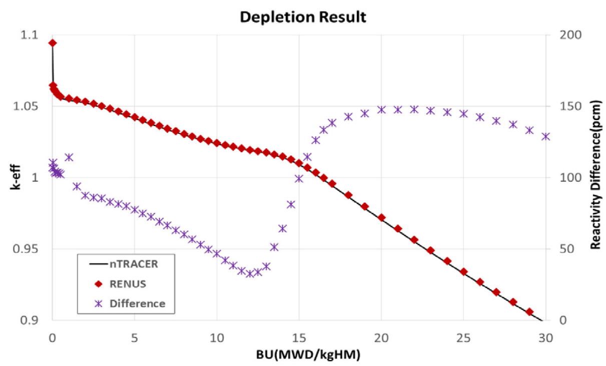

Fig. 4. Comparion of 2D CB depletion results and its difference at HFP condition with fixed temperature

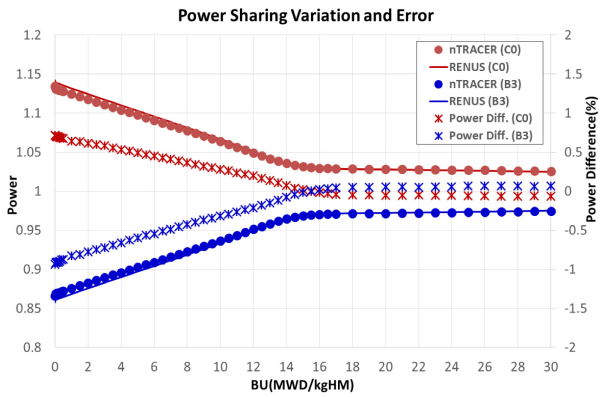

Fig. 5. Comparion of power sharing variation and its difference at HFP condition with fixed temperature

3.3 2D quarter Core

2D APR1400 quarter core problem was solved at both the HZP condition with T/H feedback and the HFP fixed uniform temperature condition without feedback. In addition to the three sets of GCs, LFM with PAT applied case was performed as well. In order to examine the leakage treatment effect, the ADFs and reflector GCs are fixed for all cases and only the GCs of fuel regions were varied.

Table IV shows the summary of the 2D core results in reactivity and assembly-wise power distribution. With the B1 corrected GC, there is a large reactivity error although it has a better agreement in power distribution. Especially, LFM with PAT applied cases show remarkable accuracy improvement in power difference as in Fig. 6.

Table IV: Summary of 2D core result

Case	*HZP(T/H on)*				*HFP(T/H off)*			
	k_{eff}	Δρ (pcm)	RMS (%)	MAX (%)	k_{eff}	Δρ (pcm)	RMS (%)	MAX (%)
nTR	1.00030	-	-	-	0.99218	-	-	-
SA	1.00052	22	6.60	12.19	0.99228	10	6.20	11.05
B1	0.99914	-116	2.10	4.65	0.99113	-106	2.03	4.37
LFM	1.00055	25	0.97	2.16	0.99257	40	0.98	2.09
L+P	1.00037	7	0.59	1.19	0.99241	24	0.58	1.07

-1.1	-1.0	-0.6	-0.7	0.0	-0.3	0.4	0.7	0.0
-1.0	-0.7	-0.8	-0.4	-0.4	0.3	0.2	0.7	-0.3
-0.6	-0.8	-0.3	-0.5	0.0	-0.1	0.5	0.8	-0.2
-0.7	-0.4	-0.5	-0.1	-0.2	0.3	0.2	0.7	-1.1
0.0	-0.5	0.0	-0.2	0.3	0.1	0.7	-0.5	
-0.3	0.3	-0.1	0.3	0.1	0.5	0.6	-0.8	
0.4	0.2	0.5	0.2	0.7	0.6	-0.9		
0.7	0.7	0.8	0.7	-0.5	-0.8			
0.0	-0.3	-0.2	-1.1					

Fig. 6. Relative power difference of LFM+PAT case at HFP fixed temperature condition in 2D APR1400 quarter core

4. Conclusions

The nTRACER-RENUS core analysis system was established by the development of the N2R utility code which functionalizes microscopic GCs with the automated depletion step selection capability. Although the nTRACER-RENUS core analysis system based on the two-step procedure requires the assumption in homogenization and group condensation, it was demonstrated that the system could result in high level of accuracy. The tests on the 1D axial problem and checkerboard problems verified the T/H and leakage feedback capability of the system. In core level calculations, it was shown that the LFM with PAT significantly improves the accuracy of the core calculation results. However, there are some differences noted in the depletion results which should be further improved in the future. The performance assessment of the nTRACER-RENUS system through a core-follow calculation is on-going.

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