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

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Jeong Jun Ho, Ban Young Suk and Joo Han Gyu
Seoul National University Reactor Physics Lab.

Contents

Motivation

☐ Recent trend for core analysis

Direct whole core calculation	+	Improved Hardware	⇨	Less Time Cost ! More Accuracy !

☐ Two-step method vs Recent trend

- It is still preferred in the industrial applications.
- Because it can give the result pretty fast with tolerable accuracy.

⇨ **Establish core analysis system** based on two-step method at SNU by development of utility code, named N2R(nTRACER-to-RENUS)

☐ Purpose of this paper

- **Introduce the detailed procedure** of generating and functionalizing GCs
- **Perform preliminary verification** of the core analysis system with N2R

About nTRACER-RENUS System

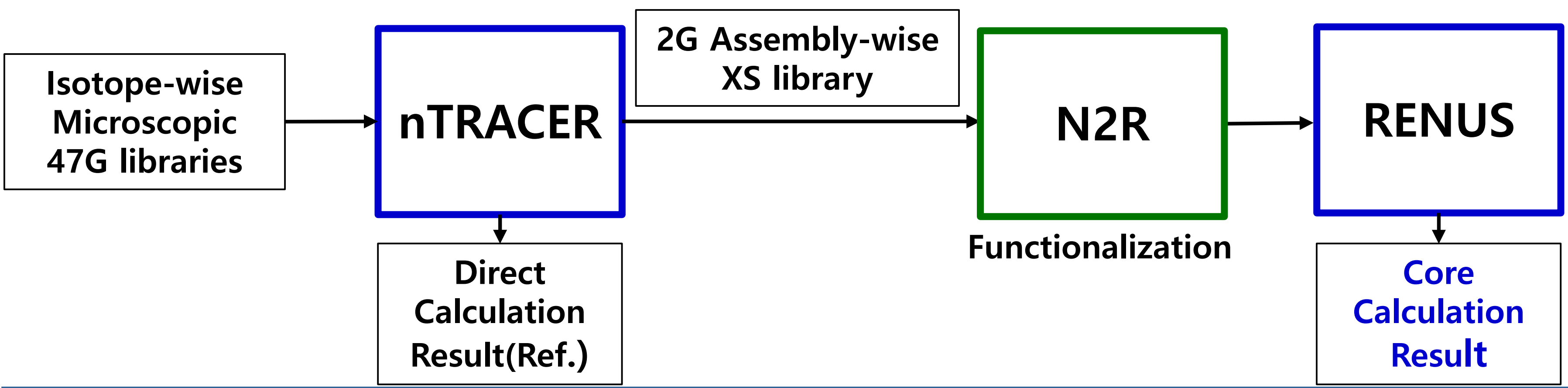
☐ nTRACER and RENUS

- **nTRACER**
  - 2D planar MOC /1D axial Nodal + 3D CMFD acceleration
  - GCs generation
- **RENUS**
  - 3D Nodal code based two-node SENM with 3D CMFD acceleration

☐ nTRACER-RENUS Core Analysis System

⇨ **Two step calculation system using nTRACER and RENUS**

☐ Procedure



Generation of Group Constants

□ Spatial Homogenization : Flux volume

$$\overline{\Sigma}_{x,g}\overline{\phi}_g V = RR_{x,g} V = \overline{\Sigma}_{x,g}\sum_i^V \phi_{g,i}V_i = \sum_i^V \Sigma_{x,g,i}\phi_{g,i}V_i \qquad \overline{\Sigma}_{x,g} = \frac{RR_{x,g}}{\overline{\phi}_g} = \frac{\sum_i^V \Sigma_{x,g,i}\phi_{g,i}V_i}{\sum_i^V \phi_{g,i}V_i}$$

□ Group Condensation : Spectrum

$$\overline{\Sigma}_{x,G}\overline{\phi}_G = \overline{\Sigma}_{x,G}\sum_{g\in G}\overline{\phi}_g = \sum_{g\in G}\overline{\Sigma}_{x,g}\overline{\phi}_g \qquad \overline{\Sigma}_{x,G} = \frac{\sum_{g\in G}\overline{\Sigma}_{x,g}\overline{\phi}_g}{\sum_{g\in G}\overline{\phi}_g}$$

□ Diffusion Coefficient

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

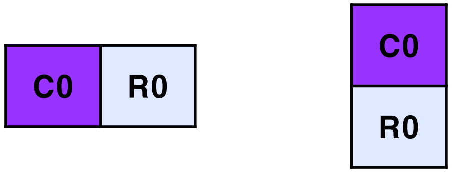
Generation of Reflector GCs

☐ Type of reflectors in a core

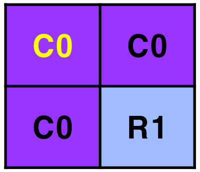
A0	A0	C3	A0	B1	A0	B3	C2	B0	R0
A0	B3	A0	B3	A0	B1	A0	B3	C0	R0
C3	A0	C2	A0	C3	A0	C3	B1	B0	R0
A0	B3	A0	B3	A0	B3	A0	B2	C0	R0
B1	A0	C3	A0	C2	A0	B1	C0	R1	R2
A0	B1	A0	B3	A0	B3	C1	C0	R0	
B3	A0	C3	A0	B1	C1	C0	R1	R2	
C2	B3	B1	B2	C0	C0	R1	R2		
B0	C0	B0	C0	R1	R0	R2			
R0	R0	R0	R0	R2					

‹ APR1400 Core ›

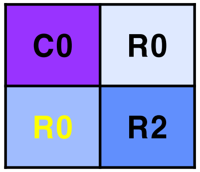
- Type 1 : I-Type



- Type 2 : L-Type



- Type 3 : Corner Type

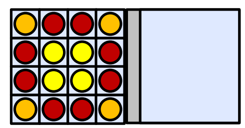


Generation of Reflector GCs

☐ Procedure

- **Solve two box heterogeneous local problem = reference**

J^*_{surf}

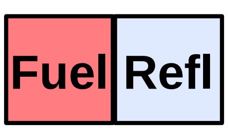
ϕ^*_{fuel}  ϕ^*_{refl}

- **Get homogenized & condensed XS :** Σ^*_{fuel}, Σ^*_{refl}
- **Solve two one-node homogeneous problems with B.C. from reference**
- **Obtain a discontinuity factor from homogeneous solution**

$$\phi^*_{surf} = f_L \phi^{fuel}_{surf} = f_R \phi^{refl}_{surf} \quad \rightarrow \quad \phi^{fuel}_{surf} = \frac{f_R}{f_L} \phi^{refl}_{surf} = f^* \phi^{refl}_{surf}$$

- **Multiply** f_{ADF} **and Get the DF of reflector**

f_{ADF} $\quad f^*$

Σ^{SA}_{fuel}  Σ^*_{refl}

$$f_{ADF} \phi^{fuel}_{surf} = f_{ADF} f^* \phi^{refl}_{surf} = f_{refl} \phi^{refl}_{surf}$$

$$\therefore f_{refl} = f_{ADF} f^*$$

$$f_{ADF} \equiv \frac{\phi_{surf}}{\phi_{avg}}$$

Functionalization of GCs

□ Development of N2R(nTRACER-to-RENUS)

- In order to functionalize the GCs generated by nTRACER
- Tabulate isotope-wise microscopic XSs → perform depletion calculation
- Apply leakage correction such as LFM and treat multiple branch cases

  → get more accuracy

* LFM :Leakage Feedback Method,
which considers actual leakage effect in a core
through functionalization on leakage fraction

□ Equation for T/H feedback and depletion

$$\sigma(BU, ppm, T_f, T_m, \rho_m) = \begin{pmatrix} \sigma(BU, ppm_0, T_{f0}, T_{m0}, \rho_{m0}) \\ + \dfrac{\partial \sigma}{\partial ppm}(ppm - ppm_0) + \dfrac{\partial \sigma}{\partial \sqrt{T_f}}(\sqrt{T_f} - \sqrt{T_{f0}}) \\ + \dfrac{d\sigma}{dT_m}(T_m - T_{m0})^{*} + \dfrac{\partial \sigma}{\partial \rho_m}(\rho_m - \rho_{T_m, P_0})^{**} \end{pmatrix} (1 + \frac{\partial \sigma}{\partial L} L)$$

$$L = \frac{\int_S J \cdot dA}{\int_V \Sigma_r \phi \cdot dV} = \frac{l}{\Sigma_r \phi}$$

* Mod. temperature term : including mod. density change

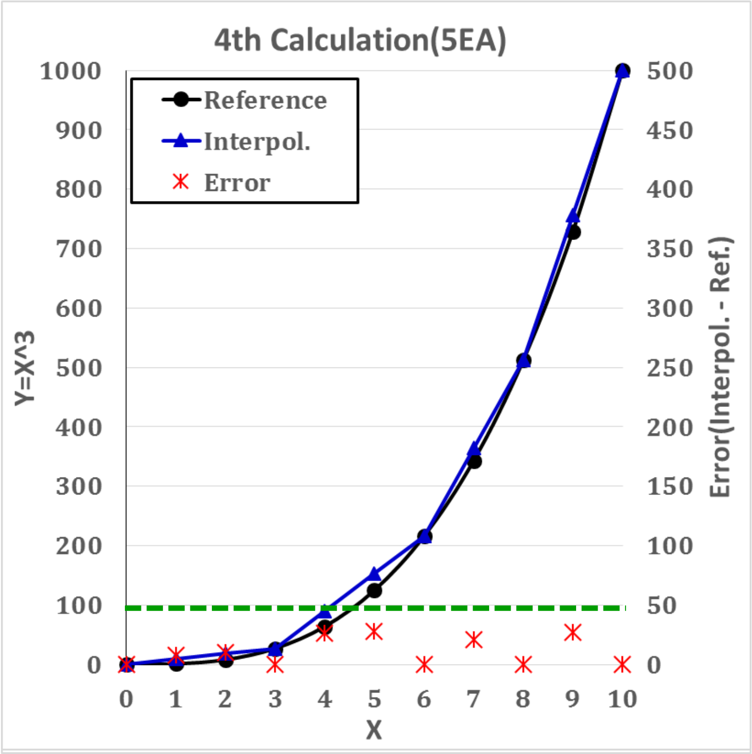
** Mod. density term : considering pressure drop of the core such as LOCA

Functionalization of GCs

※ Auto-selection scheme of burnup points

- Determine the burnup points automatically in the functionalized GC table

- Process
  - Give initial burnup points and an acceptable error as an input
  - Calculate k_∞ at non-selected points with interpolation method
    * 2nd order Lagrange method or the piece-wise linear scheme
  - Select a additional burnup point which has maximum error
  - Repeat until errors of all points are under the criteria

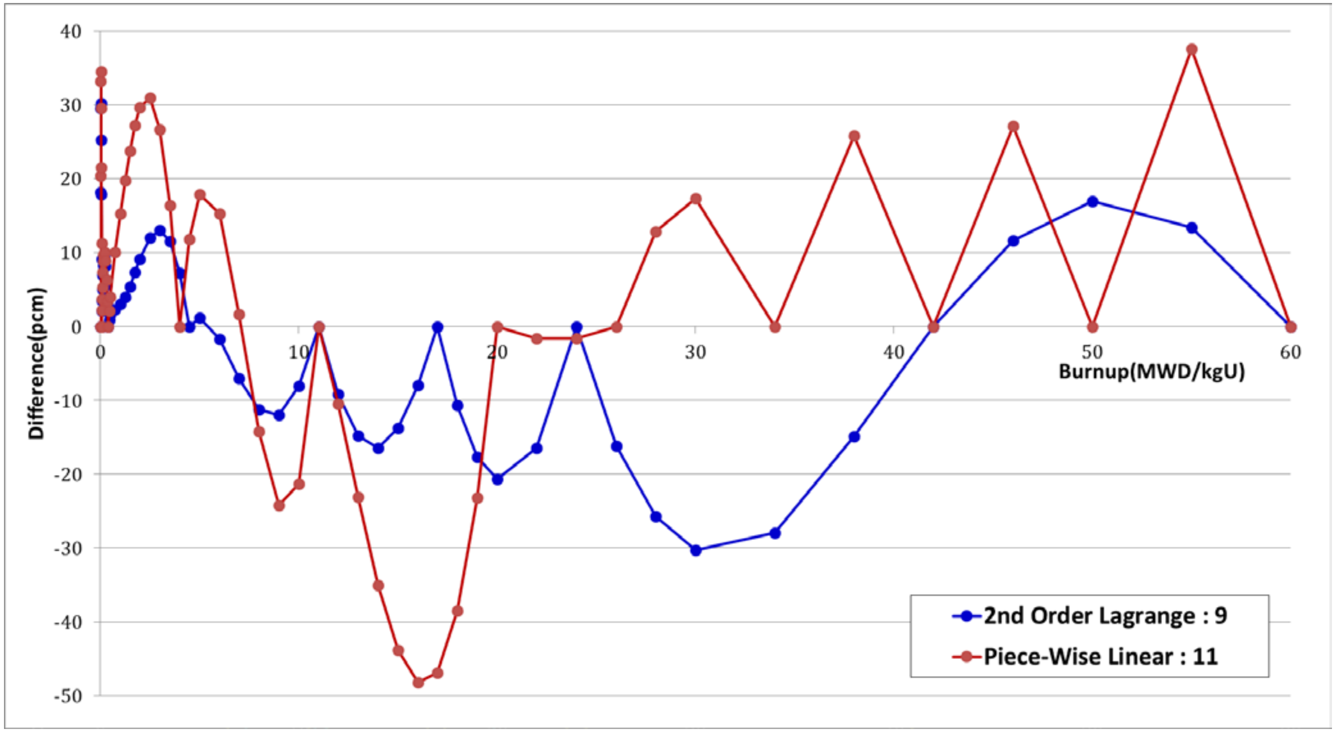


< Example : y=x^3 >

⇨ Obtain a downsized GC set with desired accuracy and fewer burnup points!

Functionalization of GCs

※ Results of Auto-selection scheme with 2 Interpolation methods



- **Total points : 61 / Initial points : 2 / Acceptable error : 50 pcm**
- **Select only 9 or 11 burnup points among 61 fine points ⇨ 1/6 !**

Verification of the System with N2R

☐ Core type for verification : APR1400

☐ Base and branch conditions of GCs : 1 + 16 cases

	Boron(ppm)	Fuel Temp. (°C)	Mod. Temp. (°C)	Mod. Density(g/cm^3)
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

☐ Problems for verification

- **Steady State : SA, CB and 2D core problem**
  *** Apply Leakage correction : B1 method, LFM and PAT**
- **T/H feedback : 1D axial SA problem**
- **Depletion : SA and 2D CB problem**

☐ Reference : nTRACER(Direct whole core transport solution, 47G)

Steady State Test

- ☐ **Single assembly : exactly same as nTRACER results**
- ☐ **Checkerboard(B3C0)**

Case		*HFP(Fixed temp., T/H off)*			*HFP(T/H on)*		
		k_{eff}	***Δρ (pcm)***	***RMS (%)***	k_{eff}	***Δρ (pcm)***	***RMS (%)***
2D	nTRACER	1.09304	-	-	1.09406	-	-
	SA*	1.09432	107	0.83	1.09566	133	0.74
	B1 **	1.09184	-101	0.73	1.09328	-65	0.75
	LFM* **	**1.09293**	**-9**	**0.10**	**1.09430**	**20**	**0.12**
3D	nTRACER	1.08887	-	-	1.08759	-	-
	SA	1.09013	106	0.84	1.08933	147	0.75
	B1	1.08765	-103	0.72	1.08695	-54	0.73
	LFM	**1.08859**	**-24**	**0.24**	**1.08782**	**19**	**0.13**

* SA : Single assembly infinite medium GC without any leakage correction
** B1 : SA GC with B1 leakage correction method
*** LFM : Leakage Feedback Method, which considers actual leakage effect in a core
**** P.RMS : Assembly-wise power RMS

B3	C0
C0	B3

- **SA GC result without any leakage correction is not bad.**
- **B1 method can give slight improvement from SA GC result.**
- **With LFM, there are remarkable accuracy improvement !**

Steady State Test

□ 2D core

Case	HFP(Fixed temp., T/H off)				HFP(T/H on)			
	k_{eff}	*Δρ (pcm)*	*P.RMS (%)*	*MAX. P. Diff. (%)*	k_{eff}	*Δρ (pcm)*	*P.RMS (%)*	*MAX. P. Diff. (%)*
nTRACER	0.99218	-	-	-	0.99313			
SA	0.99228	10	6.20	11.05	0.99321	8	3.73	6.47
B1	0.99113	-106	2.03	4.37	0.99223	-91	0.93	1.70
LFM	0.99257	40	0.98	2.09	0.99373	60	0.60	1.10
LFM+PAT*	**0.99241**	**24**	**0.58**	**1.07**	**0.99358**	**46**	**1.08**	**1.94**

* PAT : Peripheral Assembly Treatment

- **LFM case assures of accurate result**
- **LFM with PAT case has significant accuracy, although it with T/H on has more error than LFM case.**
  → It seem that PAT performed over-correction when using T/H on

Steady State Test

- **Relative power difference of LFM+PAT cases**

-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					

< at HFP with fixed temperature, T/H off >

1.9	1.7	1.7	1.1	1.0	0.1	0.1	-0.3	-1.3
1.7	1.9	1.4	1.3	0.5	0.6	-0.1	-0.3	-1.6
1.7	1.4	1.5	0.9	0.7	0.2	0.1	-0.2	-1.4
1.1	1.3	0.9	0.9	0.4	0.3	-0.3	-0.1	-1.9
1.0	0.5	0.7	0.4	0.4	-0.1	0.0	-1.3	
0.1	0.6	0.1	0.3	-0.1	-0.1	-0.3	-1.6	
0.1	-0.1	0.1	-0.3	0.0	-0.3	-1.6		
-0.3	-0.3	-0.2	-0.1	-1.3	-1.6			
-1.3	-1.6	-1.4	-1.9					

< at HFP with T/H on >

※ As the results, nTRACER-RENUS system with N2R can give very reliable solution with leakage corrections such as LFM+PAT !

T/H Feedback Test

☐ 1D axial SA problem(A0 type)

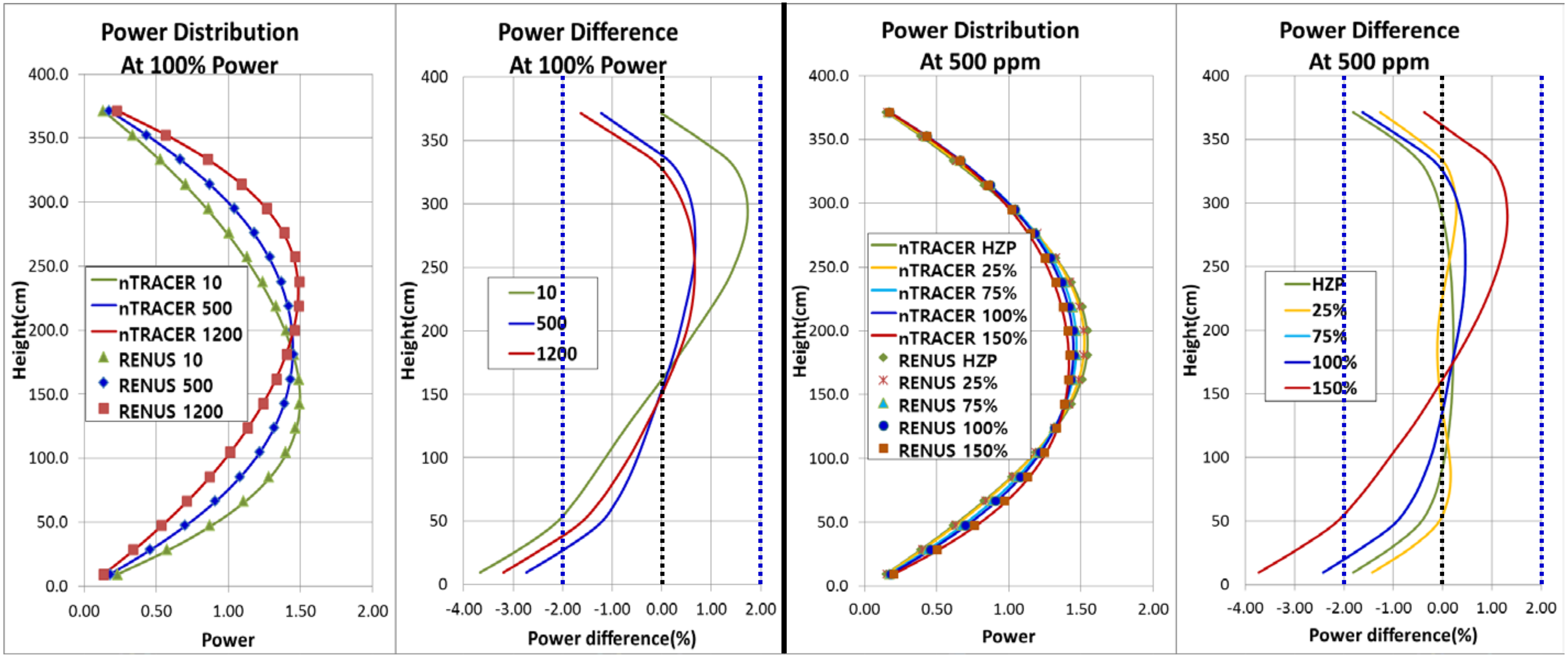
Case		*nTRACER (reference)*	k_{eff}	*Δρ (pcm)*	*P.RMS (%)*
Boron Variation (Power : 100%)	10 ppm	1.18809	1.18805	-3	1.58
	500 ppm	1.09018	1.09007	-9	0.96
	1200 ppm	0.97728	0.97717	-12	1.17
Power Variation (Boron : 500ppm)	HZP	1.09984	1.09929	-45	0.69
	25 %	1.09767	1.09723	-37	0.49
	75 %	1.09276	1.09261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

- **There are different MTC due to boron concentration and Doppler broadening effect.**
- **However, reactivity and power error are very small !**

T/H Feedback Test

- **Axial power distribution**

  : Except bottom side, Axial power error in both two variation cases is within 2%.

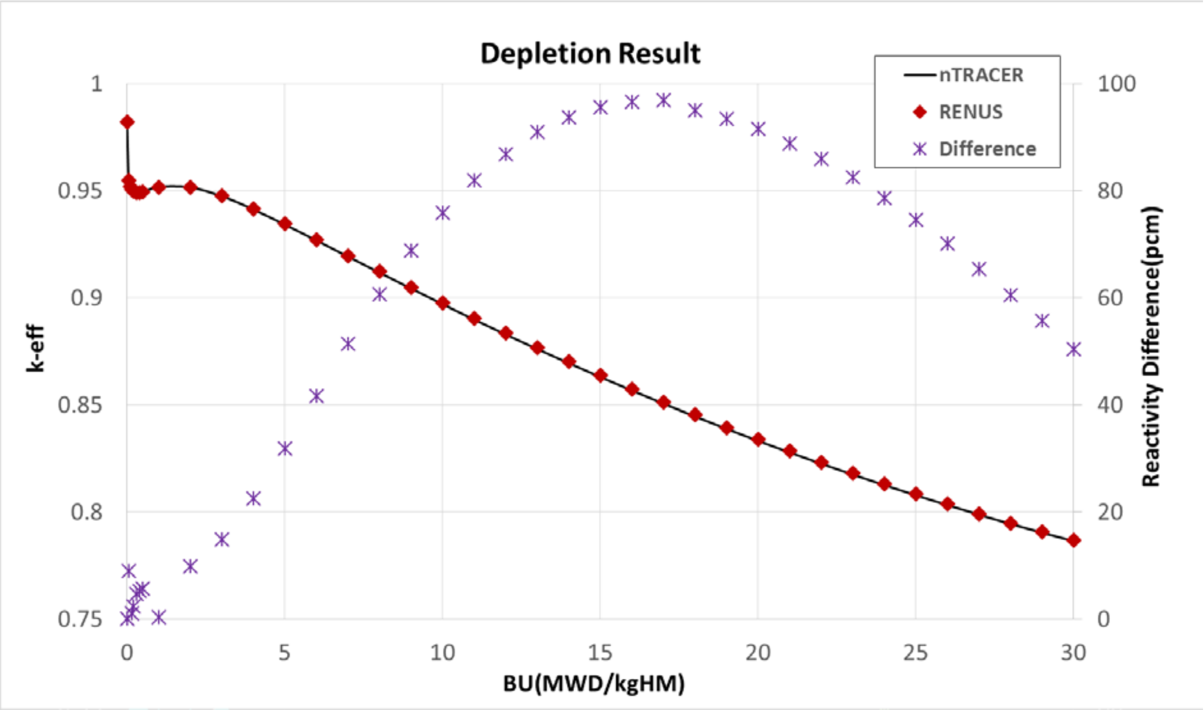


< Boron variation > **< Power variation >**

※ As the results, the system with N2R works well for T/H feedback although it uses homogenized GCs, not heterogeneous data like nTRACER.

Depletion Test

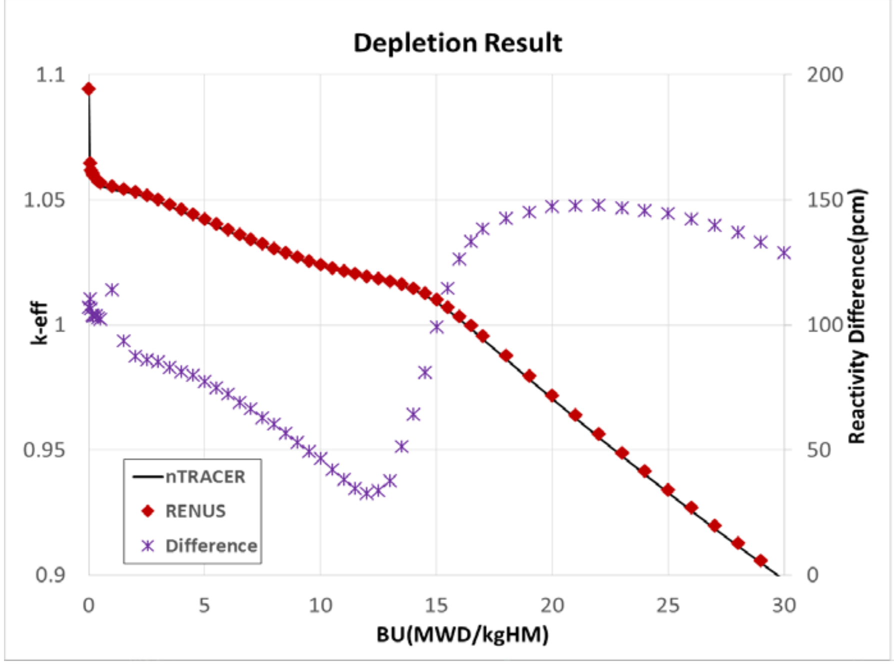
☐ Single assembly

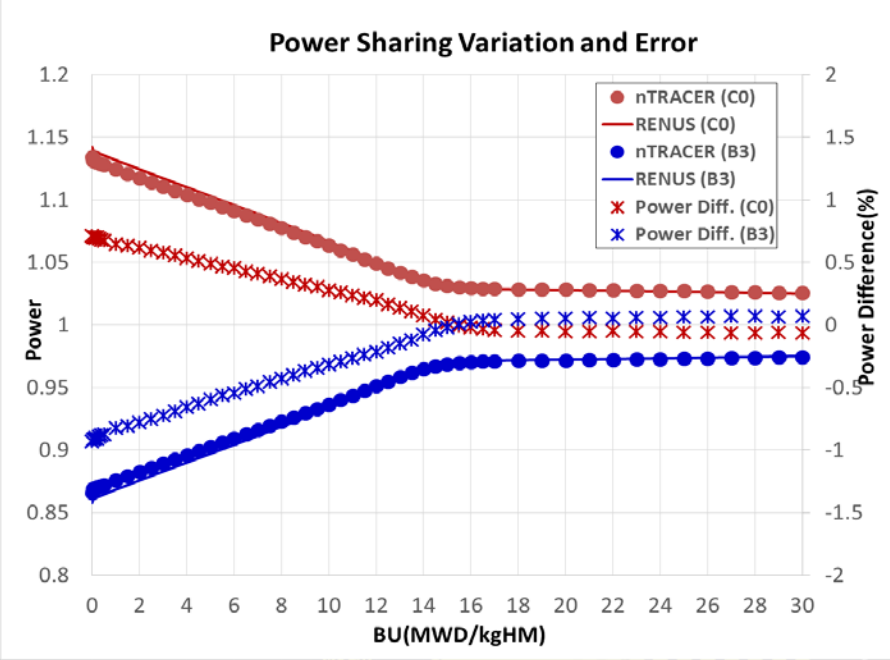


- **Maximum error : 97 pcm at 17 MWD/kgHM**
- **Reactivity error is getting bigger and smaller after maximum point.**
- **It comes from different depletion module between two codes.**

Depletion Test

☐ 2D Checkerboard





- **Maximum error : 148 pcm at 22 MWD/kgHM**
- **Reactivity error is fluctuating,
  power sharing error is getting smaller and steady.**

※ As the results, the system with N2R can perform depletion calculation with good accuracy !

Conclusions and Future work

☐ Development of N2R → Establishment of nTRACER-RENUS system

☐ Results of the system with N2R

- **Apply leakage correction such as LFM with PAT**
- **Confirm MTC and Doppler broadening effect**
- **Perform depletion calculation**

→ It has great reliability for a core analysis !

☐ Future work

- **Improvement of T/H feedback and depletion results**
- **The performance assessment through a core-follow calculation**

Question?