The Rationale of Leakage Parameters adopted in Leakage Feedback Method

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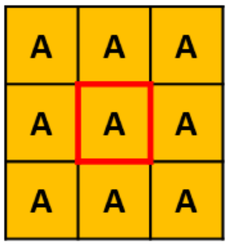
Introduction

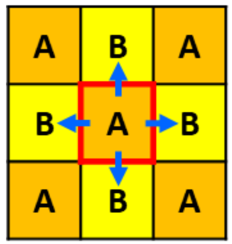
□ Concept of Leakage Feedback Method

- **Group Constants (GC) difference proportional to leakage**

SA: Single Assembly
All Reflective B.C.



$\overline{\Sigma}_G^{SA}$



$\overline{\Sigma}_G^{Core}$

$$\frac{\overline{\Sigma}_G^{Core} - \overline{\Sigma}_G^{SA}}{\overline{\Sigma}_G^{SA}} \propto Leakage$$

□ Advanced Leakage Feedback Method

$$\frac{\overline{\Sigma}_G - \overline{\Sigma}_G^{SA}}{\overline{\Sigma}_G^{SA}} = \alpha_G l_1 + \beta_G l_2 + \gamma_G \Delta\Gamma$$

- **Inner Assembly (IA)** : $\gamma = 0$
- **Peripheral Assembly (PA)*** : $\gamma \neq 0$
  - Special treatment on PA = PAT

Leakage Fraction (LF)
: leakage-to-removal ratio

$$l_G = \left(\sum_{surf} J_G^{surf} A_{surf} \right) / \left(\int_{Asy} \Sigma_{r,G} \phi_G dV \right)$$

Spectral Index Shift (SIS)
: fast-to-thermal flux ratio

$$\Delta\Gamma = \frac{\phi_1}{\phi_2} - \frac{\phi_1^{SA}}{\phi_2^{SA}}$$

Validation of LFM for Various Cores

☐ Targeted Cores Problems

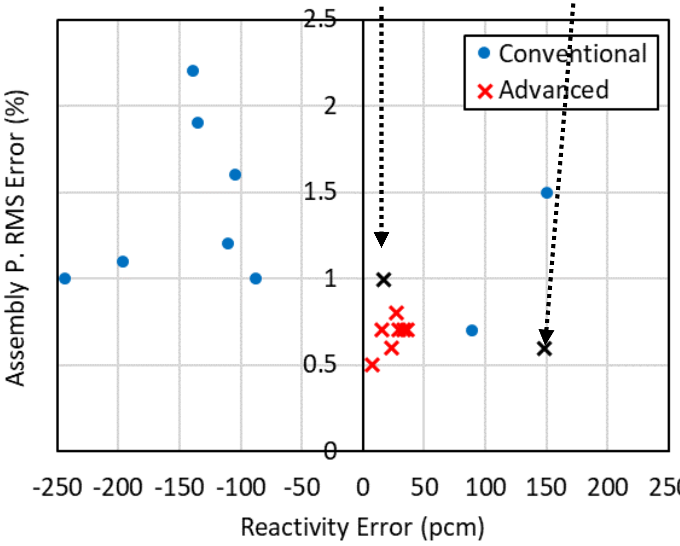
- **Assembly type: 16x16 pin (CE type), 17x17 pin (WH type: BEAVRS, VERA)**
- **Core size: 100 MW (SMR), 1000 MW (AP1000), 1400 MW (APR1400)**
- **Core state: Depletion, HZP, HFP, Control rod insertion**

Summary of Two-step Results compared with DWC results*

Case		Δρ (pcm)		RMS Error (%)		Max Error (%)	
		Conv.	Adv.	Conv.	Adv.	Conv.	Adv.
APR1400	BOC	-196	**36**	1.1	0.7	2.1	1.6
	*EOC	89	148	0.7	0.6	1.3	1.2
	HFP	**-244**	8	1.0	0.5	1.9	1.1
	HZP	-135	15	**1.9**	0.7	**4.6**	1.6
	**CR-R5	-139	16	2.2	1.0	7.8	4.4
VERA-2D		-110	23	1.2	0.6	2.9	1.6
BEAVRS-S2D		-88	29	1.0	0.7	2.2	1.9
AP1000-2D		150	27	1.5	**0.8**	2.7	**2.0**
SMR-2D		-105	33	1.6	0.7	3.2	1.0
*,**RMS Avg.		**156**	**26**	**1.4**	**0.7**	**2.9**	**1.6**
Ratio		**6.0**		**2.0**		**1.9**	

***APR1400 EOC : Simplified depletion**

****APR1400 R5 Bank In : Severely distorted P.**



	Conventional Two-Step	Advanced Two-step
Time Cost	< 2 sec	**< 2 sec**
Reactivity	~ 150 pcm	**~ 25 pcm**
Assembly Power	RMS: 1.5 %, Max: 3.0 %	**RMS: 0.7 %, Max: 1.5 %**

*** Y. S. Ban, "Development of Advanced Leakage Feedback Method for Two-step Core Analyses," Ph.D. Thesis, Seoul National University, 2018.**

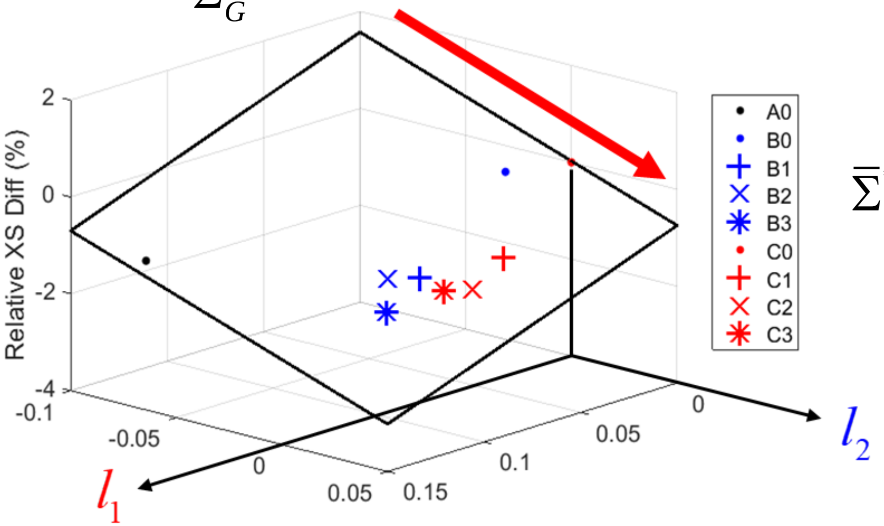
Motivation and Topic

□ Thermal LF dependency of Fast GCs

- **APR1400 C0 assembly, down-scattering XS**

C0	X
X	C0

$$\frac{\bar{\Sigma}_G^{CB} - \bar{\Sigma}_G^{SA}}{\bar{\Sigma}_G^{SA}} = \alpha_G l_1 + \beta_G l_2$$



$$\bar{\Sigma}_G^* = \sum_{g\in G} \bar{\Sigma}_g^* \tilde{\phi}_g^*$$

Normalized flux within group G $\sum_{g\in G} \tilde{\phi}_g = 1$

$$\Delta\bar{\Sigma}_g = \bar{\Sigma}_g^* - \bar{\Sigma}_g^{SA},\ \Delta\tilde{\phi}_g = \phi_g^* - \phi_g^{SA}$$

$$\bar{\Sigma}_G^* = \sum_{g\in G} \left(\bar{\Sigma}_g^{SA} + \Delta\bar{\Sigma}_g\right)\left(\tilde{\phi}_g^{SA} + \Delta\tilde{\phi}_g\right)$$

$$= \sum_{g\in G} \left(\bar{\Sigma}_g^{SA}\tilde{\phi}_g^{SA} + \tilde{\phi}_g^{SA}\Delta\bar{\Sigma}_g + \bar{\Sigma}_g^{SA}\Delta\tilde{\phi}_g + \Delta\bar{\Sigma}_g\Delta\tilde{\phi}_g\right)$$

$$= \bar{\Sigma}_G^{SA} + E_G^{Hom} + E_G^{Con} + O(E^2)$$

$$\bar{\Sigma}_G^{LFM} = \bar{\Sigma}_G^{SA}\left(1 + \alpha_G l_1 + \beta_G l_2 + \gamma_G \Delta\Gamma\right)$$

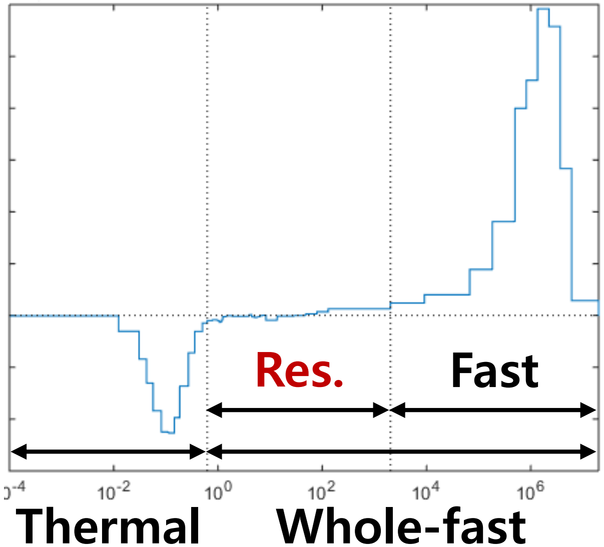
$g \notin G$ **does not appear in the formula → How thermal LF affect Fast GC?**

Physical meaning of leakage parameters?

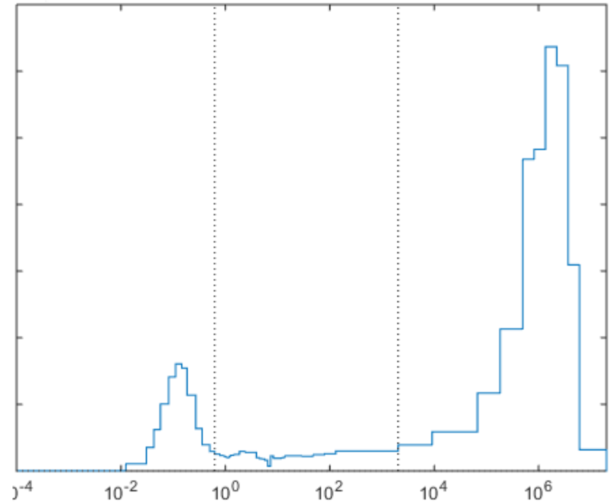
Intermediate Group Leakage

□ Leakage spectrum of B0 from checkerboards

B0/A0 Checkerboard (High/Low Enrichment)



B0/B3 Checkerboard (Different BA configuration)

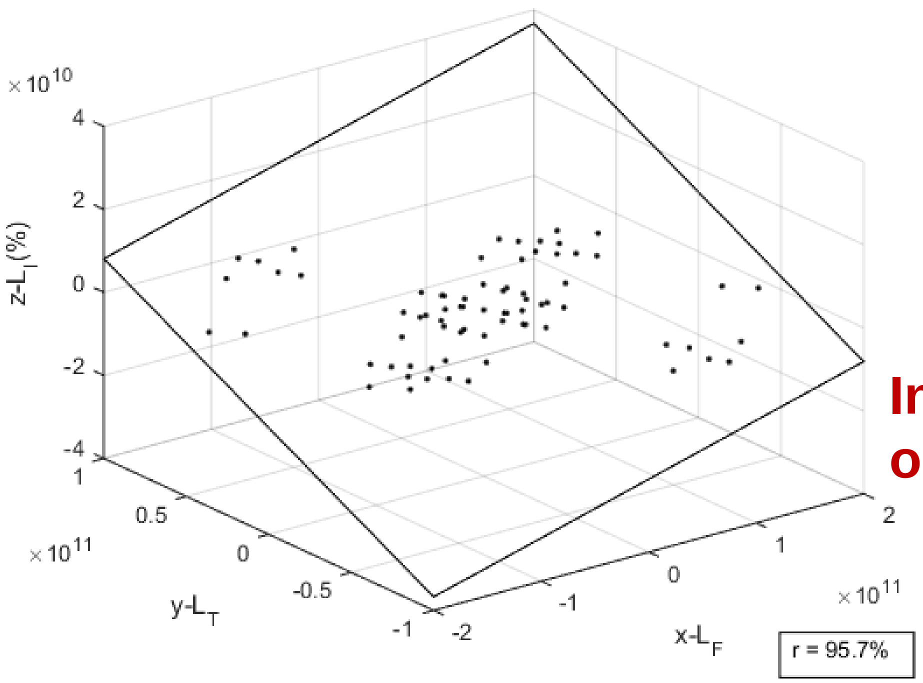


- **Fast leakage : shape of fission spectrum**
- **Thermal leakage : shape of thermal peak**

→ **Different characteristic of intermediate range leakage**

Correlation of L_R with L_F, L_T

- **Leakage points from checkerboards**
  - **X: Fast Leakage Fraction**
  - **Y: Thermal Leakage Fraction**
  - **Z: Intermediate(resonance range) Leakage Fraction**



$$L_R \approx \alpha L_F + \beta L_T$$

$$\alpha = 0.0715$$

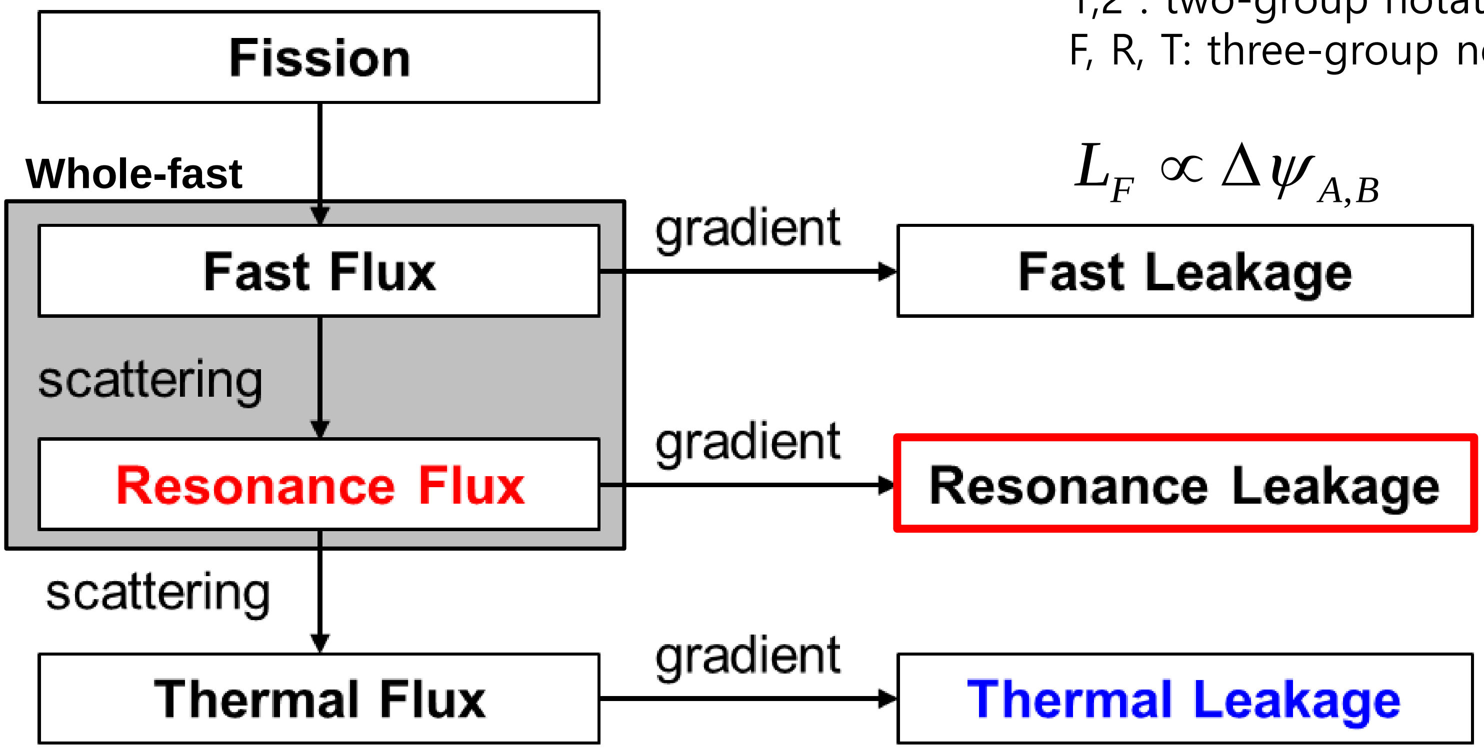
$$\beta = 0.2242 \;,\; R^2 = 95.7\%$$

Intermediate leakage depends on fast and thermal leakage

Thermal Lkg. as Indirect Representation

1,2 : two-group notation
F, R, T: three-group notation

$$L_F \propto \Delta \psi_{A,B}$$



*** Thermal leakage = indirect representation of <u>resonance flux or lkg.</u>**
through its consequence

$$\Delta\Gamma = \frac{\phi_1}{\phi_2} - \frac{\phi_1^{SA}}{\phi_2^{SA}}$$

Spectral Index Shift for PAT

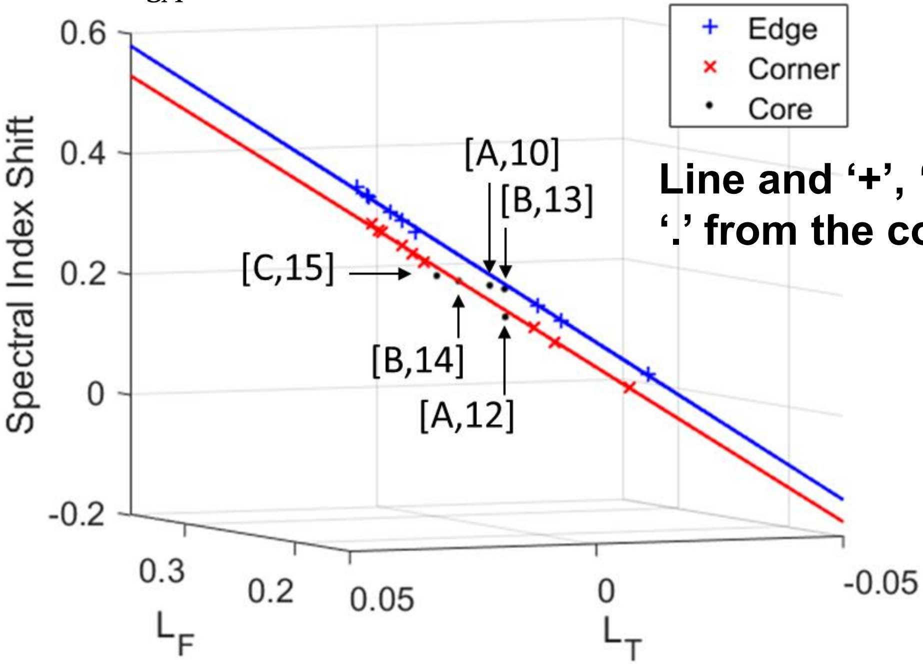
□ Peripheral Assembly Treatment

- **Edge: facing 1 side toward reflector**
- **Corner: facing 2 sides toward reflector**

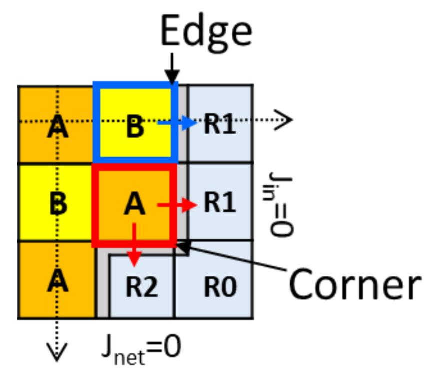
→ Different SIS tendency

	J	H	G	F	E	D	C	B	A	R
9	A0	A0	C3	A0	B1	A0	B3	C2	B0	R1
10	A0	B3	A0	B3	A0	B1	A0	B3	C0	R1
11	C3	A0	C2	A0	C3	A0	C3	B1	B0	R1
12	A0	B3	A0	B3	A0	B3	A0	B2	C0	R1
13	B1	A0	C3	A0	C2	A0	B1	C0	R2	R0
14	A0	B1	A0	B3	A0	B3	C1	C0	R1	
15	B3	A0	C3	A0	B1	C1	C0	R2	R0	
16	C2	B3	B1	B2	C0	C0	R2	R0		
17	B0	C0	B0	C0	R2	R1	R0			
18	R1	R1	R1	R1	R0					

$\Gamma - \Gamma_{SA}$



Line and '+', 'x' from the local
'.' from the core calculation



SIS = the index of leakage through reflector side

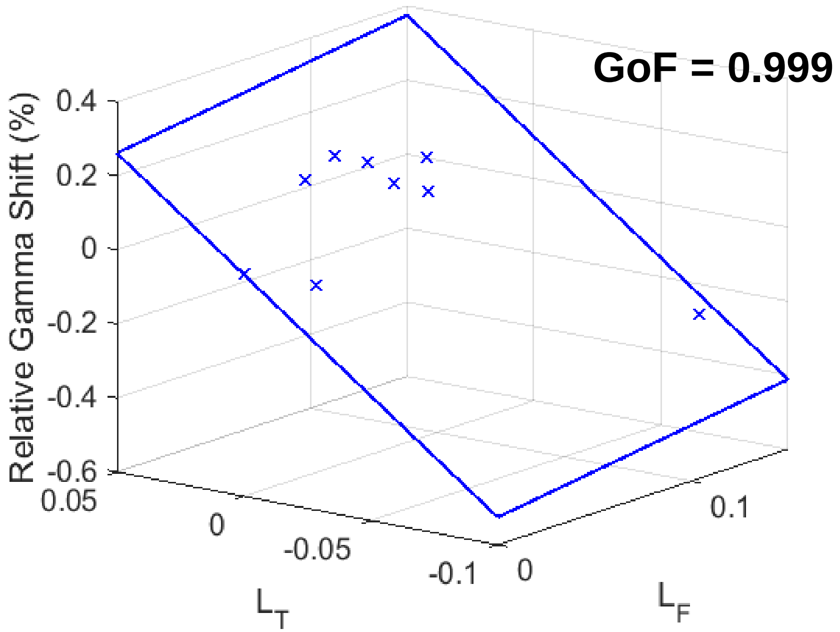
$$\frac{\bar{\Sigma}_G - \bar{\Sigma}_G^{SA}}{\bar{\Sigma}_G^{SA}} = \alpha_G l_1 + \beta_G l_2 + \gamma_G \Delta\Gamma$$

SIS in Inner Assemblies

□ Inner Assembly

- **SIS = L_{F+R}, L_T dependent variable → not used for IAs in LFM**

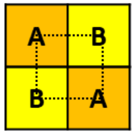
Relative SIS from APR1400 Checkerboards

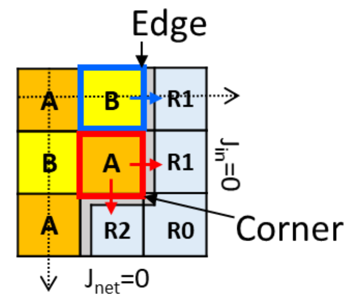


Evaluation of Fitting Formulas

□ Fitting of Few-Group Constants

- **Least square fitting, linear**
- **Fitting base points from colorsets**
  - N points from CBs, 5N points from 3x3 config.





□ Definition of GC Error

- **Target problem: 2D APR1400 (B3, C0)**
- **Relative RMS error of evaluated XS**

$$E = \sqrt{\sum_{i}^{N} \left(\frac{\Sigma^i_{Core} - \Sigma(L^i_{Core})}{\Sigma^i_{Core}} \right)^2 / N}$$

□ Fitting Parameter Sets

- L_{F+R}, L_T (LFM)
- L_{F+R}, $\Delta\Gamma$ (SIS instead of L_T)
- L_F, L_R (Impractical)
- L_{F+R}, L_T, δ (Biased fitting)
- L_{F+R}, L_T, $\Delta\Gamma$ (LFM+PAT)

	J	H	G	F	E	D	C	B	A	R
9	A0	A0	C3	A0	B1	A0	B3	C2	B0	R1
10	A0	B3	A0	B3	A0	B1	A0	B3	C0	R1
11	C3	A0	C2	A0	C3	A0	C3	B1	B0	R1
12	A0	B3	A0	B3	A0	B3	A0	B2	C0	R1
13	B1	A0	C3	A0	C2	A0	B1	C0	R2	R0
14	A0	B1	A0	B3	A0	B3	C1	C0	R1	
15	B3	A0	C3	A0	B1	C1	C0	R2	R0	
16	C2	B3	B1	B2	C0	C0	R2	R0		
17	B0	C0	B0	C0	R2	R1	R0			
18	R1	R1	R1	R1	R0					

Σ^i_{Core}, L^i_{Core}

: Evaluated GCs and LF from the reference DWC solution

$\Sigma(L^i_{Core})$

: Evaluated LFM GCs with LF from the reference

Errors of Evaluated GCs

Inner Assembly – B3

Goodness of Fitting

Fit. Para.	D_1	Σ_{a1}	Σ_{f1}	Σ_{12}
l_1, l_2	0.991	0.983	**0.941**	0.981
$l_1, \Delta\Gamma$	0.993	0.987	**0.958**	0.987
l_F, l_R	0.997	0.997	**0.996**	1.000
l_1, l_2, δ	0.994	0.988	**0.952**	0.984
$l_1, l_2, \Delta\Gamma$	**0.999**	1.000	1.000	1.000

Evaluated RMS Error (10^{-5})

Fit. Para.	D_1	Σ_{a1}	Σ_{f1}	Σ_{12}
l_1, l_2	13	30	42	**59**
$l_1, \Delta\Gamma$	13	25	39	**49**
l_F, l_R	18	11	17	**21**
l_1, l_2, δ	10	31	45	**63**
$l_1, l_2, \Delta\Gamma$	17	10	**26**	16

- **L_F, L_R case well estimated GCs → L_T = indirect parameter!**

Peripheral Assembly – C0

Goodness of Fitting

Fit. Para.	D_1	Σ_{a1}	Σ_{f1}	Σ_{12}
l_1, l_2	0.712	**0.676**	0.692	0.768
$l_1, \Delta\Gamma$	0.752	**0.750**	0.814	0.850
l_F, l_R	**0.927**	0.972	0.990	0.999
l_1, l_2, δ	0.712	**0.676**	0.695	0.769
**Edge*	0.993	**0.998**	0.973	0.996
**Corner*	0.938	**0.976**	0.992	0.994
$l_1, l_2, \Delta\Gamma$	0.990	0.999	**0.984**	1.000

Evaluated RMS Error (10^{-5})

Fit. Para.	D_1	Σ_{a1}	Σ_{f1}	Σ_{12}
l_1, l_2	122	418	219	**609**
$l_1, \Delta\Gamma$	120	390	179	**519**
l_F, l_R	45	**100**	15	35
l_1, l_2, δ	121	412	211	**595**
l_1, l_2, δ*	65	174	62	**233**
$l_1, l_2, \Delta\Gamma$	24	21	18	**28**

- ***Edge&Corner separate functionalization works fine**
- **L_{F+R}, L_T, $\Delta\Gamma$ (LFM+PAT) shows the best result**

Conclusions

- **Study on the rationales of leakage parameters**
- **Thermal leakage fraction in fast GCs**
  - **Indirect representation of the effect of intermediate range neutrons through its consequence in thermal leakage**
- **Spectral Index Shift**
  - **Representation of spectrum inside the whole-fast group**
  - **Using SIS always improves accuracy of evaluated GCs**
  - **For Peripheral Assembly**
    - A proper index of leakage through reflector (Edge and Corner PA)
  - **For Inner Assembly**
    - L_F and L_T dependent, must be reconsidered when few # of colorset

Details of updated method and results for various cases will be presented in the upcoming paper