

Applicability of the GPS Method for Burnup-dependent Leakage Correction in Pin-wise Two-step Reactor Analysis

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1. Introduction

The recently proposed GPS methodology combines two homogenization techniques: generalized equivalence theory (GET) [1] and super-homogenization (SPH) [2] and contributes to error reduction and performance improvement in the two-step reactor analysis. Discontinuity factors (DFs) and SPH factors independently improve node accuracy. Specifically, the GPS function at the beginning of cycle (BOC) state has been sufficiently validated with various benchmark problems [3]. Recently, a burnup-dependent GPS function has been introduced and proved to significantly reduce the reactivity error in the depletion progress of reactor core [4].

Meanwhile, the group constants of single fuel assembly are used to analyze the reactor problem of the conventional two-step method. On the other hand, several types of fuel assembly are arranged in the core and the inhomogeneity is increased with burnup. Therefore it is difficult to implement the asymmetric environment of the core because the fuel assembly-based group constants as reference data are evaluated on the reflective boundary condition. Thus, the pin-by-pin two-step depletion calculation essentially has power errors at the interface of fuel assemblies, which accumulates the effect as the burnup progresses. In addition, the color-set arrangement for generating GPS functions is similarly applied on the boundary condition, making it difficult to properly reflect neutron leakage correction at the interface.

In this study, therefore, the applicability of integrated GPS (i-GPS) functions to efficiently perform the two-step reactor analysis was analyzed and performance was evaluated. The lattice calculations and the reference reactor core calculation were performed using a two-dimensional DeCART2D transport code based on the Characteristics (MOC) method. The burnup-dependent GPS functions were generated from color-set computation in two ways and implemented in an in-house nodal expansion method (NEM) code with a hybrid CMFD (h-CMFD) acceleration solver.

2. Generation of Burnup-dependent XS-SPH Set

The GPS method compensates for the inaccuracy of standard two-step procedures by modifying pin-wise XS

generated by a lattice transport calculation using a modified SPH concept. In this procedure, the two-group GPS functions consisting of pin-wise XS-dependent SPH factors were established on the basis of various burnup steps.

Figure 1 shows the first step in generating a GPS function for two-step core depletion calculation. A series of color-set models are used to obtain fitting data of burnup-dependent function sets. One single color-set consists of 3×3 types and is arranged in two or three different fuel assemblies. Depending on each burnup step, the target assembly contains the material information for a particular depletion level. In previous studies, the combination of color-sets to produce GPS functions was assumed to be all fresh fuels for adjacent ones to the target which is assumed to have been depleted at each burnup step. In this study, however, the adjacent fuels in color-set combination were evaluated in two ways: (i) fresh and (ii) burned fuels at each burned step.

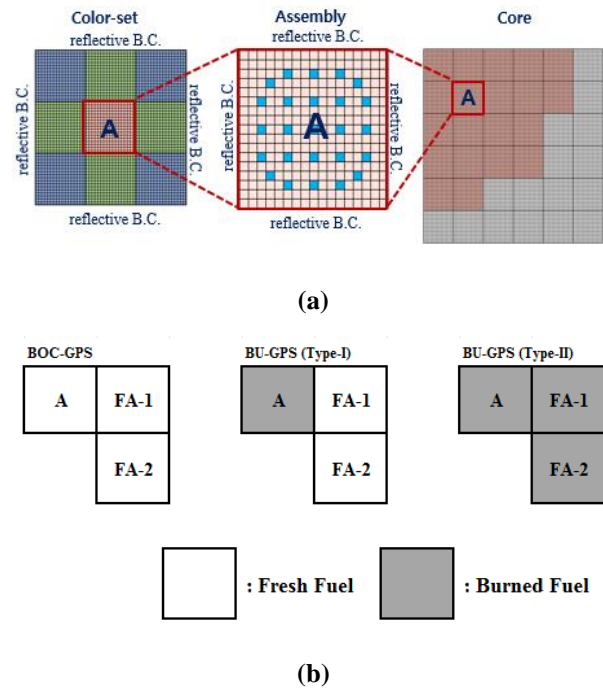


Fig. 1. (a) A color-set model for the functionalization of the target assembly loaded in the reactor core, (b) 1/8 Color-set model loaded with the perturbed fuel assembly

A process for burnup-dependent XS-SPH factor generation is shown in **Fig. 2**. The main reference group constants are obtained at each burnup step for individual fuel assembly by the transport calculations. With a series of color-set calculations, the burnup-wise SPH factor sets for a few type of XSs are obtained for the GPS functionalization.

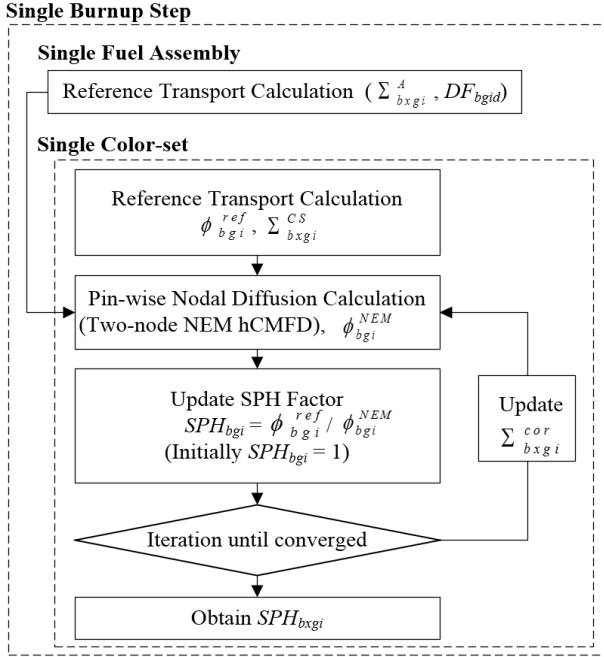


Fig. 2. Burnup-dependent XS-SPH factors generation.

Thus, the pin-wise XS-SPH factors obtained from the color-set calculations performed depending on burnup steps are evaluated as follows.

$$SPH_{bxgi}^{CS} = SPH_{bgi}^{CS} \times \frac{\sum_{bxgi}^{CS}}{\sum_{bxgi}^A} = \frac{\sum_{bxgi}^{cor}}{\sum_{bxgi}^A} \quad (1)$$

The GPS function for fuel region considers a current-to-flux ratio (CFR), a spectral index (SI), and SPH. The CFR is a factor that represents the leakage of neutrons as part of the albedo, which is defined as the ratio of in-current to out-current. The average CFRs of net leakage are used in this study. SI is a factor that can consider weight to the change of neutron spectrum with burnup. The burnup-dependent XS-SPH factors in the fuel region are parameterized as a function of the CFRs and SIs including the integrated pin-wise leakage information.

$$\Delta SPH_{bxig} = a_{bxig} \Delta CFR_{big} + b_{bxig} \Delta SI_{bi} + c_{bxig}. \quad (2)$$

The XS-SPH factors in the baffle-reflector region were determined with the BOC-based functions as follows,

$$\Delta SPH_{bxig} = a_{bxig} \Delta CFR_{bi1} + b_{bxig} \Delta CFR_{bi2} + c_{bxig}. \quad (3)$$

Meanwhile, in the actual core depletion procedure, each pin in one fuel assembly is determined to be proportional to the pin-power and inversely proportional to the amount of heavy metal in the pin as shown in Eq.(4).

$$\Delta BU_{pin} = \Delta BU_{core} \frac{P_{pin}/H_{pin}}{P_{core}/H_{core}} \quad (4)$$

For each burnup step, the library of reference group constants data including a variety of cross-sections and DFs are stored for the fuel assemblies loaded in the core. In addition, the GPS function set from the Eq.(3) is generated depending on the specific burnup steps. Therefore, the group constants with different pin burnup are linearly interpolated or extrapolated based on the data libraries on the reference burnup step as shown in the **Fig.3**.

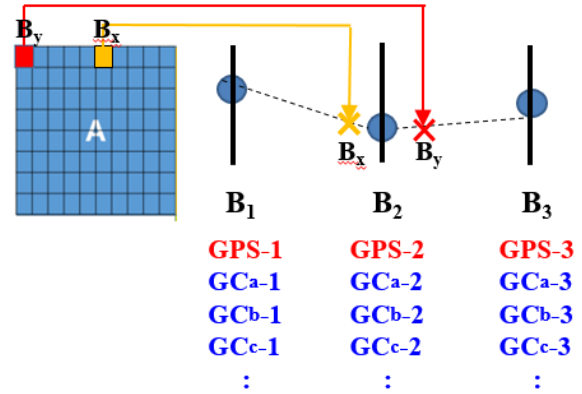


Fig. 3. GPS functions and group constants interpolation/extrapolation with burnup

3. Numerical Results

This study adopts a modified KAIST model [5] as shown in **Fig.4**. Three types of fuel assembly (UOX-1, UOX-2, and UOX-2(Gd)) with 17×17 lattices were loaded for the core inner region. Each assembly consists of 289 pins including 264 fuel pins and 25 guide tubes. The enrichment (and density) of UOX-1 and UOX-2 fuel are 2.0 wt%- and 3.3 wt% (10.4 g/cm³), respectively, and the UOX-2(Gd) is the Gd-loaded UOX-2 (10.06 g/cm³). The total power of the core is 0.5427 MWth and the number of burnup steps are 38 steps up to 20 MWd/kgHM.

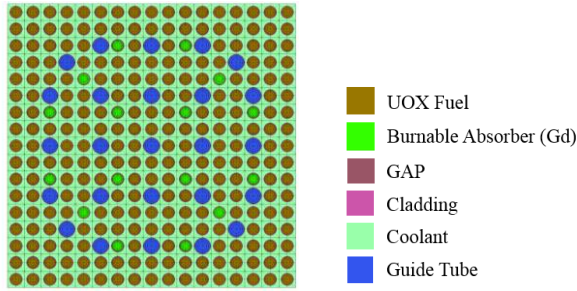


Fig. 4. Configuration of UOX-type Fuel assembly

In general pin-by-pin two-step methods, the error in the interface of fuel assembly appears to be large, making it difficult to compensate for neutron leakage. Therefore, in the color-set model to create a GPS function, the range of CFR must be sufficient to ensure that the range of leakage correction in actual core calculation is sufficient. Meanwhile, sufficient perturbation, which can represent more physical differences compared to the surrounding characteristics, shall be given to affect the center of the inside of the fuel assembly so that there are an enough ranges of CFRs.

In this study, the GPS functions were produced with two processes (i) using adjacent fresh fuels and (ii) using adjacent burned fuels. The method (i) has a sufficient CFR range, but does not sufficiently reflect the actual depletion environment. Conversely, the method (ii) is relatively narrow in range of CFR, but it can well reflect the surrounding depletion environments. Therefore, in this study, the GPS function uses the method (i) only, and the i-GPS means to use the integrated method of (i) and (ii) processes. Figure 5 shows the reactor core model for two-step analysis and how the i-GPS function generated with two-type color-sets are applied to the reactor problem. The SPH-XSs generated by color-sets with the adjacent burned fuels are applied to two lines located at the edge of the fuel assembly.

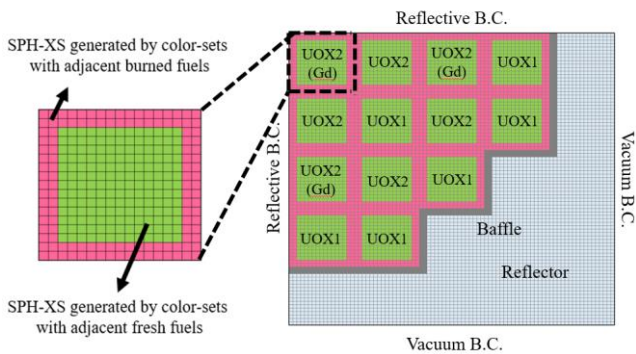


Fig. 5. Configuration of the small reactor problem applied with the i-GPS method

The burnup-dependent GPS functions were applied to two-step calculations. The performances between the original GPS function and the i-GPS function on two-step calculation were compared with reference transport calculation. Figure 6 shows the normalized peak-pin power error at specific burnup steps. The maximum error was found to be within 1% of all cases. Overall, results using the i-GPS method represented the least error.

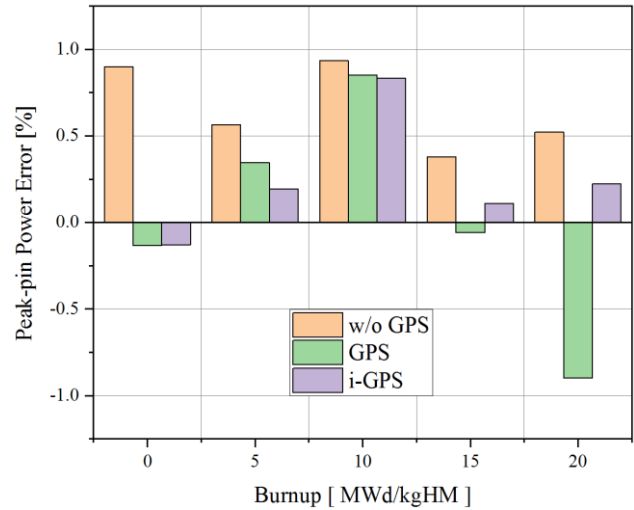


Fig. 6. Peak-pin power error at several burnup steps

Figure 7 shows the reactivity errors of two-step calculations without GPS, with GPS, and with i-GPS functions. Compared to the two step method without GPS, it has been shown to significantly reduce reactivity error when applying GPS functions. Especially, the typical GPS functions is shown to perform better in terms of decreasing reactivity error than i-GPS.

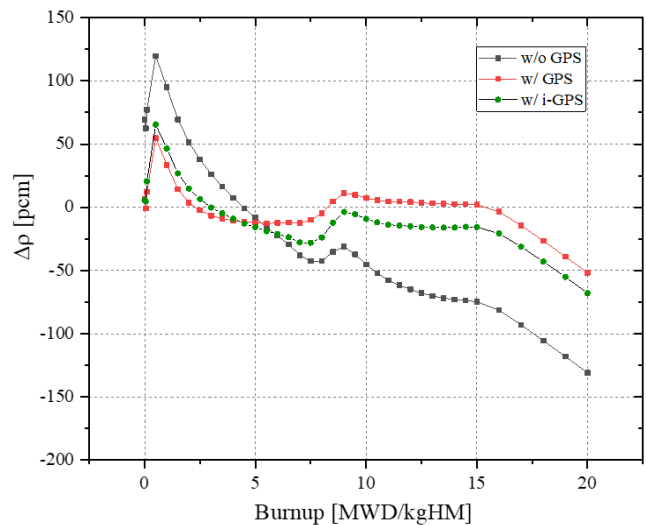


Fig. 7. Reactivity errors of two-step reactor analysis

Figure 8 shows the reference power and the power errors of each assembly in the core at 20 MWd/kgHM (last burnup step). Compared to the results produced from the two-step calculation without GPS, the application of typical GPS functions has a large increasing and decreasing deviation in power errors depending on the pin position. However, as a result of the application of i-GPS, the overall pin power errors were improved despite the last step of burnup cycle. This is because the GPS function generated with adjacent fresh fuel does not sufficiently reflect the surrounding depletion environment, whereas the i-GPS function has enough perturbation effect on the inside of the assembly, while also reflecting a similar environment outside the assembly.

Power (Reference)	1.759	1.579	1.178	0.554
w/o GPS	1.454 (0.554)	2.843 (0.776)	2.525 (0.815)	4.435 (1.508)
GPS	1.385 (0.443)	2.585 (0.706)	2.993 (0.910)	4.081 (1.316)
i-GPS	1.126 (0.265)	2.343 (0.722)	2.001 (0.577)	2.948 (1.139)
	1.579	1.152	1.060	0.416
	2.843 (0.776)	4.561 (1.597)	2.766 (0.863)	6.466 (2.194)
	2.585 (0.706)	5.599 (1.924)	3.921 (2.011)	7.644 (1.881)
	2.343 (0.722)	4.266 (1.574)	2.450 (1.095)	4.374 (1.643)
	1.178	1.060	0.515	
	2.525 (0.815)	2.766 (0.863)	6.551 (2.575)	
	2.993 (0.910)	3.921 (2.011)	9.150 (2.275)	
	2.001 (0.577)	2.450 (1.095)	4.750 (1.951)	
	0.554	0.416		
	4.435 (1.508)	6.466 (2.194)		
	4.081 (1.316)	7.644 (1.881)		
	2.948 (1.139)	4.374 (1.643)		

Fig. 8. Maximum relative errors and RMS errors of power at 20 MWd/kgHM

4. Conclusion

To improve the efficiency of neutron leakage correction along with burnup in two-step core analysis, the applicability of i-GPS function was analyzed in this study. While the typical GPS method is most efficient in terms of improving reactivity error, it has difficulty resolving interface power errors during core depletion. On the other hand, the i-GPS function, which applies the adjacent fresh fuel-based color-set to the inner assembly region and the adjacent burned fuel to the interface, was evaluated to make the most improvement of power error with burnup. Therefore, the application of the GPS function with the integrated method in generating color-sets is expected to be effective for two-step core depletion analysis, and more benchmark calculations are needed to verify the consistent applicability of this method.

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REFERENCES

- [1] K. S. Smith, "Assembly homogenization techniques for light water reactor analysis," *Progress in Nuclear Energy*, 17(3), pp.303-335 (1986).
- [2] A. Hebert, "A consistent technique for the pin-by-pin homogenization of a pressurized water reactor assembly," *Nuclear Science and Engineering*, 113(3), pp. 227-238 (1993).
- [3] H. Yu, W. Kim and Y. Kim, "A leakage correction with SPH factors for two-group constants in GET-based pin-by-pin reactor analyses," *Annals of Nuclear Energy*, 129, pp.30-55 (2019).
- [4] H. Jeong, H. Yu, and Y. Kim, "Burnup-dependent GPS Method with Leakage Correction and Spectral Weighting in Core Depletion Analysis", *Transactions of the American Nuclear Society*, Vol.123, 2020 ANS Virtual Winter Meeting, November 16-19 (2020).
- [5] N. Z. Cho, "Benchmark Problems in Reactor and Particle Transport Physics: Benchmark Problem 1A~4A," <http://nurapt.kaist.ac.kr/benchmark> (2000).