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Recent Developments of Lattice Physics Code STREAM

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1. Introduction

Three new advanced features have been implemented in the lattice physics code STREAM [1] for higher accuracy and performance in the analyses of Light water reactors (LWRs).

First, the resonance interference factor (RIF) library is upgraded. The previously reported resonance interference treatment method with RIF library in STREAM showed significant improvements in accuracy of k-inf and multi-group cross sections [2,3]. In this paper, the RIF library has been extended to include more isotopes to analyze a variety of fuel types including UO_2 and MOX fuels. With the application of the new RIF library and method to the UO_2 and MOX pin depletion problems, STREAM shows reactivity errors of less than 80 pcm at all burnup steps.

Second, the inflow transport approximation has been implemented. In LWRs analyses, the anisotropic scattering effect is generally treated by the transport corrected cross section (XS) with an isotropic scattering approximation. However, the conventional transport approximation can gives significant error for high neutron leakage problems. Therefore, a more rigorous inflow transport correction method is implemented in order to mitigate this problem [4]. The inflow transport approximation solves P_N transport equation in order to get high order flux moments required for the calculation of transport XS.

Third, the high order scattering model is implemented. The anisotropic scattering effect can be treated accurately by P_N high order scattering model. Although the high order scattering model takes too long execution time to be used in daily production work, the model can give exact solution for treating anisotropic scattering effect useful as a reference. STREAM uses the inflow transport approximation as a default option, and the high order scattering model is used to verify the solution from transport approximation. The inflow transport approximation and high order scattering model are verified with a small core problem with high neutron leakage.

2. Updated Features

2.1 Resonance Interference Factor Library

The RIF library method of STREAM has been developed in previous researches [2,3]. In this paper, the RIF library is extended to treat both of UO_2 and MOX fuel. The previous version of RIF library was developed to analyze resonance isotopes from UO_2 depletion problem. The RIF library was developed based on the depletion chain of CASMO-4E [5]. The updated RIF library is developed based on MCNP6 [6] depletion chain, and the library covers resonance isotopes of UO_2, MOX, and gadolinia fuels. The number of isotopes in the RIF library is 40, and the number of grids of atom ratio is 20.

2.2 Inflow Transport Approximation

The conventional methods such as consistent-P_N and outflow transport approximations are simple to implement in the code. However, the crude assumptions in the methods can give significant errors for high neutron leakage problems. The inflow transport approximation in Eq. (1) is known as more accurate method.

$$\Sigma_{tr,g} = \Sigma_{t,g}^{1} - \frac{\sum_{g'=1}^{G} \Sigma_{s,g'\to g}^{1} \varphi_{g'}^{1}}{\varphi_{g}^{1}} \quad . \tag{1}$$

However, the inflow approximation requires a good knowledge of the flux moment from some previous calculation.

The inflow transport approximation of STREAM solves the 1D multigroup P_N equation in Eq. (2) to get high order flux moments.

$$\begin{aligned} &\mu \frac{\partial}{\partial z} \sum_{l=0}^{\infty} \frac{2l+1}{2} P_l(\mu) \varphi_g^l(z) + \sum_{l=0}^{\infty} \frac{2l+1}{2} P_l(\mu) \Sigma_{t,g}^l \varphi_g^l(z) \\ &= \frac{1}{2} \chi_g \sum_{g=1}^{G} \nu \Sigma_{f,g} \varphi_g^0(z) + \sum_{l=0}^{\infty} \frac{2l+1}{2} P_l(\mu) \sum_{g'=1}^{G} \Sigma_{s,g'\to g}^l \varphi_{g'}^l(z) \end{aligned} \quad .(2)$$

2.3 High Order Scattering Model

The classical spherical harmonics approach is used in the implementation of high order scattering into the 2D method of characteristics solver of STREAM [7]. The scattering source is defined as follows:

$$\begin{aligned} &S(r,m,\Omega) \\ &= \int_0^\infty dE' \int_0^{4\pi} d\Omega' \left[\sigma_s(r,E' \to E, \Omega' \to \Omega) \psi(r,E',\Omega') \right] \end{aligned} \quad .(3)$$

The expressions of scattering source and flux moments in discrete angles can be derived by using Legendre polynomial expansion to scattering XS and spherical harmonics expansion to angular flux moments.

STREAM can model the P_1 to P_5 high order scattering in the transport analyses.

3. Verification

3.1 Pseudo Depletion of Pincell Problem

UO_2 and MOX Pincell depletion problems are designed to verify the RIF library method. The models are same as 5 wt.% enriched UO_2 and 8 wt.% content reactor-recycle MOX pincell problem at HFP in Mosteller benchmark [8]. The two pincells are depleted to 60 MWD/kgU with 34 burnup steps. These problems are made to verify the resonance interference treatment of STREAM not depletion chain and method. Therefore, the depletion calculations are performed by MCNP6 [6], and the isotopes of each burnup step are extracted and used to make STREAM inputs. All of isotopes in ENDF/B-VII.0 neutron data are considered in MCNP depletion calculation.

Figures 1 and 2 show the results of pincell depletion analyses. "Ignored" indicates the STREAM without resonance interference treatment; "Con" indicates conventional resonance interference model [9]; and "RIF" indicates STREAM with the updated RIF library. The STREAM results are compared with those of MCNP6. It is noted that "Ignored" and "Con" have significant bias as a function of burnup, and the order of k-inf error is around 200~600 pcm. The RIF method shows significant improvements in the accuracy of k-inf. Most k-inf errors are less than 80 pcm.

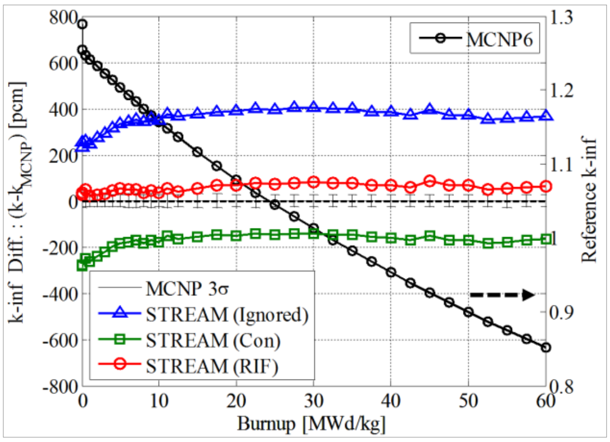

Fig. 1. Results of UO_2 pincell depletion analyses.

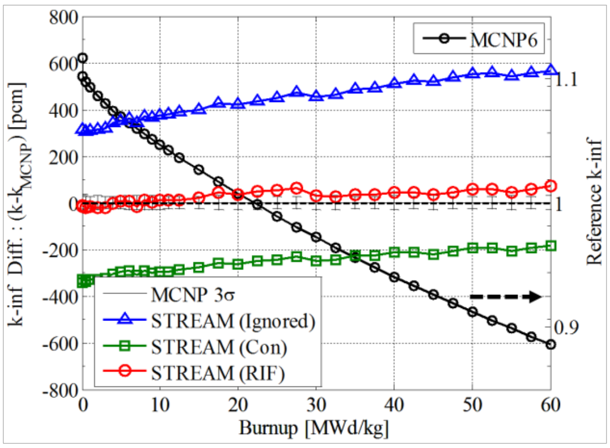

Fig. 2. Results of MOX pincell depletion analyses.

3.2 B&W1484 I 2D core problem

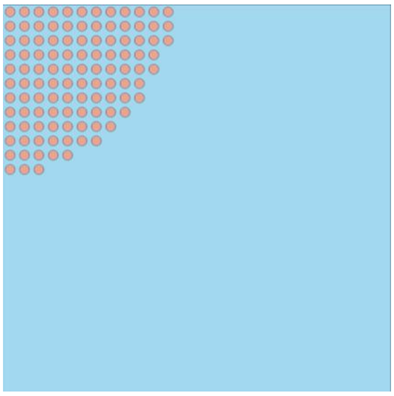

Fig. 3. Fuel pin configuration of B&W1484 I core.

B&W1484 I 2D core [10] problem is analyzed. The size of core is small as shown in Fig. 3, and a large amount of neutrons is leaked out of the core, which makes a challenging problem to the nuclear reactor analysis code with approximations in the anisotropic scattering treatment. The problem is analyzed by transport corrected P_0 calculations and high order scattering calculations (P_1 ~ P_5). The results are shown in Tables I and II.

Table I: k-eff results of B&W analyses

Code	Condition	k-eff	Diff. [pcm]
MCNP6	-	1.01567	±2
STREAM	P_0 (Consistent)	1.11879	10312
	P_0 (Outflow Tr.)	1.00347	-1220
	P_0 (Inflow Tr.)	1.01541	-26
	P_1	1.01287	-280
	P_2	1.01564	-3
	P_3	1.01548	-19
	P_4	1.01550	-17
	P_5	1.01550	-17

Table II: Pin power error of B&W analyses

Code	Condition	Pin Power Diff. [%]	
		PW.[1)]	Max.
MCNP6	-	±0.03	±0.04
STREAM	P_0 (Consistent)	3.97	10.65
	P_0 (Outflow Tr.)	0.46	0.92
	P_0 (Inflow Tr.)	0.56	1.11
	P_1	0.73	1.61
	P_2	0.55	1.12
	P_3	0.56	1.12
	P_4	0.56	1.13
	P_5	0.56	1.13

1) Power weighted average of pin power difference.

The P_0 isotropic scattering calculations with the conventional transport approximations such as consistent and outflow show a large amount of errors in k-eff which are 10312 and 1220 pcm, respectively. On the other hand, STREAM with the inflow transport approximation shows as small error as 26 pcm. STREAM with P_2 ~ P_5 high order scattering models show accurate and similar results each other. However, the P_1 is not sufficient to treat the anisotropic scattering effect sufficiently. The results of pin power distribution are also very accurate. The inflow transport approximation and P_2 ~ P_5 high order scattering treatment show consistent results each other.

4. Conclusions

Three new advanced features are implemented in the lattice physics code STREAM. STREAM with the upgraded RIF library can analyze both of UO_2 and MOX fuel depletion problems with errors less than 80 pcm for all burnup steps. The inflow transport approximation and high order scattering model make it possible to treat highly anisotropic scattering accurately. The results from the inflow transport approximation and high order scattering treatment are accurate and consistent each other. Newly implemented features provides STREAM with high fidelity in LWRs analyses.

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