RESONANCE SELF-SHIELDING METHODOLOGY IN MPACT

Yuxuan Liu, Benjamin Collins, Brendan Kochunas and William Martin
Department of Nuclear Engineering and Radiological Sciences
University of Michigan
2355 Bonisteel Blvd., Ann Arbor, MI, 48109
yuxuanl@umich.edu; bscollin@umich.edu; bkochuna@umich.edu; wrm@umich.edu

Kang-Seog Kim and Mark Williams
Oak Ridge National Laboratory
One Bethel Valley Road, P.O. Box 2008, Oak Ridge, TN 37831-6172, USA
kimk1@ornl.gov; williamsml@ornl.gov

ABSTRACT

The resonance self-shielding methods of the neutron transport code Michigan PArallel Characteristics based Transport (MPACT) are described in this paper. Two resonance-integral table based methods are utilized to resolve the resonance self-shielding effect. The subgroup method is a mature approach used in MPACT as the basic functionality for the resonance calculation. Another new iterative method, named the embedded self-shielding method is also implemented in MPACT. Comparisons of the two methods as well as their numerical verifications are presented. The results show that MPACT is capable of modeling the resonance self-shielding in a variety of PWR benchmarking cases, including difficult fuel lattice cases with poison, control rods or mixed gadolinia fuel rods.

Key Words: Resonance Self-shielding, MPACT, Subgroup method, ESSM

1. INTRODUCTION

The **M**ichigan **PA**rallel **C**haracteristics based **T**ransport (MPACT) is a neutron transport code developed at the University of Michigan using the 3-D Method of Characteristics (MOC). In order to obtain the problem-dependent multigroup cross sections, the resonance self-shielding calculations must be performed before one is able to do the whole-core MOC calculations. In general, the goal of the resonance calculations is to obtain the effective cross sections of an isotope at reaction channel x for group g

$$\sigma_{x,g} = \frac{\int_{\Delta u_g} \sigma_x(u)\phi(u)du}{\int_{\Delta u_g} \phi(u)du} \tag{1}$$

It is not possible to determine the rigorous neutron spectra for a specific problem before one performs the real 3-D whole-core transport calculations, so the spectra used in the calculation of effective cross sections are approximated in the energy and/or spatial domains.

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There are in general two ways of performing the resonance self-shielding calculation for the deterministic neutron transport methods. The best approach for assuring the accuracy in the energy domain is to solve the slowing-down equations for the problem of interest. The continuous-energy (CE) cross sections are needed to resolve the resonance behavior. Because of the limited computational resources, neutron slowing-down codes such as CENTRM [1] and RMET21 [2] usually assume 1-D cylindrical geometry that has been converted from the square pin cell using the Wigner-Seitz approximation. The assumption of 1-D cylindrical geometry does not account for the inter-pin spatial self-shielding effects in the actual reactor geometry. The second approach utilizes pre-computed resonance integral (RI) tables, which are established by slowing-down solution over a range of background cross sections. Based on the equivalence theory [3], different methods can be derived in order to determine the equivalence cross sections to account for spatial self-shielding. The Bondarenko background cross section method [4] is the conventional method incorporating Dancoff factors to account for the spatial self-shielding. The subgroup method [5] is another RI table based method where the RI tables are usually converted to a set of subgroup levels and weights so that the equivalence cross sections are subgroup-level dependent. Recently another promising RI table based method, the iterative self-shielding method [6] [7] was proposed by Korea Atomic Energy Research Institute (KAERI) and Oak Ridge National Laboratory (ORNL). ORNL entitled it Embedded Self-Shielding Method (ESSM) because compared to the conventional Bondarenko method in which the Dancoff factors should be approximated or evaluated outside the transport calculation, ESSM provides tighter coupling between the neutron transport and self-shielding calculations, so that the heterogeneous self-shielding effects are consistent with the multigroup transport calculations of the whole system.

The MPACT code is capable of using both the subgroup method and ESSM for the resonance self-shielding calculations based on the multigroup libraries with subgroup parameters, such as HELIOS library [8]. As the code has been designed for easy extension of new libraries by implementing a small set of interfacing functions associated with the library, it is very straightforward to add new multigroup libraries to perform the resonance and transport calculations. Specifically, the 60 group library generated by ORNL has been implemented into MPACT for the initial verifications. The library is processed from ENDF/B-VII.0 using sequences of SCALE-6.1 system [9] as well as optimization code for generating subgroup parameters. In this paper, the fundamentals of self-shielding treatments in MPACT are discussed in Section 2 and a variety of benchmarking verifications are presented in Section 3.

2. Methodology

The presentation of resonance self-shielding treatment begins with the derivation of the neutron spectra to be used in the resonance integral calculations. The subgroup method and ESSM are respectively discussed in the second subsection. Other features of the resonance treatment in MPACT are discussed in the last subsection.

2.1. Resonance Self-shielding Treatment

The relatively accurate approach to obtain the spectrum in Eq. (1) is to solve the slowing-down equation for a problem of interest

CASL-U-2015-0008-000

$$\nabla \cdot \Omega\varphi(r,u,\Omega) + \sum_i \Sigma_{t,i}(r,u)\varphi(r,u,\Omega) = \frac{1}{4\pi}\sum_i \int_{u-\varepsilon_i}^{u} \Sigma_{s,i}(r,u')\phi(r,u')\frac{e^{u'-u}}{1-\alpha_i}du' \quad (2)$$

where *i* is summed over all isotopes of the material, and ε_i is the maximum lethargy gain when a neutron scatters off isotope *i*. Three major assumptions have been made in this equation for the resolved resonance energy range: (1) the scattering source is isotropic, including only s-wave elastic reactions; (2) up-scattering is neglected; and (3) the direct fission source is neglected. In order to decouple the lethargy dependence in the scattering source from lethargy $u-\varepsilon_i$ to u, the Intermediate Resonance (IR) approximation [10] is employed to achieve

$$\nabla \cdot \Omega\varphi(r,u,\Omega) + \sum_i \Sigma_{t,i}(r,u)\varphi(r,u,\Omega) = \frac{1}{4\pi}\left(\sum_i \lambda_i \Sigma_{p,i}(r) + \sum_i (1-\lambda_i)\Sigma_{s,i}(r,u)\phi(r,u)\right) \quad (3)$$

By neglecting the resonance scattering term, $\lambda_i\Sigma_{RS,i}(r,u)$ $\left(where\ \Sigma_{RS,i}(r,u) = \Sigma_{s,i}(r,u) - \Sigma_{p,i}\right)$, and assuming isotropic fluxes in the second term of the right hand side, a much simpler equation is formed where there is no flux dependence in the source term

$$\nabla \cdot \Omega\varphi(r,u,\Omega) + \sum_i \left[\Sigma_{a,i}(r,u) + \lambda_i\Sigma_{p,i}(r)\right]\varphi(r,u,\Omega) = \frac{1}{4\pi}\sum_i \lambda_i\Sigma_{p,i}(r) \quad (4)$$

For an infinite homogenous medium, the solution of Eq. (4) can be written as

$$\phi_{\text{hom}}(u) = \frac{\sum_i \lambda_i\Sigma_{p,i}}{\sum_i \Sigma_{a,i}(u) + \sum_i \lambda_i\Sigma_{p,i}} \quad (5)$$

The equivalence theory correlates the solution of the homogeneous resonance problem with the heterogeneous problem by introducing the equivalence cross section

$$\phi_{het}(u) = \frac{\sum_i \lambda_i\Sigma_{p,i} + \Sigma_e}{\sum_i \Sigma_{a,i}(u) + \sum_i \lambda_i\Sigma_{p,i} + \Sigma_e} = \frac{\Sigma_b}{\sum_i \Sigma_{a,i}(u) + \Sigma_b} \quad (6)$$

By introducing Eq. (6) into Eq. (1), the effective cross section is a function of the background cross section Σ_b, so a table of effective cross section (or RI) can be built through various background levels. With these pre-calculated RI tables, once the equivalence cross section of a region is properly determined, the effective cross sections can be directly interpolated.

All the RI table based methods are aiming at estimating the equivalence cross sections of the system. The Bondarenko background cross section method determines an approximate value of the equivalence cross section by using the rational approximation as well as evaluating Dancoff

CASL-U-2015-0008-000

factors. ESSM iteratively solves the fixed source problem (FSP) to converge the equivalence cross section of a system, while subgroup method evaluates the RI by quadrature approximation based on calculations of the equivalence cross sections at a variety of subgroup levels. Once the equivalence cross section is obtained, the background cross section can be used to either interpolate RIs for all reaction channels in ESSM or complete the quadrature calculation in the subgroup method.

2.2. Subgroup Method and ESSM

The subgroup method transforms the integration variable from neutron energy to absorption cross section. Eq. (6) gives us important information that the flux depression is mainly due to the absorption cross sections. Although the absorption cross sections are a strong function of energy (or lethargy), it is more efficient to perform the integration of Eq. (1) with absorption cross section as the integration variable rather than neutron energy [8].

$$\sigma_{x,g} = \frac{\int_{\Delta u_g} \sigma_x(u)\phi(u)du}{\int_{\Delta u_g} \phi(u)du} = \frac{\int_{\Delta u_g} f(u)du}{\int_{\Delta u_g} \phi(u)du} = \frac{\int f(\sigma)\frac{du}{d\sigma}d\sigma}{\int \phi(\sigma)\frac{du}{d\sigma}d\sigma} \qquad \left(f(u) = \sigma_x(u)\phi(u)\right) \quad (7)$$

The integrals of Eq. (7) can be cast into a quadrature form represented by the subgroup levels and weights

$$\sigma_{x,g} \cong \frac{\sum_n \sigma_{x,g,n}\phi_{g,n}w_{x,g,n}}{\sum_n \phi_{g,n}w_{x,g,n}} \quad (8)$$

The subgroup levels and weights are determined by searching for the desired fit from a set of pre-computed RI tables parameterized by background cross sections. In order to obtain the same set of subgroup levels and weights for the numerator and denominator of Eq. (8), the summation of the weights are forced to unity by including zero-level parameters $w_{x,g,0}$ and $\sigma_{x,g,0}$ [8].

Subgroup calculations are performed for each absorption levels by solving the FSP, Eq. (4), and the resulting fluxes can be used in Eq. (8) to estimate the effective cross sections. However, it is preferable to represent the level dependent flux in Eq. (8) by introducing Eq. (5),

$$\sigma_{x,g} \cong \frac{\sum_n \sigma_{x,g,n}\frac{\sigma_{b,g,n}}{\sigma_{a,g,n}+\sigma_{b,g,n}}w_{x,g,n}}{\sum_n \frac{\sigma_{b,g,n}}{\sigma_{a,g,n}+\sigma_{b,g,n}}w_{x,g,n}} \quad (9)$$

An assumption is made in this equation that there is no resonance interference among isotopes within the broad energy group *g*, so the flux depression is represented by the specific resonant isotope being considered. As a practical matter, Eq. (9) is used for evaluation of the effective

CASL-U-2015-0008-000

cross sections instead of directly using $\phi_{g,n}$ from the fixed source transport solution. This alternative option is chosen because the dependence of $\sigma_{b,g,n}$ on $\sigma_{a,g,n}$ is much weaker than the dependence of $\phi_{g,n}$ on $\sigma_{a,g,n}$. The number of $\sigma_{b,g,n}$ capable of describing this dependence is therefore smaller than the number of subgroup levels used in the quadrature representing the effective cross section. Thus fewer fixed source calculations are required for the resonance calculations. Similar with the subgroup treatment of HELIOS code, MPACT uses four absorption levels for the FSP calculation, and the resulting tables of $\Sigma_{e,n}(\sigma_{a,n})$ are interpolated to seven levels for the evaluation of effective cross sections. Another treatment for the subgroup method to save computation time is to group the resonance isotopes into several categories. Each category contains a subset of resonance isotopes having overlapping, but not equally strong resonances. The FSP is solved per category rather than per resonance isotope.

ESSM also solves the FSP to determine the equivalence cross sections, but the quadrature representation is replaced by iterations between fixed source solver and self-shielded parameters. Figure 1 depicts the ESSM procedures. The effective absorption is a monotonous function of background cross section, as shown by the solid blue line. Considering a problem with a real effective cross section $\sigma_{a,real}$ the ESSM is looking for, the method starts with an initial guess of $\sigma_{b,0}$ associated with an effective $\sigma_{a,0}$ interpolated from the RI tables. Relative to $\sigma_{a,real}$, the smaller $\sigma_{a,0}$ introduced into Eq. (4) for solving the FSP should result in a larger background cross section $\sigma_{b,1}$ relative to $\sigma_{b,real}$. Therefore, iteration is required between the FSP and the RI interpolation to converge the background cross sections or specifically, the equivalence cross sections.

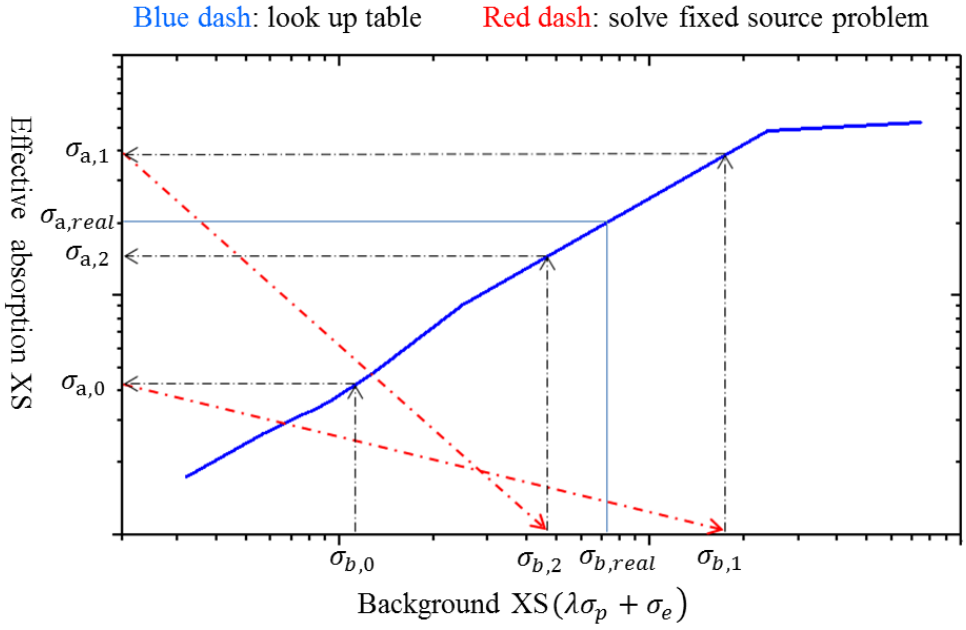

Figure 1. Conceptual illustration of ESSM procedures

Comparisons of the subgroup method and ESSM yield the following important differences: (1) the subgroup method requires an auxiliary code to calculate the subgroup levels and weights, which yields quadrature errors, while ESSM embeds the entire resonance calculation within the transport method, and (2) the computational time for the subgroup method is determined by the number of subgroup levels used in the fixed source calculations, while the computational time for ESSM depends on the average number of iterations to converge the solution. Both of the methods are implemented in MPACT and the numerical comparisons are given in Section 3.

2.3. Other features of resonance treatment in MPACT

RI table based methods such as subgroup and ESSM have difficulty treating the interference effect among resonant isotopes. This is due to the fact that the RI tables are generated at different temperatures and dilutions for each single resonant isotope by solving the slowing-down equation with CE cross sections. The interference effect is neglected at this step and is assumed to be treated at the Multi-group level, e.g., by Bondarenko iteration described in the WIMS code [11]. Ref. [12] describes our research on improving the treatment of resonance interference by incorporating a 0-D slowing-down solution for the mixture of resonance isotopes. This feature will be added into MPACT once MPACT has a verified slowing-down solver as well as a point-wise cross section library, but for now, the conventional Bondarenko iteration method at the multigroup level is used to roughly estimate the interference effect.

Taking advantage of the availability of resonance scattering RI tables in the multigroup library, shielded resonance scattering cross sections are determined in MPACT. The products of subgroup calculations are the shielded absorption cross sections of resonance nuclides, as well as the tables of the equivalence cross sections against subgroup levels for each resonance category. The shielded absorption cross section of a resonance nuclide is first converted back to the effective absorption cross section of the representative isotope of the category, such that the equivalence cross section can be interpolated using the table of $\Sigma_{e,n}(\sigma_{a,n})$. Then the background cross section associated with the shielded absorption can be simply determined. For ESSM, the background cross section associated with the shielded absorption cross section is already determined when the iteration is complete. This background cross section is used to interpolate the integral of resonance scattering so that the shielded P0 scattering cross section of each resonance group can be calculated. Compared to the unshielded scattering cross section provided by the library, a ratio is defined as

$$f_{iso,g} = \frac{\sigma_{s,iso,g}^{shielded}}{\sigma_{s,iso,g}^{unshielded}} \tag{10}$$

The transport corrected scattering matrix can be renormalized by multiplying the ratios:

CASL-U-2015-0008-000

$$\sigma_{s0,iso,g->g'}^{shielded} = \begin{cases} f_{iso,g}\sigma_{s0,iso,g->g'}^{unshielded} & g \neq g' \\ f_{iso,g}\left(\sigma_{s0,iso,g->g}^{unshielded} - \sum_{g'}\sigma_{s1,iso,g->g'}^{unshielded}\right) & g = g' \end{cases} \quad (11)$$

The corrections of high order scattering terms are performed using the same ratios as for the P0 scattering.

3. Verification Results

Two sets of benchmarking problems are selected for the verifications of the resonance self-shielding models in MPACT. The first subsection briefly describes the benchmarking problems, followed by the results in the second subsection.

3.1. Benchmarking problems

In this section, the resonance treatment is verified by several benchmark problems [13] that have been developed for use by Consortium for Advanced Simulation of Light Water Reactors (CASL) at ORNL. In this paper, Benchmark Problem Set 1 and 2 from Ref. [13] are used for our initial verification calculations with MPACT.

Benchmark Problem Set 1 consists of four simple two-dimensional pin cell cases with variations in the fuel and/or coolant temperatures. The problem consists of a single fuel rod cell at beginning-of-life and hot-zero-power conditions. Information on the geometry and materials is not provided but the temperatures for the four cases are given in Table 1. Benchmark Problem Set 1 tests the correctness of the resonance models and the temperature interpolation.

Table 1 Temperatures of cases in Problem Set 1

Case	Moderator Temperature*	Fuel Temperature	Moderator Density
1A	565K	565K	0.743 g/cc
1B	600K	600K	0.661 g/cc
1C		900K	
1D		1200K	

* Clad temperature is set at moderator temperature

Benchmark Problem Set 2 is designed to test MPACT's capability to model a two-dimensional array of fuel rods (a fuel lattice) typical of the central axial region of a PWR fuel assembly, specifically a single Westinghouse 17x17-type fuel lattice at beginning-of-life. In addition to the fuel rods similar to the Benchmark Problem Set 1, other materials such as silver-indium-cadmium (AgInCd), boron carbide (B_4C), Pyrex (borosilicate glass - B_2O_3-SiO_2), and B_4C-Al_2O_3 are used as neutron poisons inserted into the guide tubes, and stainless steel 304 is used for the

instrument tube thimble and other structural materials. With regard to the resonance calculation, this set verifies the MPACT's capability to resolve the inter-pin spatial self-shielding effects among different kinds of fuel/control rods. Detailed information of the geometries and materials can be found in Ref. [13], so this paper only provides brief information identifying the most significant characteristics of each case, as shown in Table 2. In the "description" column, the integers are given as the number of special fuel or control rods inserted into the assembly.

Table 2 Specifications of Problem Set 2

Case	Description	Moderator Temperature*	Fuel Temperature
2A	No poisons	565K	565K
2B		600K	600K
2C			900K
2D			1200K
2E	12 Pyrex		600K
2F	24 Pyrex		
2G	24 AgInCd		
2H	24 B_4C		
2I	Instrument Thimble		
2J	Instrument + 24 Pyrex		
2K	Zoned (3.1%+3.6%) + 24 Pyrex		
2L	80 IFBA		
2M	128 IFBA		
2N	104 IFBA + 20 WABA		
2O	12 Gadolinia		
2P	24 Gadolinia		

* Clad temperature is set at moderator temperature

3.2. Verifications Results

Subgroup method and ESSM performs the FSP using the same spatial mesh and MOC parameters (4 polar angles, 16 azimuthal angles and 0.03cm ray spacing). The accuracy of the resonance model can be shown by directly comparing the self-shielded cross sections generated from MPACT with the cross sections tallied by the Monte Carlo method. We obtained the reference cross sections by performing MCNP5 calculations using the ACE library processed from ENDF/B-VII.0, identical to the source of the multigroup library for MPACT. The pin cell case 1B (600K everywhere) is chosen for our comparisons as the 600K CE library is provided with MCNP5 release. In Figure 2-4, the relative errors of the subgroup method and ESSM are presented along with the reference effective cross sections for U-238 and U-235. Good agreements for both methods with the MCNP reference results are found in most energy groups, except for some groups of U-235 where the relative errors exceed 10%. These groups correspond to the energy where U-238 has strong absorption resonance. Because U-238 dominates the

CASL-U-2015-0008-000

neutron spectra in the LWR applications, the interference of U-238 with other isotopes yields spectra that differ substantially from the original spectra that are used for generating the RI tables, and this will result in large errors for the effective cross sections for these isotopes such as U-235. On the other hand, the errors are cancelled out to some extent for the calculation of the eigenvalue. For example, Figure 3 and 4 indicate that the absorption and fission effective cross sections of U-235 have errors in the same direction, thus having a smaller effect on eigenvalue. Ref. [12] investigates the interference issues in more detail and the results show that the interference effect accounts for an eigenvalue difference of 50-100 pcm for most cases.

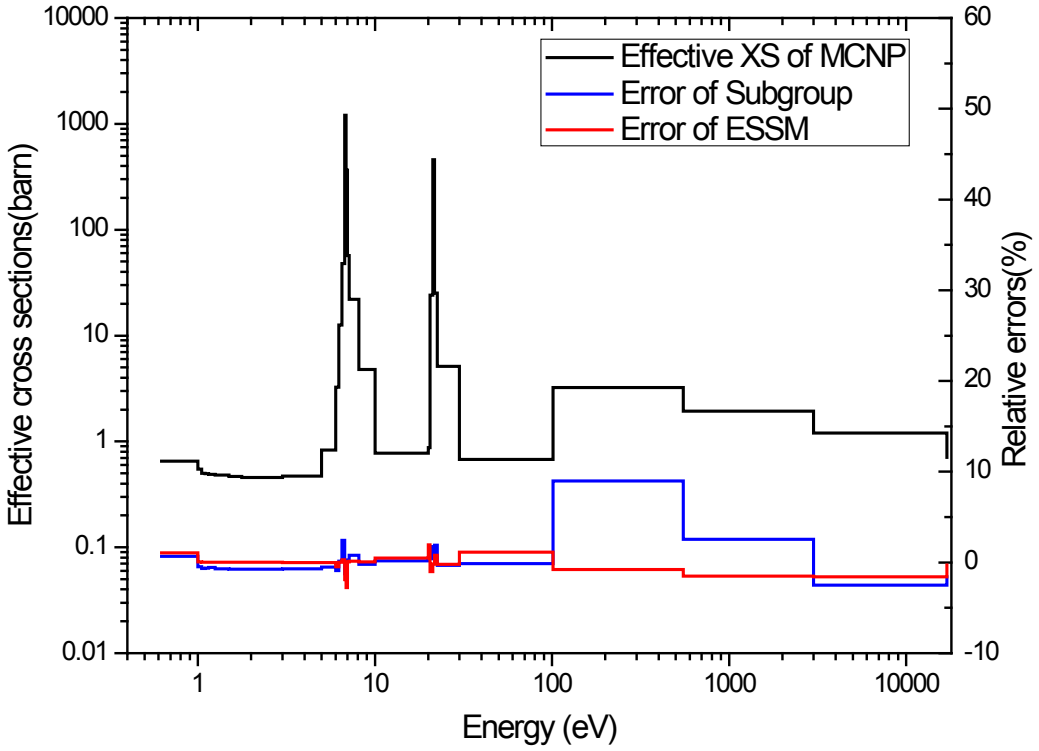

Figure 2. Relative Errors of U-238 effective absorption

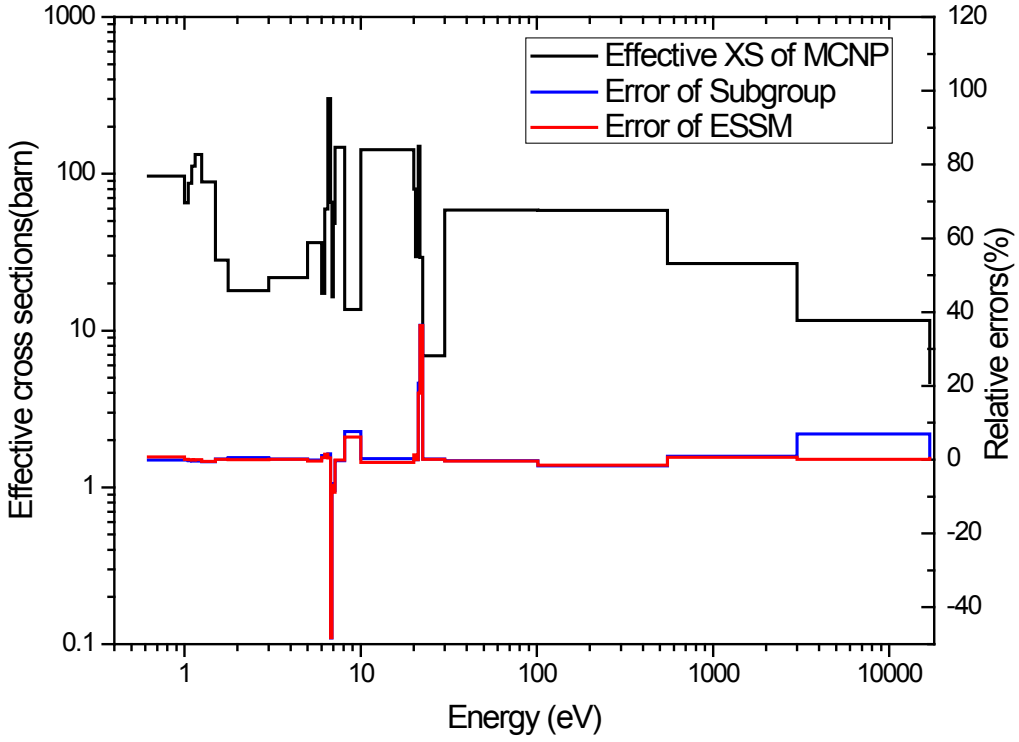

Figure 3. Relative Errors of U-235 effective absorption

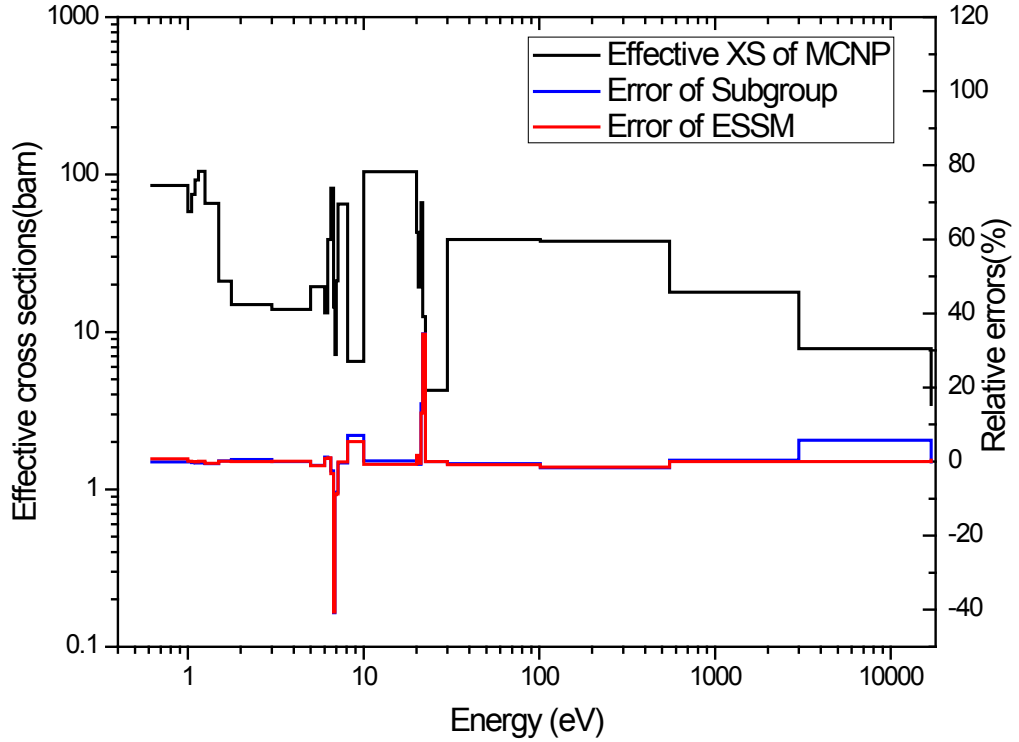

Figure 4. Relative Errors of U-235 effective fission

The eigenvalues of all the cases are compared in Table 3. The reference solutions are obtained by CE KENO-VI (SCALE 6.2 dev) and provided in Ref. [13]. The eigenvalue results reflect the accuracy of both the subgroup method and ESSM when producing self-shielded cross sections. Cases 2L-2N which includes the very thin IFBA coating, have larger errors relative to other cases. As the RI tables are generated with regular fuel rods in heterogeneous 1-D configurations, the flux dips due to the IFBA coating will definitely impact the relationship between background cross sections and self-shielded cross sections. Thus, further investigations are needed for the IFBA cases. Another observation is that all the values obtained by ESSM are greater than the subgroup method. In spite of the quadrature errors arising from the generation of the subgroup parameters, a subtlety that the subgroup method differs from ESSM is the category treatment mentioned in Section 2. Instead, ESSM considers the absorption of resonance isotopes as a whole material for computational efficiency when solving the FSP equations. This treatment underestimates the equivalence cross sections as compared to singling out each category for the fixed source calculations. The consequence of the smaller equivalence cross sections is the smaller effective absorptions for isotopes, which finally results in a larger eigenvalue.

Table 3 K_{eff} comparisons of Problem Set 1 and 2

Case		K_{eff} by KENO	Subgroup*	ESSM*
Pin cell	1A	1.187606 ± 0.000107	1.1867658 (-84)	1.1886754 (107)
	1B	1.182935 ± 0.000071	1.1817303 (-120)	1.1842350 (130)
	1C	1.172386 ± 0.000075	1.1702463 (-214)	1.1732990 (91)
	1D	1.163150 ± 0.000069	1.1609213 (-223)	1.1648666 (172)
Fuel lattice	2A	1.182507 ± 0.000033	1.1813807 (-113)	1.1824494 (-6)
	2B	1.184033 ± 0.000023	1.1821842 (-185)	1.1837465 (-29)
	2C	1.174434 ± 0.000022	1.1716159 (-282)	1.1736527 (-78)
	2D	1.166137 ± 0.000022	1.1630141 (-312)	1.1658590 (-28)
	2E	1.070441 ± 0.000025	1.0691999 (-124)	1.0702036 (-24)
	2F	0.976903 ± 0.000025	0.9759061 (-100)	0.9767874 (-12)
	2G	0.849236 ± 0.000024	0.8518333 (260)	0.8528098 (357)
	2H	0.789746 ± 0.000024	0.7925492 (280)	0.7930715 (333)
	2I	1.180561 ± 0.000024	1.1789848 (-158)	1.1801171 (-44)
	2J	0.976101 ± 0.000024	0.9751481 (-95)	0.9760292 (-7)
	2K	1.020999 ± 0.000024	1.0200254 (-97)	1.0209066 (-9)
	2L	1.019538 ± 0.000024	1.0152701 (-427)	1.0161132 (-342)
	2M	0.939462 ± 0.000025	0.9341363 (-533)	0.9348299 (-463)
	2N	0.870430 ± 0.000025	0.8667651 (-366)	0.8671722 (-325)
	2O	1.048367 ± 0.000024	1.0475327 (-83)	1.0485989 (23)
	2P	0.927999 ± 0.000026	0.9272782 (-72)	0.9282266 (23)

* The values in the bracket are Δk in pcm

CASL-U-2015-0008-000

The computation time of the benchmark cases is summarized in Table 4. Basically, the computing time for resonance calculation is determined by the number of FSP to be solved. For the subgroup method, this number is determined by the number of resonance categories assigned to the problem and the number of subgroup levels. Because we performed all the calculations using four categories with four subgroup levels for each category, the computing time does not vary much from case to case. For ESSM, it is the convergence rate of the equivalence cross sections that determines the total number of FSP to be solved. The average number of iterations for our benchmark cases is in the range 3-6 (convergence criterion of equivalence cross section: 0.1%), which is as the same order of subgroup levels in the subgroup method, so the time savings for ESSM compared to the subgroup method is primarily due to not using resonance categories in ESSM. In all, the resonance computing time is less than one third of the total time for all the cases when the MOC parameters are identical for both FSP and eigenvalue calculations, so the resonance calculation is not the limiting factor for the efficiency of the overall method.

Table 4 Computing time (s) of benchmark cases

Case		Subgroup		ESSM	
		Resonance[a]	Total[b]	Resonance	Total
Pin cell	1A	4	22	1	17
	1B	5	23	1	19
	1C	5	23	1	19
	1D	5	23	1	19
Fuel lattice	2A	455	1481	144	1160
	2B	470	1520	143	1178
	2C	450	1466	145	1175
	2D	453	1437	150	1189
	2E	467	1517	140	1165
	2F	477	1541	148	1221
	2G	473	1511	186	1259
	2H	464	1476	147	1205
	2I	444	1452	143	1160
	2J	473	1529	144	1216
	2K	472	1554	150	1201
	2L	467	1521	143	1180
	2M	476	1508	148	1240
	2N	493	1591	255	1398
	2O	481	1529	161	1220
	2P	495	1562	162	1240

[a] Resonance is the time spent on the resonance self-shielding calculation
[b] Total time includes everything of the transport calculation

4. Conclusions

CASL-U-2015-0008-000

The MPACT neutron transport code utilizes two methods for the resonance self-shielding calculations. These methods are based on the pre-calculated RI tables and are capable of resolving the spatial self-shielding effect in 2-D lattice geometry. The subgroup method evaluates the self-shielded cross sections by quadrature approximation so that the equivalence cross sections accounting for the spatial shielding effect are calculated on a variety of subgroup levels. The ESSM iteratively solves the FSP to converge the equivalence cross section for the system. Both methods are able to correctly produce self-shielded cross sections for the whole-core transport calculations of MPACT and the computing time for the resonance calculation is no more than one third of the total time of the transport calculation.

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