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Improved multi-group cross sections with resonance treatment for future applications involving minor actinides

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ABSTRACT

In the future study for thorium reactors and minor actinide transmutation reactors, resonance self-shielding treatment for them becomes remarkable issue for criticality and isotope depletion. Resonance treatment for important minor actinides and other resonant absorbers has been carried out with subgroup method. The updated multi-group cross sections and subgroup data is replaced with existing multi-group library. The results from neutron transport code nTRACER with updated multi-group cross section library were compared with existing library and solutions from MCNP. The resonance interaction of uranium with important minor actinides has been accommodated through modified interference treatment by interference correction in subgroup method. The results for cross sections and multiplication factor for pin and assembly problems showed improvement from systematic resonance treatment for resonant absorber nuclides including ^{237}Np and ^{243}Am.

1. Introduction

Plutonium and minor actinides (MA) in spent nuclear fuel represent a considerable nuclear proliferation concern and have a major contribution to the long-term radiotoxicity of nuclear waste. In order to enhance the destruction of plutonium and minor actinides in thermal reactors, the amount of uranium loaded into the core must be minimized. Fertile free and thorium based fuels can serve this purpose. However fuel cores based on fertile free fuels exhibit a large reactivity swing and less favorable Doppler reactivity coefficient (Shwageraus et al., 2004). Whereas thorium fuel has advantage of less reactivity swing due to continuous buildup of ^{233}U with almost no production of minor actinides and Plutonium.

Minor actinide nuclides such as Np-237, Am-241 and Am-243 have large thermal neutron capture cross sections in the thermal energy region of neutron spectra. Therefore the potential of rapid transmutation of minor actinides can help to reduce the proportion of long-lived isotopes in the radioactive waste (Liu et al., 2013a). The main limitation of thermal reactors is that the total loading of minor actinide targets may need to be restricted to avoid excessive impacts on core reactivity control and reactivity feedback characteristics. Because of such considerations, the potential for minor actinide transmutation in thermal reactors has largely been overlooked in recent years in favor of fast reactors. However, there is potentially an advantage in favor of thermal reactors because there are already more than four hundred in commercial operation, whereas there are only fast reactor prototypes available. Due to large thermal spectrum cross sections for neutron absorption which limits the inventory of minor actinides in much smaller neutron flux field in thermal rectors than fast reactors. As a consequence thermal reactors will discharge a smaller actinide inventory than fast reactors and therefore reduce the reprocessing costs.

In the view of applying multi-group calculations to more advanced future applications of thermal reactors, the accuracy of self-shielded neutron cross sections becomes very important in the prediction of integral parameters obtained by solving a neutron balance equation. The cross section needed for static calculations consist of primarily multi-group cross sections and resonance parameters. The multi-group cross sections are the reaction cross sections obtained for the energy group structure of the library. The absorption, nu fission, scattering, transport cross sections and the scattering matrices of various orders primarily constitute the multi-group library. These cross sections are obtained by conventional method of averaging the cross sections with the spectrum weighting.

Some isotopes with sufficiently large concentration makes self-shielding significant due to large and complex variation of cross sections in the resonance energy range. As often the case these isotopes may co-exist in same region such as fuel. Hence, interference among their resonances results in the complexity of resonance self-shielding. Therefore, different methods are being employed

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for self-shielding calculations with their range of applicability. One kind of self-shielding method, based on collision probabilities, is efficient just for small systems. In which an equivalent pin cell calculation simulates an infinite regular lattice. However, a more realistic neutronic coupling between cells, gaps and their possible items requires an evaluation of the flux of entire system of assembly with gaps and therefore becomes too large for employing collision probabilities (Stamm'ler and Abbate, 1983). Self-shielding calculations with ultra-fine energy group structure (Sugimura and Yamamoto, 2007; Zhong et al., 2006) could be more accurate approach, considering the enhanced capabilities of modern computational hardware. However, its expansion to general and complex geometries is not feasible in routine reactor design calculation.

The subgroup method (Levitt, 1972; Chiba, 2003) is one of the most popular choice for self-shielding calculations because of being simplest and fast with the advantage of application to arbitrary geometry. In this approach each multi-group is divided into sub groups according to the magnitude of total cross sections hence further reducing the variation of cross sections in each subgroup than the one group of conventional multi-group (Nikolaev, 1976). The subgroup equation is very similar to the multi-group transport equation which makes subgroup method more suitable with various transport methods including method of characteristics (MOC).

Various new design concepts of advanced reactors with complicated fuel assembly and core designs require self-shielding method with high accuracy and computational efficiency to handle complex fuel components. In this study subgroup method is employed for self-shielded cross section calculation. The subgroup data is generated first by conserving the reference self-shielded cross sections, obtained by solving the neutron slowing down equation in continuous energy group structure for various dilutions (background cross sections) cases. The subgroup data is generated without considering the resonance interference among the resonant absorber nuclides therefore it must be included at the calculation stage of self-shielded cross sections for the mixture of resonant absorber nuclides using interference term in subgroup method. Sometimes interference problem results in relatively larger errors while estimating self-shielded cross sections. Researchers has employed the idea of including the resonant absorber nuclide in advance at the generation step of subgroup data to obtain better self-shielded cross sections (Joo et al., 2009). However this technique of considering resonance interference in advance could not conserve the self-shielded cross section for every mixture of resonant absorber nuclides (Kim and Hong, 2010). The researchers have also used resonance integral table as new method in which resonance interference effect is included through a linear function of the fractional particle number density. However the accuracy of this method depends on the resonance integral table and its expansion for large number of resonant absorber nuclides is difficult (Hong and Kim, 2010; Hong et al., 2009). An approach of interference correction has been proposed in our recent work which is based on the consistent use of subgroup data, at the generation step and as well as its application step by considering the predominant resonant absorber nuclides at the generation stage of subgroup data (Sohail and Kim, 2013).

Currently HELIOS (Stamm'ler, 2005) multi-group library considers limited isotopes as resonant absorber and ^{241}Am is the only resonant absorber from category of minor actinides nuclides. However some of other non-resonant minor actinides ^{237}Np and ^{243}Am have high absorption cross sections with large variation in resonance energy range as shown in Fig. 1. Higher concentration of these isotopes will have significant effect on self-shielding calculations. Therefore multi-group calculations for applications such as actinide's transmutation (Liu et al., 2013a,b) in thermal reactors or

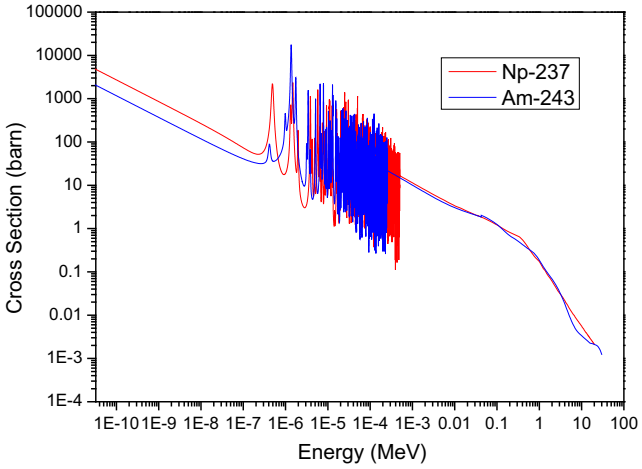

Fig. 1. Capture cross section of some important minor actinides.

higher concentration of minor actinides would need more precise resonance treatment of some otherwise non resonant absorber nuclides. The parameters such as destruction rates and residual amounts of non-resonant minor actinides will depend on the accuracy of their self-shielded cross sections obtained for multi group and burnup calculations. In current study we carried out resonant treatment of ^{237}Np and ^{243}Am beside other resonant absorber nuclides using subgroup method. These isotopes have been included as resonant absorber in our current multi group library for transport calculations. Subgroup data for these isotopes is generated using the established procedure and verified with the reference cross sections obtained from ultrafine calculations. The required multi-group calculations are performed using subgroup method to quantify the effect of resonance treatment of ^{237}Np and ^{243}Am.

2. Resonance treatment by subgroup method

Effective self-shielded cross sections for the resonant absorber nuclides are obtained by the resonance treatment in all the resonance groups. The self-shielded cross section in each coarse energy group can be obtained by averaging point wise cross section data with neutron energy spectrum. Therefore average cross section, $\sigma_{x,g}$ in coarse group g in terms of lethargy variable (u) for reaction type x is given by Eq. (1) (Stamm'ler, 2005).

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

The evaluation of effective cross sections becomes complicated due to the presence of sufficient concentration of resonant absorber nuclides. The flux $\varphi(u)$ of Eq. (1) will therefore have dips at various resonances of $\sigma(u)$.

The lethargy dependence in Eq. (1) is uniquely through $\sigma_a(u)$, therefore it allows to replace the integration variable u by σ_a. Owing to this σ_a dependence, the group average self-shielded cross section in Eq. (1) of each resonant absorber nuclide i can be expressed in terms of its quadratures in σ_a. Therefore the effective cross section in each coarse group (group index has been omitted for simplicity) for resonant absorber nuclide i is given by the following equation (Stamm'ler, 2005).

$$\sigma_{xi} = \frac{\sum_n \omega_{xni}\sigma_{xni}\phi_n}{\sum_n \omega_{ani}\phi_n} \tag{2}$$

where the discrete values of subgroup levels, σ_{xni} are the cross section values to which each resonance peak of isotope i, has been sub divided and the probability of each subgroup level is given by