An Improved XS Functionalization Concept for Soluble-Boron-Free SMR under Flexible Operation

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1. Introduction

As renewable energy generation expands, nuclear power plants are expected to operate with greater flexibility, rather than a constant and base-load operation. Small modular reactors (SMRs) are adopting soluble-boron-free (SBF) cores to simplify plant systems and reduce corrosion. Together, flexible operation (FO) and SBF cores introduce significant neutronic challenges for conventional analysis methods.

A highly efficient two-step procedure—such as DeCART2D/MASTER [1,2]—is widely used in light water reactor design and analysis. This methodology relies on a conventional cross-section (XS) functionalization for nodal core calculations. Due to the neutronic characteristics inherent in FO/SBF cores, such as frequent power maneuvers and repetitive control rod insertions, this study focuses on improving the XS functionalization in the two-step procedure to enhance analysis fidelity. As a preliminary investigation, this study proposes an improved XS functionalization concept by identifying key factors affecting the XS tablesets, laying the groundwork for a future nodal code capable more accurate core analysis for next-generation reactors.

2. Conventional XS Tablesets Generation: Limitations and Considerations for FO/SBF Cores

In the two-step DeCART2D/MASTER procedure, DeCART2D produces few-group XSs by solving a two-dimensional single-assembly transport problem and varying the key state variables, which typically include boron concentration, fuel temperature, moderator density or temperature, and control rod insertion. These XSs are then compiled into function-based tablesets. MASTER then uses the compiled tablesets to solve the three-dimensional core with two-group diffusion theory.

In MASTER, microscopic XSs are determined as in Eq. (1), while macroscopic XSs for control rod worth are obtained as in Eq. (2) depending on whether the control rod is inserted or withdrawn.

For XS tablesets generation, DeCART2D performs a base depletion calculation under fixed reference conditions (boron concentration, fuel temperature, moderator temperature or density, and rod state). Variation calculations are also carried out for these variables at a specific burnup point. A key limitation of this methodology is that the history effects of state variables during depletion are neglected, as the base depletion calculation is performed under a fixed set of reference conditions. Consequently, the resulting XS tablesets cannot accurately account for the spectral effects that arise from deviations from this reference state.

$$\begin{aligned}\sigma(B,Sb,T_f,\rho_m) &= \sigma(B_0,Sb_0,T_{f0},\rho_{m0}) \\ &+ \left.\frac{\partial\sigma}{\partial B}\right|_B (B-B_0) + \left.\frac{\partial\sigma}{\partial Sb}\right|_B (Sb-Sb_0) \\ &+ \left.\frac{\partial\sigma}{\partial\sqrt{T_f}}\right|_B (\sqrt{T_f}-\sqrt{T_{f0}}) + \left.\frac{\partial\sigma}{\partial\rho_m}\right|_B (\rho_m-\rho_{m0})\end{aligned} \tag{1}$$

$$\Sigma_{rodded} = \Sigma_{unrodded} + \Delta\Sigma_{cr} \tag{2}$$

While this simplified approach is generally acceptable for conventional soluble-boron cores operating under base load, or full-power, conditions, an improved XS generation methodology is required for FO/SBF cores for following reasons:

A. Effect of Control Rod Depletion

The control rods are frequently inserted during operation to control excess reactivity, compensating for the absence of soluble boron. Due to this insertion, it is necessary to consider not only the depletion of control rod absorber material but also the local neutron spectrum hardening caused by control rods' repetitive movement. Therefore, the burnup history of control rods is crucial for accurately reflecting the effect of control rod depletion. Park et al. [3] suggested generating two types of XS sets—one based on control-rod-out depletion and another on control-rod-in depletion—and combining them using a history index weighted by the integrated burnup in the rod-in state. Similarly, Jeong et al. [4] proposed a simple history index that reduced reactivity differences to within 500 pcm.

B. Effect of Xenon Variation

In conventional core analysis, operations are performed assuming an equilibrium xenon state, and thus few-group XS sets reflecting the neutron spectrum under equilibrium xenon conditions have been sufficient. However, in daily flexible operation of SMRs, the core power changes frequently, causing the xenon concentration in each node to vary accordingly. This continuous change in xenon concentration leads to ongoing fluctuations in the neutron spectrum. If these variations are not properly accounted for, errors in the cross-section data arise, which in turn reduce the accuracy of core simulations under flexible operation conditions. Therefore, to achieve precise core analysis for SMRs with flexible operation, it is essential to consider the dynamic effects of xenon concentration and the resulting neutron spectrum changes.

C. Effect of Moderator Temperature

Similar to xenon, changes in moderator temperature or density cause variations in the neutron spectrum during both normal and flexible operation. However, conventional depletion calculations typically assume a fixed reference moderator temperature. This assumption introduces inaccuracies in core depletion analysis. In particular, moderator temperature has a dominant influence on axial power distribution, and neglecting its burnup-dependent history effects leads to increased errors in modeling axial power profiles. Therefore, considering the burnup history effect of moderator temperature is essential to improve the accuracy of core analysis in flexible operation scenarios.

3. Assessment of the Proposed XS Tableset Generation Methodology

In this chapter, the three effects described in Chapter 2—control rod depletion, xenon fluctuation, and moderator temperature change—were quantitatively evaluated.

3.1. Effect of Control Rod Depletion

Two depletion cases—rod-in and rod-out—were compared to see how rod insertion state affects XSs of major nuclides in the node. The results shown in Figures 1, 2, and 3 show significant differences in the microscopic thermal nu-fission XS($\nu\sigma_f$) of ^{235}U, the microscopic fast absorption XS(σ_a) of ^{238}U, and the microscopic thermal absorption XS(σ_a) of effective Gd(merged Gd isotopes). In these figures, series label beginning with "AIC" indicates the absorber's exposure during depletion, and "DP/noDP" indicate whether the absorbers themselves were modeled as depletable or non-depletable. The highlight that the spectral history associated with the control rod's presence is a dominant factor. In contrast, minor variations in the insertion history and depletable control rod during the rod-in depletion were found to have a negligible impact on XS.

The depletion of the control rod absorber material itself was examined. For a representative Ag-In-Cd (AIC) absorber, the macroscopic fast absorption XSs(Σ_a) showed little change with depletion as shown in Figure 4, whereas the macroscopic thermal absorption XSs(Σ_a) varied significantly with depletion, especially on ^{113}Cd as shown in Figure 5 and moreover the thermal absorption XSs were much larger than the fast absorption XSs. This indicates that XS tablesets for control rod absorber should be functionalized with respect to the absorber's own depletion.

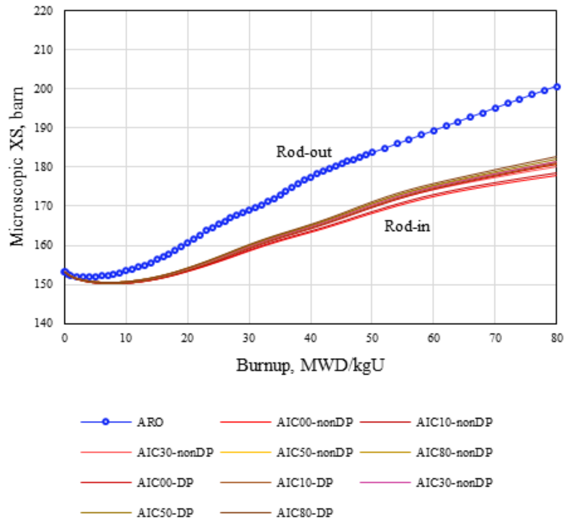

Fig. 1. Microscopic thermal nu-fission XS of ^{235}U vs. Burnup

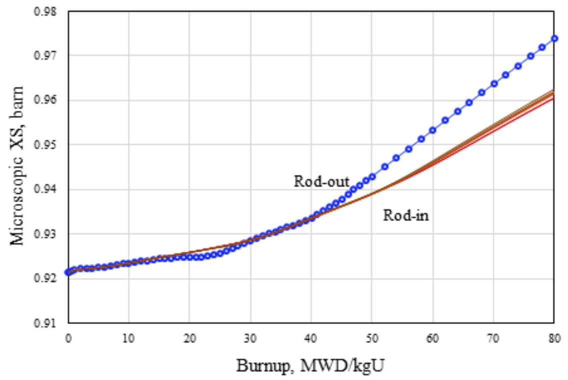

Fig. 2. Microscopic fast absorption XS of ^{238}U vs. Burnup[1]

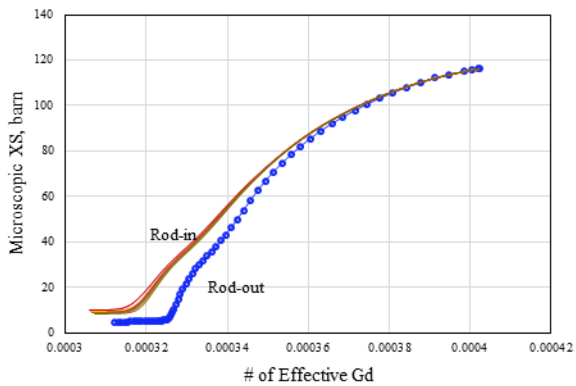

Fig. 3. Microscopic thermal absorption XS vs. # of effective Gd[1]

[1] The legend is as shown in Fig. 1.

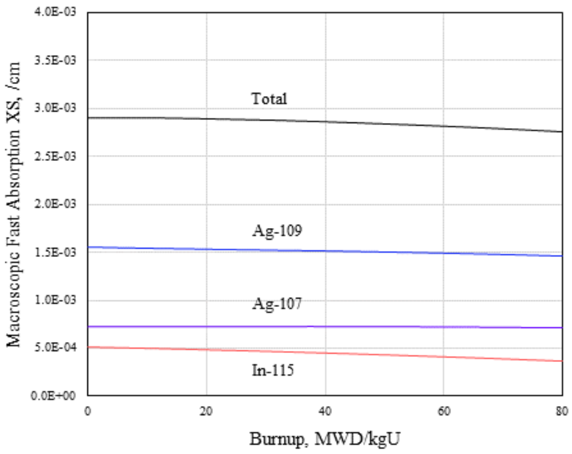

Fig. 4. Macroscopic fast absorption XS of nuclides vs. Burnup

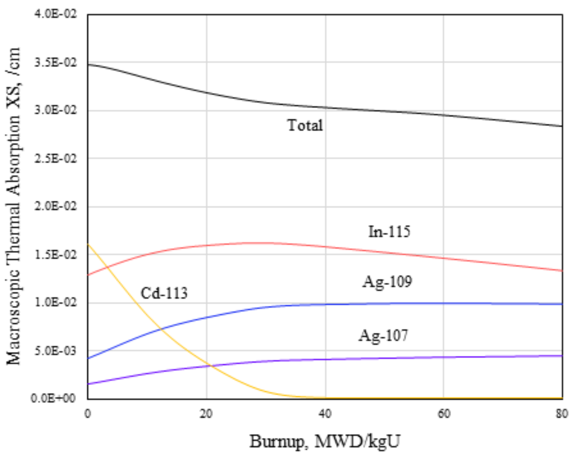

Fig. 5. Macroscopic thermal absorption XS of nuclides vs. Burnup

3.2. Effect of Xenon Variation

To assess the effect of xenon variation, the impact of varying xenon number density on the major reaction XSs of key nuclides was evaluated. The spectrum change caused by the xenon number density is defined as shown in Equation (3).

$$\Delta\sigma_i = \frac{\partial\sigma}{\partial N_{Xe}}(N_{Xe} - N_{Xe,ref}) \tag{3}$$

The changes in the node's macroscopic fast absorption XS(Σ_a), the microscopic thermal nu-fission XS($\nu\sigma_f$) of ^{235}U, and the microscopic fast absorption XS(σ_a) of ^{238}U were calculated. The results are presented in Figures 6, 7, and 8, respectively.

The analysis revealed that the change in group constants with respect to xenon number density exhibits a clear linear relationship, allowing this effect to be incorporated through linear functionalization.

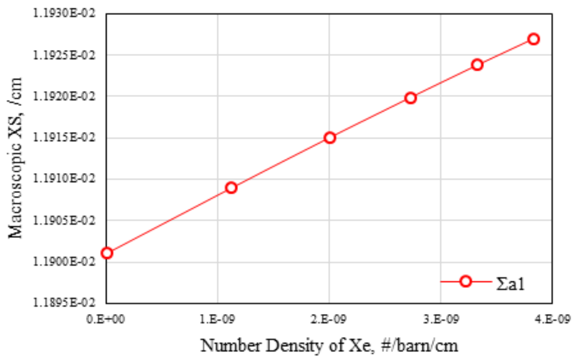

Fig. 6. Macroscopic fast absorption XS of Node vs. # of Xenon

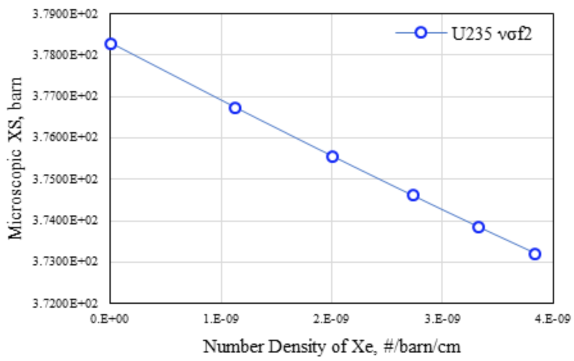

Fig. 7. Microscopic thermal nu-fission XS of ^{235}U vs. # of Xenon

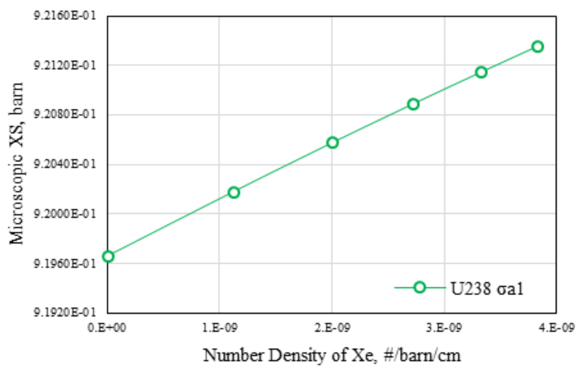

Fig. 8. Microscopic fast absorption XS of ^{238}U vs. # of Xenon

3.3. Effect of Moderator Temperature

Two approaches were used to evaluate the impact of moderator temperature on XS. The first approach used a fixed moderator temperature to generate XS for all burnup points like a conventional way. The second approach generated XS sets at each burnup point using the specific average moderator temperature up to that point, where the average moderator temperature is simply calculated as the average of moderator temperatures from BOC to that burnup point, to reflect the depletion history. These approaches were applied to the node's macroscopic thermal absorption XS(Σ_a) and the microscopic thermal nu-fission XS($\nu\sigma_f$) of ^{235}U. The XS fraction was defined by ratio of XS from two approaches.

Figure 9 shows the XS fraction using the first approach, which tends to a tendency for the fraction to increase as burnup increases. In contrast, Figure 10 shows the XS fraction produced applying the second approach using the moderator temperature corresponding to each burnup point, which is calculated by the average moderator temperature from the beginning of the cycle to that point.

These results demonstrate that in depletion calculations, it is essential to reflect the moderator temperature corresponding to each burnup point in order to generate accurate XS tablesets.

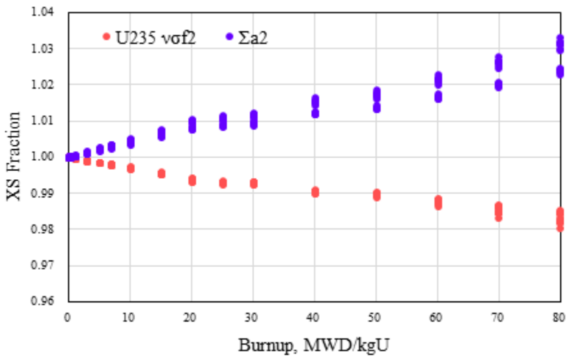

Fig. 9. XS Fraction w/o average moderator temperature variation

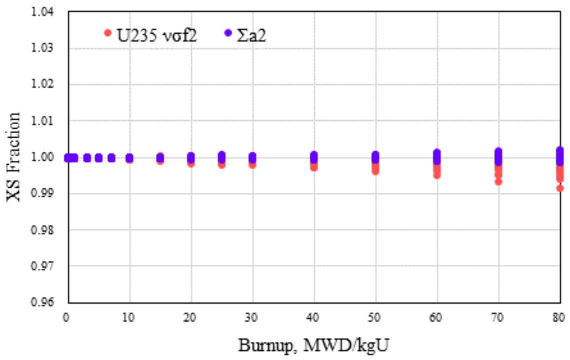

Fig. 10. XS Fraction w/ average moderator temperature variation

4. Conclusion

This study quantitatively demonstrated the necessity of improving XS functionalization within the conventional two-step procedure for analyzing flexible and soluble-boron-free operations in SMR cores. The investigation of three key factors—control rod depletion, xenon concentration fluctuation, and moderator temperature variation—revealed that neglecting these effects introduces significant numerical errors in group constants.

Based on these results, future work will focus on developing a new XS functionalization scheme that explicitly incorporates these three effects. This enhanced approach is expected to significantly improve the accuracy and reliability of SMR core analysis. Furthermore, this new format, tableset generation method and its application will be implemented to validate and enable precise reactor core calculations.

ACKNOWLEGEMENTS

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