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Improved Control Rod XS Treatment for Top Reflectors in DeCART2D/MASTER

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1. Introduction

In large pressurized water reactors (PWRs), the axial height of the core is about 3.8 m, and thus the composition of the axial reflector has only a minor impact on the core power distribution and reactivity. Consequently, the effect of control rods in the top reflector region has generally been neglected or treated with simplified cross-section (XS) models.

In small modular reactors (SMRs), however, the influence of the axial reflector composition on core characteristics becomes more significant. In cases such as boron-free operation in i-SMRs, fuel in the upper part of the core with inserted control rods undergoes little burnup during the early cycle, and a localized power increase may occur when the rods are withdrawn at the end of the cycle. This effect can be further enhanced when cutback is applied to the upper part of burnable absorbers to mitigate axial peaking. Therefore, an appropriate treatment of the top reflector composition and XSs is essential in such cores.

In addition, when strong absorber rods such as enriched B_4C control rods are used, simplified modeling of control rods in the top reflector may cause noticeable errors in the upper core power distribution.

Although the DeCART2D [1]/MASTER [2] code system developed at KAERI includes an improved model for generating axial reflector XSs beyond the conventional two-node approach [3], the treatment of control rods in the top reflector has still been simplified. This paper introduces a newly implemented function in DeCART2D/MASTER for improved control rod XS modeling in the top reflector region.

2. DeCART2D/MASTER Code System

DeCART2D/MASTER is a two-step procedure-based core design code system developed at KAERI. It has been applied to SMART PPE design and the SMART100 standard design approval [4], and more recently to the i-SMR conceptual design.

DeCART2D performs single-assembly calculations to produce assembly-wise XSs, and separate 2D and 1D calculations to generate reflector XSs. PROLOG [5] and PROMARX [6] convert these into libraries for MASTER, which then evaluates various core characteristics such as reactivity and power distribution. Fig. 1 illustrates the overall structure of the code system.

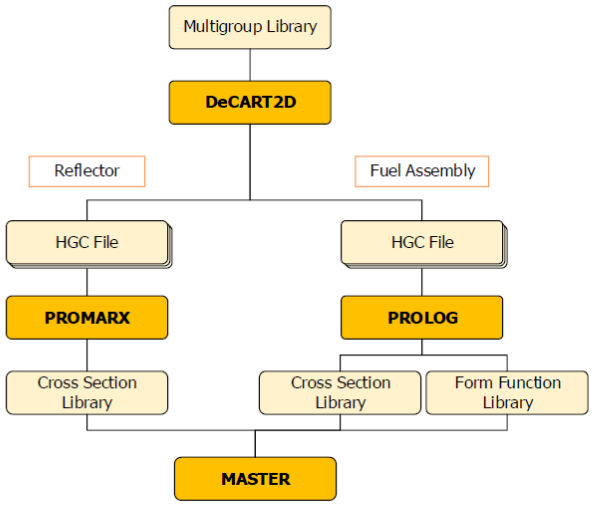

Fig. 1. Overall workflow of the DeCART2D/MASTER code system, showing the generation of assembly and reflector XSs by DeCART2D, library processing by PROLOG and PROMARX, and core analysis by MASTER.

3. Previous Treatment of Control Rod XS in the Top Reflector

In the previous MASTER library format for axial reflector XSs as shown in Fig. 2 [7], microscopic XSs of B-10 and H_2O, together with macroscopic XSs of structures, were defined. This format could account for variations in boron concentration and water density, but not for the direct effect of control rod materials.

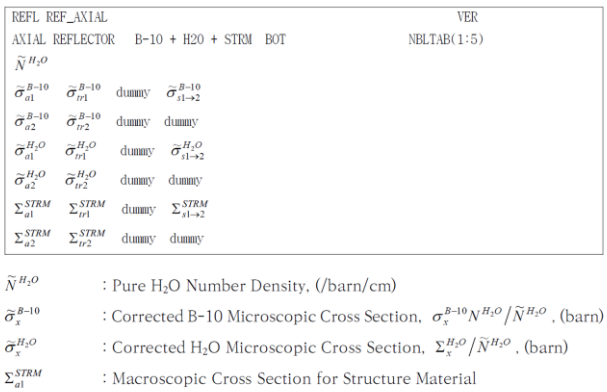

Fig. 2. Previous format of the MASTER library for axial reflector XSs, in which only microscopic XSs of B-10 and H_2O and macroscopic XSs of structures are considered, without explicit control rod treatment.

When control rods were present in the top reflector mesh, MASTER simply applied the control rod XSs defined in the adjacent fuel region. However, since the neutron spectrum differs between fuel and reflector regions, this approach could not properly reproduce the control rod XSs in the top reflector. While such inaccuracy was negligible in large PWRs, it may introduce non-negligible errors in small cores, thereby requiring improvement.

4. Newly Implemented Control Rod XS Treatment in the Top Reflector

To address this limitation, a new control rod XS treatment function for the top reflector has been implemented in DeCART2D/MASTER. Fig. 3 shows the revised library format.

REFL REF_AXIAL VER

AXIAL REFLECTOR B-10 + H2O + STRM BOT NBLTAB(1:5)

$\tilde{N}^{H_2O}$

$\tilde{\sigma}_{a1}^{B-10}$	$\tilde{\sigma}_{tr1}^{B-10}$	dummy	$\tilde{\sigma}_{s1\to2}^{B-10}$	Unrodded
$\tilde{\sigma}_{a2}^{B-10}$	$\tilde{\sigma}_{tr2}^{B-10}$	dummy	dummy	
$\tilde{\sigma}_{a1}^{H_2O}$	$\tilde{\sigma}_{tr1}^{H_2O}$	dummy	$\tilde{\sigma}_{s1\to2}^{H_2O}$	
$\tilde{\sigma}_{a2}^{H_2O}$	$\tilde{\sigma}_{tr2}^{H_2O}$	dummy	dummy	
Σ_{a1}^{STRM}	Σ_{tr1}^{STRM}	dummy	$\Sigma_{s1\to2}^{STRM}$	
Σ_{a2}^{STRM}	Σ_{tr2}^{STRM}	dummy	dummy	
$\tilde{\sigma}_{a1}^{B-10}$	$\tilde{\sigma}_{tr1}^{B-10}$	dummy	$\tilde{\sigma}_{s1\to2}^{B-10}$	Rodded (CR1)
$\tilde{\sigma}_{a2}^{B-10}$	$\tilde{\sigma}_{tr2}^{B-10}$	dummy	dummy	
$\tilde{\sigma}_{a1}^{H_2O}$	$\tilde{\sigma}_{tr1}^{H_2O}$	dummy	$\tilde{\sigma}_{s1\to2}^{H_2O}$	
$\tilde{\sigma}_{a2}^{H_2O}$	$\tilde{\sigma}_{tr2}^{H_2O}$	dummy	dummy	
Σ_{a1}^{STRM}	Σ_{tr1}^{STRM}	dummy	$\Sigma_{s1\to2}^{STRM}$	
Σ_{a2}^{STRM}	Σ_{tr2}^{STRM}	dummy	dummy	
$\tilde{\sigma}_{a1}^{B-10}$	$\tilde{\sigma}_{tr1}^{B-10}$	dummy	$\tilde{\sigma}_{s1\to2}^{B-10}$	Rodded (CR2)
$\tilde{\sigma}_{a2}^{B-10}$	$\tilde{\sigma}_{tr2}^{B-10}$	dummy	dummy	
$\tilde{\sigma}_{a1}^{H_2O}$	$\tilde{\sigma}_{tr1}^{H_2O}$	dummy	$\tilde{\sigma}_{s1\to2}^{H_2O}$	
$\tilde{\sigma}_{a2}^{H_2O}$	$\tilde{\sigma}_{tr2}^{H_2O}$	dummy	dummy	
Σ_{a1}^{STRM}	Σ_{tr1}^{STRM}	dummy	$\Sigma_{s1\to2}^{STRM}$	
Σ_{a2}^{STRM}	Σ_{tr2}^{STRM}	dummy	dummy	
$\tilde{\sigma}_{a1}^{B-10}$	$\tilde{\sigma}_{tr1}^{B-10}$	dummy	$\tilde{\sigma}_{s1\to2}^{B-10}$	Rodded (CR3)
$\tilde{\sigma}_{a2}^{B-10}$	$\tilde{\sigma}_{tr2}^{B-10}$	dummy	dummy	
$\tilde{\sigma}_{a1}^{H_2O}$	$\tilde{\sigma}_{tr1}^{H_2O}$	dummy	$\tilde{\sigma}_{s1\to2}^{H_2O}$	
$\tilde{\sigma}_{a2}^{H_2O}$	$\tilde{\sigma}_{tr2}^{H_2O}$	dummy	dummy	
Σ_{a1}^{STRM}	Σ_{tr1}^{STRM}	dummy	$\Sigma_{s1\to2}^{STRM}$	
Σ_{a2}^{STRM}	Σ_{tr2}^{STRM}	dummy	dummy	

Fig. 3. Revised MASTER library format for axial reflector XSs, extended to include additional data sets for up to three types of control rod materials in the top reflector region.

The new format incorporates additional data for cases with inserted control rods. MASTER has been extended to handle up to three types of control rod materials, thus enabling the treatment of both unrodded conditions and up to three rodded conditions in the top reflector. Fig. 4 shows an example of top reflector regions with different compositions depending on control rod insertion.

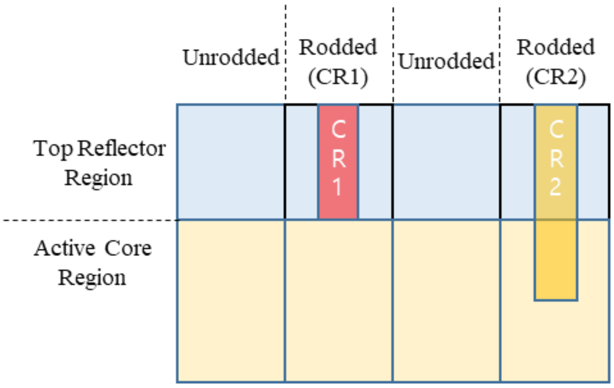

Fig. 4. Example of top reflector regions with different compositions depending on control rod insertion. The 1st and 3rd regions use unrodded XSs, while the 2nd and 4th regions use rodded XSs of control rod type 1 (CR1) and type 2 (CR2), respectively, as defined in Fig. 3.

For this purpose, DeCART2D performs 1D model calculations with control rod branch options, as illustrated in Fig. 5, to generate HGC files. PROMARX, with extended functionality, then processes these files to automatically produce the new MASTER reflector XS libraries. This procedure is consistent with that used for assembly control rod XS generation, ensuring seamless integration within the existing two-step framework.

```
cell 21  2 / MIX_AXT10
              ...
assembly RAXT 360 1
 576*21
rad_conf 360 CENT 1 1
 RAXB FA FA FA FA FA FA FA RAXT
              ...
/
BRANCH CR1 VARIATION
 burnup 0.0
 mat    MIX_AXT10  MIX_AXT11
/
BRANCH CR2 VARIATION
 burnup 0.0
 mat    MIX_AXT10  MIX_AXT12
```

Fig. 5. Example of DeCART2D input with branch variations for generating HGC files of rodded top reflector regions, enabling automatic production of the new MASTER reflector XS library through PROMARX.

5. Numerical Results

To evaluate the effect of the proposed top-reflector control rod XS treatment in DeCART2D/MASTER, key nuclear design parameters such as reactivity, axial offset, and local pin peaking factor are analyzed in a representative core based on i-SMR and SMART100 design data. The detailed design data are not provided for security reasons.

Three top reflector options were compared: (i) without CR model, (ii) with homogenized CR model, and (iii) with explicit CR model (new). Core depletion calculations under the all-rods-out (ARO) condition were performed.

Figs. 6-8 summarize the results as a function of burnup. Significant differences are observed between the cases without and with CR treatment in the top reflector across all parameters. Between the homogenized and explicit CR models, the maximum differences are about 60 pcm in reactivity and about 1% in local pin peaking factor.

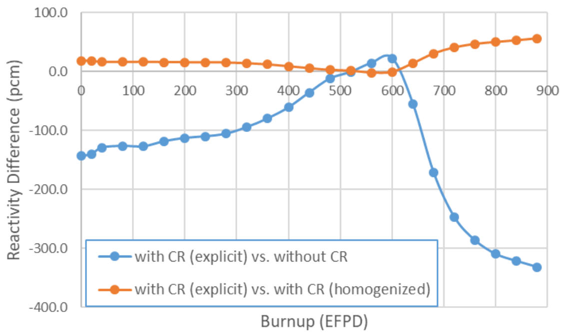

Fig. 6. Reactivity differences among the three top-reflector options. Neglecting CRs in the top reflector yields the largest deviation; the maximum difference between the homogenized and explicit models is about 60 pcm.

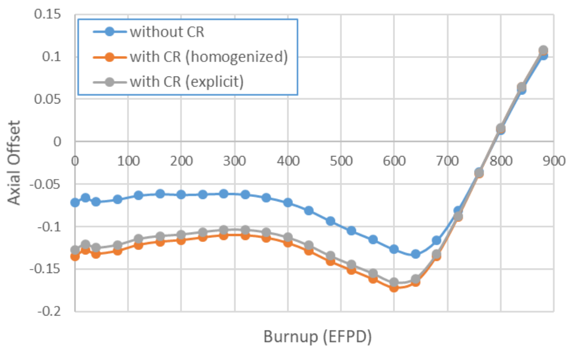

Fig. 7. Axial offset (AO) behavior versus burnup. A noticeable discrepancy appears when CRs in the top reflector are neglected.

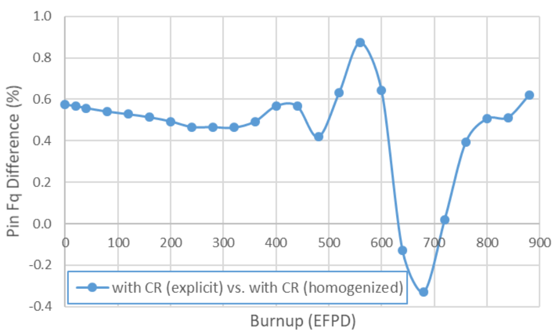

Fig. 8. Difference in local pin peaking factor between the homogenized and explicit CR models in the top reflector; the maximum is about 1%.

6. Conclusions

A new function for improved control rod XS modeling in the top reflector region has been implemented in the DeCART2D/MASTER code system. The newly implemented function is designed to be fully compatible with the existing two-step procedure and requires no modification of the downstream MASTER input structure. This ensures easy adoption in routine core design calculations. Validation is in progress, and the function will be incorporated into the official version after further verification and impact assessment. This improvement is expected to enhance the accuracy of SMR core design and to support future applications in design calculations, safety evaluations, and related analyses.

ACKNOWLEDGMENT

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