Core Follow Calculation for a VVER-1000 Reactor in Cycles 1 through 6 using DeCART2D/MASTER

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Abstract – *Core follow calculation for Bulgarian Kozloduy NPP Unit 6 whose core type is the VVER-1000 reactor has been performed by using the DeCART2D/MASTER two-step core design code system for cycle 1 through cycle 6 to evaluate the hexagonal core design capability of DeCART2D/MASTER. In this procedure, homogenized group constants (HGCs) for each fuel assembly (FA) type, radial reflector, and axial reflector are generated first by DeCART2D. Then the PROLOG and PROMARX codes are used to convert HGCs of FAs and reflectors to MASTER cross section library format, respectively. Core follow calculation is performed for cycles 1 through 6 by using MASTER. Critical boric acid computed by MASTER are compared to the reference measured data as well as the data computed by other reference design codes. Although the MASTER results have large difference compared to the measured data, the solutions obtained by MASTER and other reference codes have enough consistency. It means that the measured data has considerable uncertainty or there is large inconsistency between nominal and as-built core design data. By confirming that critical boric acid curves obtained by MASTER and other reference codes are similar enough, it is concluded that the DeCART2D/MASTER code system has enough capability for hexagonal core design.*

I. INTRODUCTION

The two-step procedure based DeCART2D [1]/ MASTER [2] code system has been being developed in KAERI (Korea Atomic Energy Research Institute) for the core design of PWRs (Pressurized Water Reactors) including SMRs (Small Modular Reactors). DeCART2D is a neutron transport code based on 2-D MOC (Method Of Characteristics) and its main purpose is to generate assembly-wise homogenized and group condensed effective group constant used in nodal diffusion core analysis codes such as MASTER for two-step procedure. MASTER is a neutron diffusion nodal code for PWR core design with equipping various calculation capabilities such as static and transient neutronics calculation, depletion calculation, reactivity coefficient calculation, and others.

One of the most significant features of this code system is its applicability for not only rectangular but hexagonal cores. Prototype of DeCART2D has been developed for rectangular core analysis first and its applicability is extended to hexagonal core by employing hexagonal modular ray tracing technique with equipping hexagonal CMFD scheme [3]. Also, MASTER has a capability to be applied for hexagonal core design by equipping TPEN (Triangle-based Polynomial Expansion Nodal) [4] as the nodal method valid for hexagonal nodes. DeCART2D also has one-node TPEN kernel to generate equivalent group constant for MASTER to preserve reaction rates in DeCART2D and MASTER. Thus reliable hexagonal core design can be achieved in DeCART2D/MASTER.

In order to ensure the credibility of the reactor cores designed by core design codes and codes themselves, sufficient code verification and validation (V&V) work is essential. There are various ways for code V&V and comparison of core follow calculation results with the measured core operating data or appropriate reference data is regarded as one of the surest methods.

In this regard, V&V of the DeCART2D/MASTER has been performed by Hanbit NPP (Nuclear Power Plant) core follow calculation. Also, core follow analyses for Palo Verde, BEAVRS, and VERA cores are planned to be performed. However, these cores are the rectangular type, so it is necessary to validate the hexagonal analysis capability of DeCART2D/MASTER using proper data measured and computed in hexagonal cores.

In 2013, KAERI and SOFIA University had signed MOA (Memorandum Of Agreement) for technical cooperation on nuclear reactor core analysis technology development. The key contents of this MOA are that KAERI offers the DeCART2D code package files such as execution, library, manual, and sample inputs whereas SOFIA University provides various core design data of Kozloduy NPP (KNPP) Unit 6 that is the VVER1000 type operated in Bulgaria [5]. Using the data, computational input models of the VVER1000 core for DeCART2D/MASTER have been prepared and its core follow analysis for cycles 1 through 6 has been done.

In this paper, the procedure for the core follow calculation of VVER1000 using DeCART2D/MASTER are presented. In the following section, generation of homogenized group constant (HGC) using DeCART2D is addressed. Preparation of MASTER cross section (XS) library from the DeCART2D HGC is then covered. How to perform the core follow calculation using MASTER is introduced in the third section. The last section provides the core follow results and its discussion by comparing them with the reference data which are measured and computed data from other code packages.

II. GENERATION OF HOMOGENIZED GROUP CONSTANT USING DECART2D

As the first step of the DeCART2D/MASTER core calculation system, HGC data are generated by DeCART2D version 1.1. The following computational options are used for HGC generation.

- 47/18 neutron/gamma energy group XS library based on the ENDF/B-VII.1
- 0.02 cm ray spacing, 8 azimuthal angles in 60° or 90° domain and 3 polar angles in 90° domain for ray discretization.
- Subgroup method for resonance treatment
- Transport correction based anisotropic scattering treatment

There are three types of HGC for fuel assemblies, radial reflectors, and axial reflectors, respectively. How to generate their HGC is covered in the following subsections.

1. HGC for Fuel Assemblies

There are four types of TVS fuel assembly (FA) loaded in the Bulgarian VVER1000 in cycles 1 through 6. Also, two types of TVSM FA are loaded in the cycle 6. The most significant difference between TVS and TVSM is that 18 burnable absorbers are loaded in the guide tube for the first cycle in TVSM FAs. Also, they have slight difference in density of fuel material, pin cell geometry, and others. Their detail design parameters can be found elsewhere [5].

Each type in TVS and TVSM FAs is dependent on the fuel enrichment. The information for fuel pins in each assembly type is described in Table I.

Table I. The Number of Fuel Pins and Enrichment Loaded in Each Fuel Assembly Type in the VVER1000 Core for Cycles 1 through 6

	Type	Pin Type 1		Pin Type 2	
		Number	UO_2 w/o	Number	UO_2 w/o
TVS	20FS	312	2.0		
	30FS	312	3.0		
	32FS	234	3.3	78	3.0
	33FS	312	3.3		
TVSM	42FL	246	4.4	66	3.6
	44FL	312	4.4		

As noted in Table I, total 312 fuel pins are loaded in each assembly and there is no burnable absorber. Fig. 1 represents the radial fuel configuration of 1/6 rotational FA consisting of uniform enrichment such as 20FS, 30FS, and 33FS FA types. Configuration of 32FS is same but two different enrichment types of fuel pin are loaded.
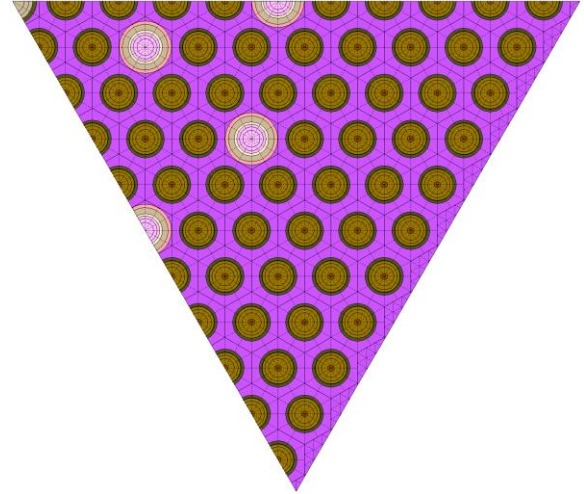

Fig. 1. Radial fuel configuration of TVS FA for the uniform enrichment case

And each pin cell configurations for fuel, central tube, and guide tube are presented in Fig. 2.
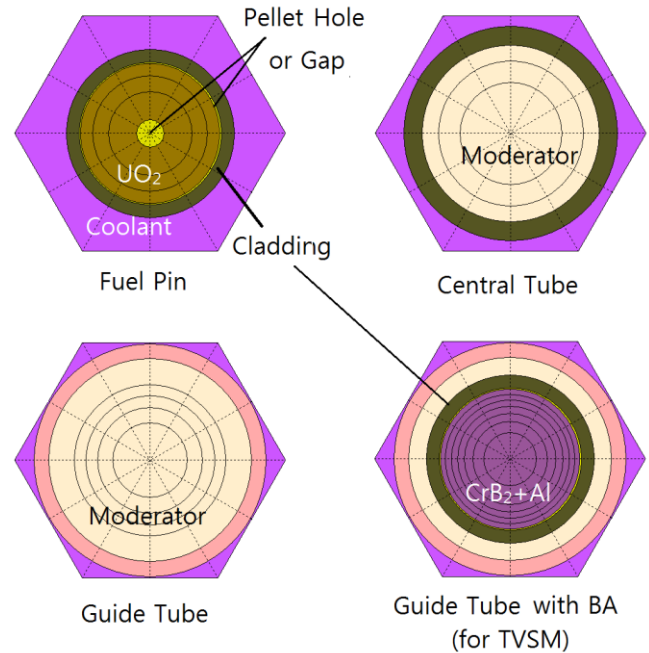

Fig. 2. Pin cell configuration for fuel, central tube, and guide tube TVS and TVSM types

FA HGC generation model for DeCART2D is the conventional single FA model with reflective boundary condition. In order to obtain functionalized HGC on burnup step and XS variation on boron concentration, fuel temperature, moderator density, and control rod insertion, reference depletion and corresponding various branch calculations are performed.

2. HGC for Radial Reflector

In the DeCART2D/MASTER based core design system, HGC data for radial reflectors are generated by analyzing 2D whole core problem whose configuration is the BOC (Beginning Of Cycle) of initial core. The initial VVER1000 core has 1/12 symmetry and
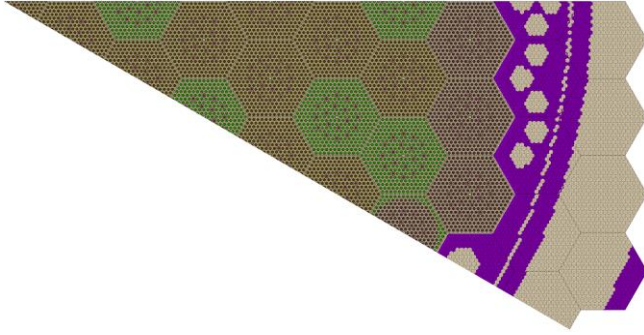Fig. 3 shows the pin-wise configuration of that.

Fig. 3. Pin-wise configuration of the 2D 1/12 VVER1000 core

Fig. 4 shows the radial configuration of 20FS FA which is selected as the representative fuel assembly since this FA type is loaded the most in cycle 1.
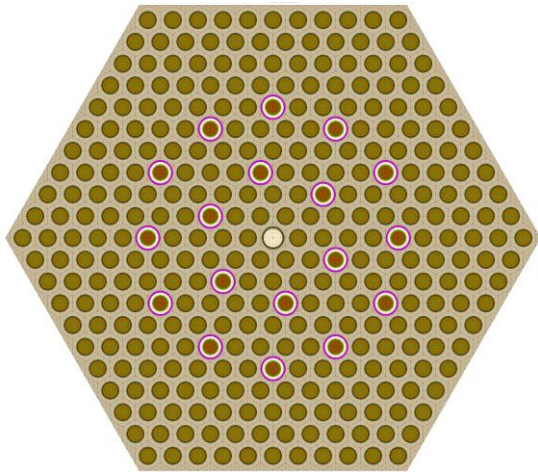
Fig. 4. Radial configuration of 20FS FA

In the 2D 1/12 core model, core baffle, water gap, water hole, and coolant channels in reflector regions are modeled semi-explicitly. Their configurations are slightly modified from the exact one that pin cells occupying the interface of baffle and a channel are treated as a full baffle or channel cell. It is determined by observing the volume ratio of two materials in each cell.

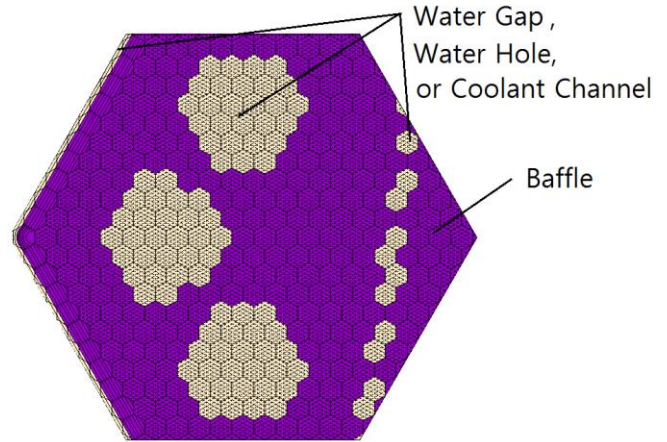Fig. 5 shows the detail configuration of the reflector node where 3 water holes exist.

Fig. 5. Configuration of reflector node

3. HGC for Axial Reflector

The reflector/FA two-node model has been widely adopted to generate axial reflector HGC in various core design code systems. However, it cannot consider actual axial flux shape and surface discontinuity factor (SDF) at the interface between fuel and reflector regions since the fuel rod is assumed to be parallel although they are perpendicular in fact. Moreover, the conventional two-node model is not available in hexagonal cores.

Instead of using the two-node model, simplified 1D model [6] is adopted to generate axial reflector HGC in the DeCART2D/MASTER system. As described in the previous work [6], the configuration of the active core region is designed to have repeated arrangement of fuel and moderator on the radial direction and uniform composition is arranged on the axial direction to reflect the real configuration of fuel rods in the active core region, which is orthogonal to reflector regions. Thus more realistic neutron flux distribution and SDFs can be attained. Fig. 6 shows how to model the active core region in the 1D core model.
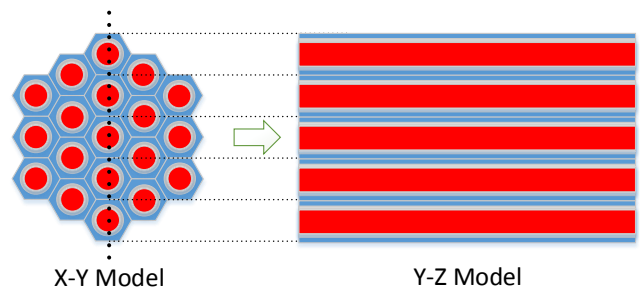

Fig. 6. How to model the active core region in the 1D core model

In this model, all pin cells are assumed as a fuel cell with uniform enrichment of 3.0 w/o in this VVER-1000 case and other fuel materials that have different enrichment, and central and guide tubes are neglected. The theoretical basis can be found in the previous work [6].

In the problem specification [5], the composition of bottom and top reflectors are given for 29.0 and 32.2 cm thickness, respectively. Also, axial reflector node size is recommended to be 30.0 cm in MASTER. Thus 28.05 cm node size is used, which is a multiple of pin pitch 1.275 cm and is the closest to 29 cm for the bottom reflector size. Fig. 7 shows the simplified 1D VVER1000 core model and Fig. 8 shows the detail view of Fig. 7 by focusing on the three fuel rods.

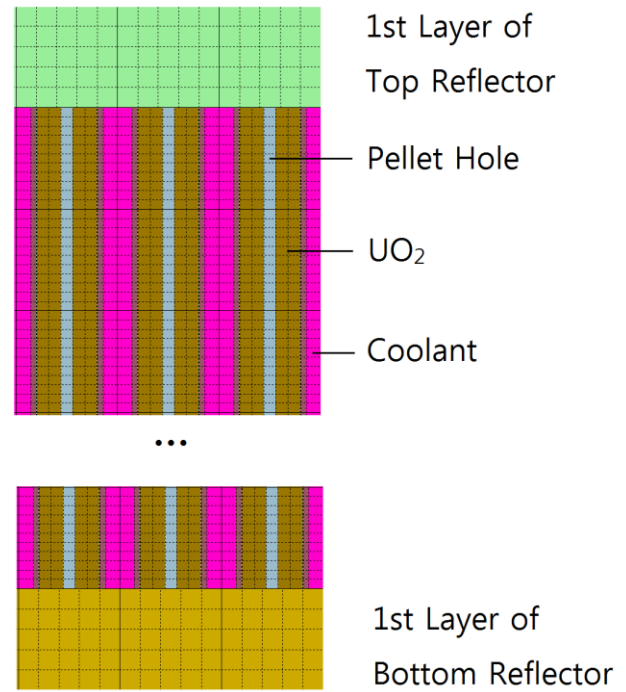Fig. 7. Pin-wise configuration of the simplified 1D VVER1000 core

Fig. 8. Detail view of the simplified 1D VVER1000 core

III. GENERATION OF MASTER XS LIBRARY FROM DECART2D HGC DATA

In order to use the FA and reflector HGC generated from DeCART2D in MASTER, they should be converted to satisfy the library format available in MASTER. The PROLOG code [7] has been officially used to read FA HGCs and convert them to the MASTER XS library format. On the other hand, reflector XS processing routine has not been systematic because reflector HGC is free from burnup dependency and it consists of single macroscopic data plus microscopic for only H_2O and B-10, so its processing is much simpler compared to FA data given as microscopic data for more than 20 isotopes.

As the DeCART2D reflector XS generation model becomes more complex, however, the necessity of methodical code establishment like to PROLOG is raised. The PROMARX (PROcessor for Master Reflector Xs library) code [6] is being developed to fulfill this requirement. It has a capability to process both radial and axial reflector XS. Also, it can treat both rectangular and hexagonal cores with various symmetric options available in DeCART2D. It can consider multi-node reflector regions with proper region-wise homogenization and SDF treatment on the interface between fuel and reflector regions.

The MASTER XS library for the VVER1000 core follow analysis is prepared by both PROLOG version of 4.1 and prototype of PROMARX. Data for 19 heavy nuclides, Iodine, Xenon, lumped fission product, water, soluble boron,

and lumped material of residual isotopes are prepared for FA XS in PROLOG. There are 3 types of radial reflector such as 'EDGE', 'CORNER', and 'NOOK' where the number of neighboring FAs is 1 or 2 for 'EDGE', 3 for 'CORNER', and 0 for 'NOOK'. The axial reflector is categorized to top and bottom reflectors as adopted typically. XS data for these 5 reflector types are prepared by PROMARX.

IV. CORE FOLLOW CALCULATION USING MASTER

Axial core configuration, core loading pattern, control rod map, operation history, inlet and outlet temperature corresponding to the burnup step, and other various core design and operating data [5] are applied to make MASTER core follow analysis model. 354 cm active core region is split to 18 planes whose size is 17 cm for two outmost planes and 20 cm for inner planes. Coolant temperature on the core power is calculated as a linear function from least square fitting by using the measured coolant temperature data in various core power points. Fig. 9 shows the fitted inlet temperature in cycle 1. The depletion input lines are prepared using the core operating data, and the maximum burnup interval is set to 10 EFPD. Overhaul between cycles is considered by zero power depletion.
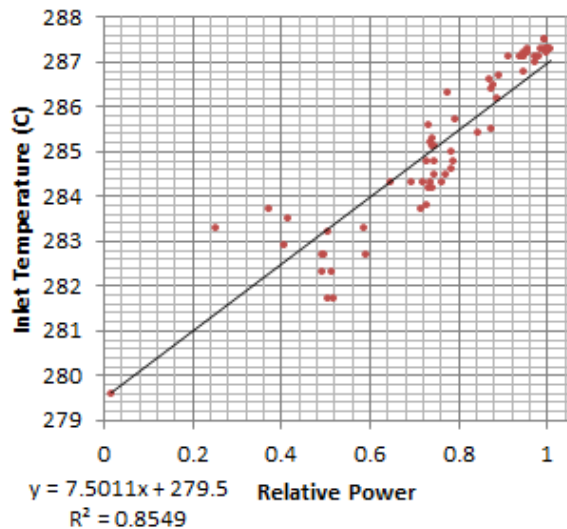

$y = 7.5011x + 279.5$
$R^2 = 0.8549$

Fig. 9. Least square fitting of inlet temperature on power

Core follow for VVER1000 has been done on cycle 1 through cycle 6 using MASTER version 4.0. Fig. 10 through Fig. 15 show the CBA (Critical Boric Acid) curve for these cycles computed by MASTER where y-axis is for CBA in g/kg and x-axis is burnup in EFPD. Measured CBA

data provided by SOFIA University are also plotted in the figures to compare.

In consideration of the relation between CBA and CBC (Critical Boron Concentration) that 3g/kg boric acid is identical to 525 ppm boron concentration, about 160 ppm discrepancy is observed between computed and measure data at BOC in cycle 1. Since it is calculated by MASTER that the boron worth is -10.39 pcm/ppm at BOC of cycle 1, the 160 ppm difference can be converted to about 1700 pcm reactivity difference. It is obviously huge difference. This tendency is also observed in other cycles from 2 to 6 as presented in Fig. 11 through Fig. 15.

Since SOFIA University had provided not only the measured data but the figures for CBA curves computed by their design codes, further comparison can be done. Fig. A.1 through Fig. A.6 attached in Appendix A are the figures, and the detail description of the reference codes are also provided in Appendix A. Note that the figures are only provided for the computed data. Although these figures are not clear to recognize well, it can be confirmed that CBAs computed by the reference codes are also over-estimated at BOC compared to the measured data.

Table II and Fig. 16 show the measured and computed CBCs at BOC of each cycle in order to investigate this tendency more clearly. The number in the parenthesis under the cycle index is the burnup point in EFPD. It should be noted that the CBC data of the reference BIPR-7A and HELHEX codes are not the exact value but the estimated value from Fig. A.1 through Fig. A.6. From Fig. 16, it is clearly confirmed that most of computed CBCs are over-estimated regardless of codes except at the cycle 5.

On the other hand, EOC CBCs have good agreement between measured and computed data as presented in Table III and Fig. 17. It means that cycle length is well estimated in the codes. From the two tendencies that CBCs are over-estimated at BOC whereas real and computed cycle lengths match well, it can be deduced that boron worth computed in each code is under-estimated.

V. CONCLUSIONS

Using the core design data for Bulgarian KNPP unit 6 provided by SOFIA University according to the MOA between SOFIA University and KAERI, core follow calculation for cycles 1 through 6 has been performed by the DeCART2D/MASTER core design code system developed in KAERI. Core follow calculation procedure consists of three steps. In the first step, DeCART2D HGC of each FA type, and radial and axial reflector nodes are obtained by constructing DeCART2D input models for single FA for each FA type, 2D 1/12 core, and simplified 1D core, respectively. These HGC files are converted to the MASTER XS library format by using the PROLOG and PROMARX codes for FA and reflector HGCs, respectively in the second step. Core follow calculation using MASTER
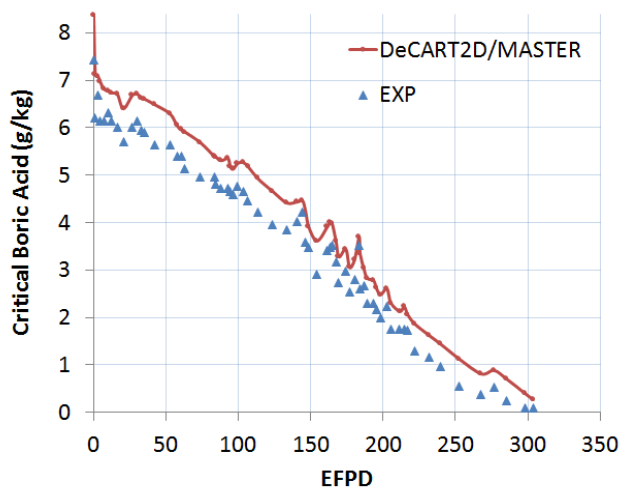
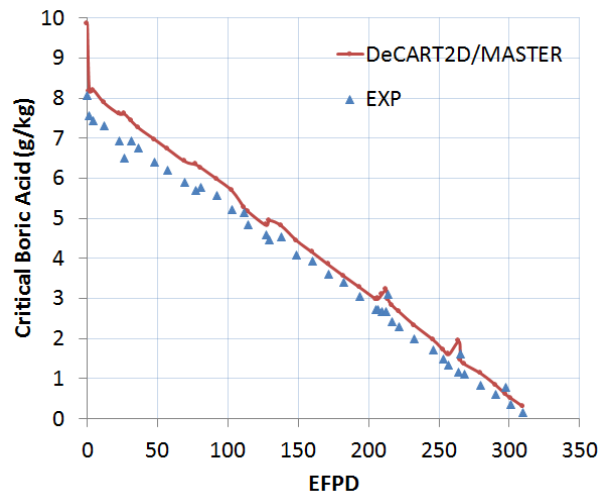Fig. 10. Cycle 1 CBA curve calculated by MASTER

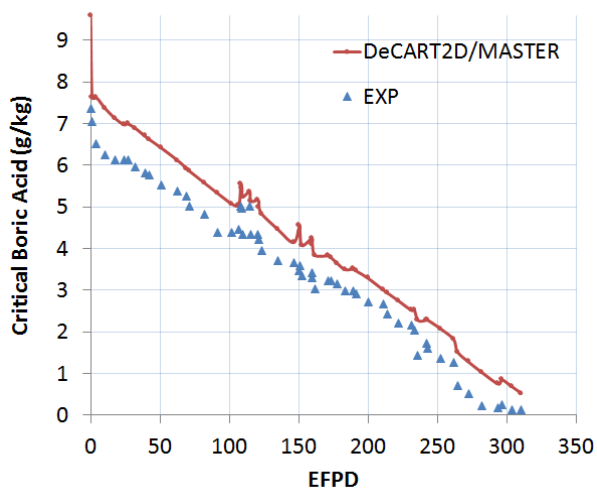Fig. 13. Cycle 4 CBA curve calculated by MASTER

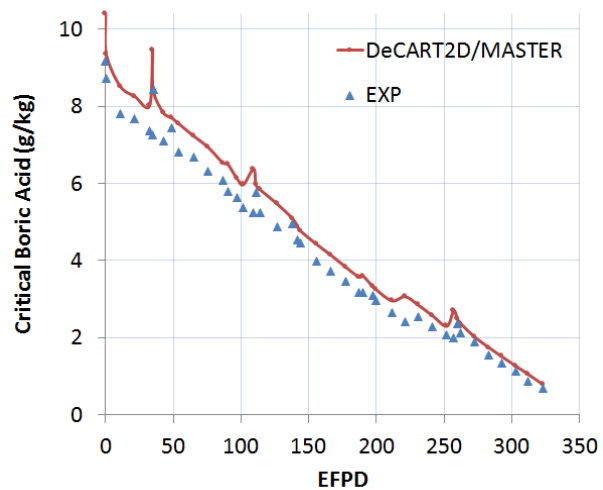Fig. 11. Cycle 2 CBA curve calculated by MASTER

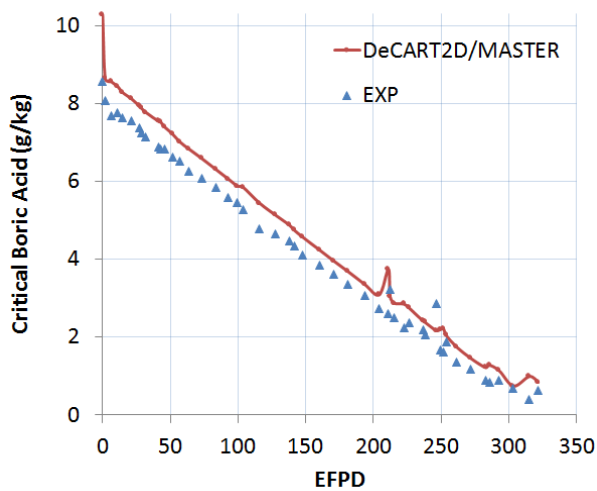Fig. 14. Cycle 5 CBA curve calculated by MASTER
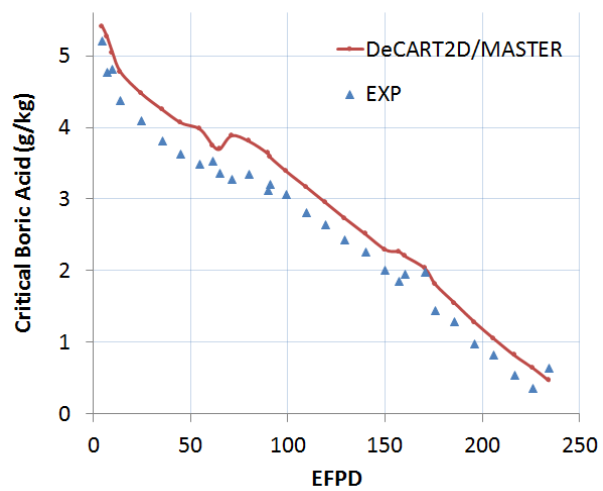

Fig. 12. Cycle 3 CBA curve calculated by MASTER

Fig. 15. Cycle 6 CBA curve calculated by MASTER

Table II. Measured and Computed CBCs at BOC in Each Cycle

	Measured	MASTER	BIPR-7A	HELHEX
C1 (1.1)	1085	1245	1181	1138
C2 (1.1)	1236	1335	1260	1295
C3 (1.9)	1411	1511	1470	1444
C4 (1.5)	1323	1429	1356	1348
C5 (0.5)	1530	1638	1488	1453
C6 (4.6)	912	947	901	936

Table III. Measured and Computed CBCs at EOC in Each Cycle

	Measured	MASTER	BIPR-7A	HELHEX
C1 (1.1)	18	47	35	35
C2 (1.1)	23	92	88	79
C3 (1.9)	109	146	140	140
C4 (1.5)	28	54	53	35
C5 (0.5)	117	137	140	123
C6 (4.6)	112	81	70	53
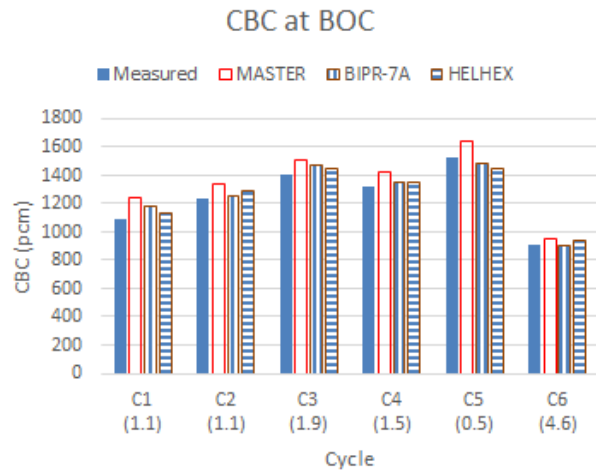
Fig. 16. Comparison of Measured and Computed CBCs at BOC in Each Cycle
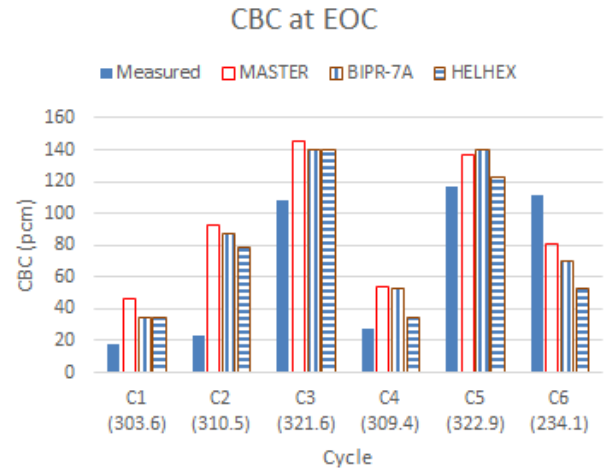

Fig. 17. Comparison of Measured and Computed CBCs at EOC in Each Cycle

is the last step. Axial core configuration, core loading pattern, control rod map, operation history, inlet and outlet temperature corresponding to the burnup step, and other various core design and operating data are applied to the MASTER core follow input model in this step.

CBA curves computed by MASTER are compared to the reference measured data as well as the results computed by other reference design codes described in Appendix A for cycle 1 through cycle 6. Although the MASTER results have large difference compared to the measured data at BOC of each cycle, the solutions obtained by MASTER and other reference codes have enough consistency. Thus it can be deduced that measured data has considerable uncertainty or there would be undesirable inconsistency between nominal and as-built core design data. By confirming that CBA curves obtained by MASTER and other reference codes match well, DeCART2D/MASTER hexagonal core analysis capability is verified.

APPENDIX A: REFERENCE CBA CURVES FOR CYCLE 1 THROUGH CYCLE 6

SOFIA University provided figures representing CBA curves computed by their own nodal code HEX3DA and Russian code BIPR-7A contained in the KASKAD code package developed in Kurchatov institute. Two HEX3DA solutions are provided where the 'HELHEX' solution is generated from the HELIOS-1.5/HEX3DA system and 'DECHEX' is generated from DeCART2D/HEX3DA. Fig. A.1 through Fig. A.6 show their CBA curve for cycle 1 through 6, respectively. The meaning and unit of x- and y-axis are same to that of Fig. 10 through Fig. 15. (CBA in g/kg and burnup in EFPD)
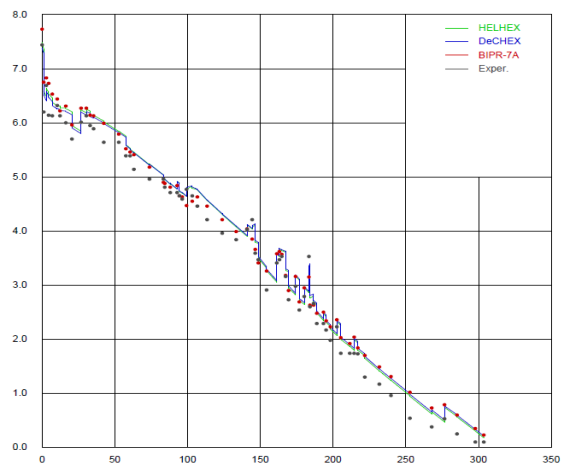
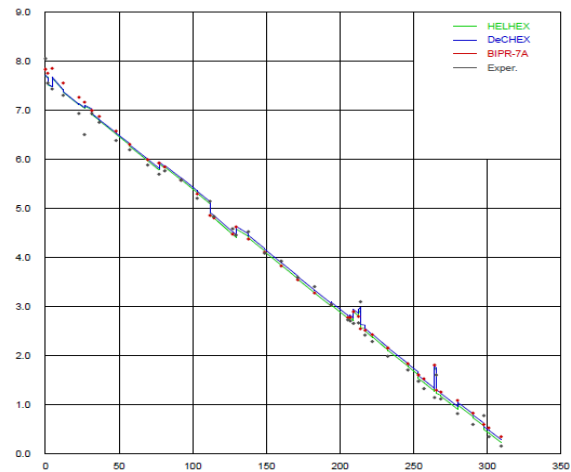Fig. A.1 Reference CBA curves for cycle 1

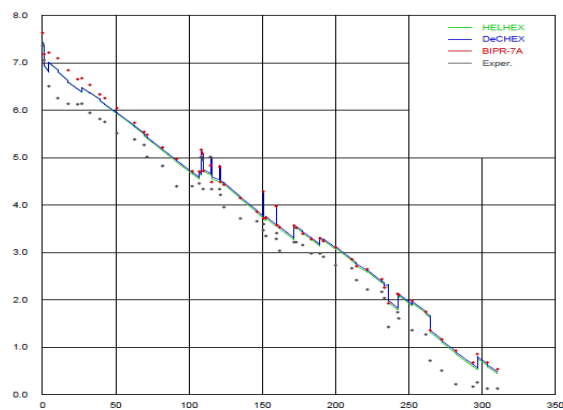
Fig. A.4 Reference CBA curves for cycle 4

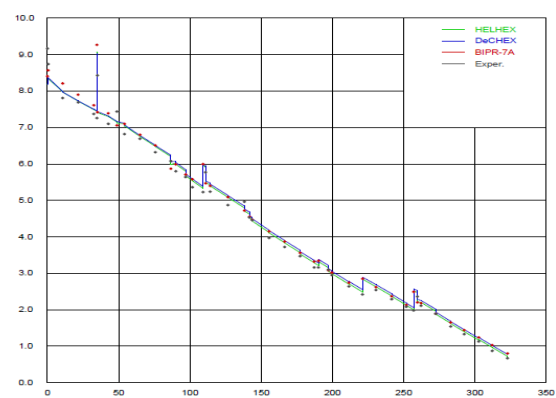Fig. A.2 Reference CBA curves for cycle 2

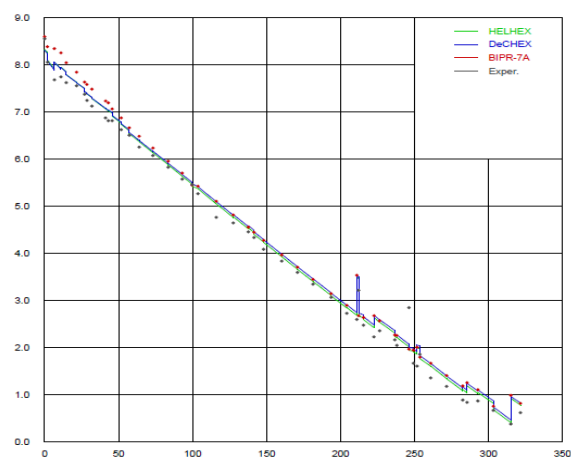Fig. A.5 Reference CBA curves for cycle 5
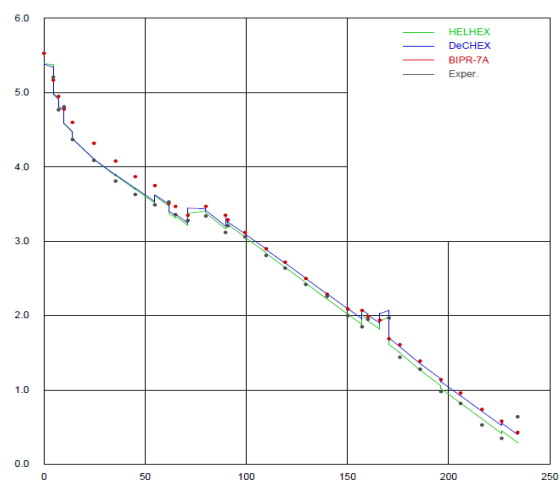

Fig. A.3 Reference CBA curves for cycle 3

Fig. A.6 Reference CBA curves for cycle 6

REFERENCES

1. J. Y. Cho, et al., "DeCART2D v1.1 User's Manual," KAERI/UM-40/2016, 2016.
2. J. Y. Cho, et al., "MASTER v4.0 User's Manual," KAERI/UM-41/2016, 2016.
3. J. Y. Cho, et al., "Whole Core Transport Calculation Employing Hexagonal Modular Ray Tracing and CMFD Formulation," *Journal of Nucl. Sci. and Tech.,* 45, 740 (2008)
4. J. Y. Cho et al., "Hexagonal CMFD Formulation Employing Triangle-based Polynomial Expansion Nodal Kernel," *Proc. M&C 2001*, Salt Lake City, Utah, September 9-13, 2001, American Nuclear Society (2001) (CD-ROM)
5. SOFIA University, "Provision of Kozloduy-6 core design and operating data in accordance with MOA signed btw. KAERI and SOFIA University," 2013.
6. C. B. Shim, et al., "Improvement of Axial Reflector Cross Section Generation Model for PWR Core Analysis," Transactions of the Korean Nuclear Society Autumn Meeting, Gyeongju, Korea, October 27-28, 2016.
7. J. S. Song, et al., "PROLOG1.1 User's Manual," KAERI/UM-4/99, 1999