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Study on Burnable Absorber Optimization and Fuel Management Strategy for 2 Batch APR1400 Very-Low-Boron Core

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1. Introduction

The soluble boron is very useful chemical shim to control the excess reactivity in PWRs. However, the use of soluble boron also raises several significant concerns, such as soluble boron-induced corrosion of structures and a generation of large amount of liquid waste. Moreover, a higher boron concentration in a longer cycle (e.g. 24 months) core can cause a positive moderator temperature coefficient (MTC) at hot zero power (HZP) condition as well as low power operation. Recently, it is required to have more negative MTC to mitigate the consequence of the anticipated transient without scram (ATWS), and a lower CBC is preferred to relax the boron dilution accident (BDA).

On the other hand, demand on flexible fuel management up to 24 month operation is increasing. A longer fuel cycle with a fixed outage time will yield a higher plant availability, which offsets the increased fuel cycle costs. It also lessens the radiation exposure on the operation and maintenance personnel. Extension to 24-month fuel cycle removes one outage in every six year operating period compared to 18-month fuel cycle. Therefore, the fuel cycle management with refueling interval of 24 months may bring down the total costs.

In APR1400 Very-Low-Boron (APR1400-VLB) core design, a "very low boron" concentration is pursued to achieve two goals. The first goal is to minimize the adverse effects of the soluble boron in the primary system. The second goal is to enable the passive frequency control (PFC) operation [1], in which no active reactivity controls are required during a frequency control operation utilizing a strong negative MTC.

In the following sections, previous design of APR1400-VLB [2] and study performed for optimization of burnable absorber, fuel assembly axial configuration, and fuel management scheme are described.

To perform physics studies on the APR1400-VLB core with extended cycle length, a Monte Carlo (MC) and diffusion hybrid two-step procedure is utilized in the current work. The Serpent 2 code with the ENDF/B-7.1 library is used for the fuel assembly (FA) lattice calculations and the COREDAX [3], a nodal diffusion code, is used for 3-D nodal calculations of the APR1400-VLB cores.

2. Previous APR1400-VLB design

Table I shows major design parameters of the APR1400-VLB core. The maximum allowable enrichment of the fuel rods is 5.00 wt% with 95.5 % theoretical density of the UO_2 pellet. There are 136 fresh FAs and 105 reloaded FAs. The fuel assembly has same configuration of typical 16×16 CE-type fuel. There is no radial fuel rod zoning and axial blanket except CSBA (Centrally Shielded Burnable Absorber) [4] cutback of 14.5 cm for both top and bottom of core.

Table I: APR1400 core major technical parameters

Parameters	Value	Unit
Thermal Power	3983	MWth
Active Core Height	381	cm
Fuel Assembly Type	16×16	
Number of Fuel Assemblies	241	
Fuel Loading Scheme	2-batch	
No. of Feed Fuel Assemblies	136	
Fuel Enrichment	5.00	wt%
CSBA Design	3-ball	
CSBA Cutback	14.5	cm
Enrichment in Cutback Region	3.00	wt%
Reactivity Swing	< 5,000	pcm
Target Cycle Length	670	EFPD

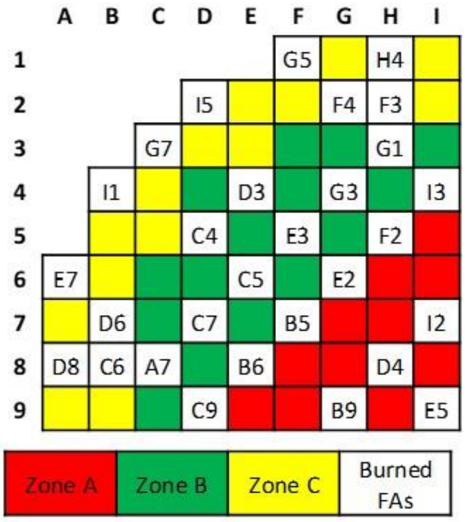
The previously proposed loading pattern for APR1400-VLB core is depicted in Fig. 1. The fresh FAs loaded in APR1400-VLB are divided into 3 zones. In all fuel locations, 3-ball type CSBA shown in Fig. 2 are loaded except for cutback region. The larger CSBA ball is placed into high power regions, zone A, to reduce fuel depletion rates and power peaking. On the other hand, smaller CSBA balls are loaded to zone B and C as the powers at these zones are lower.

Fig. 3 shows CBC vs. cycle length for CSBA-loaded APR1400-VLB cores with and without Er-doped GTs for water-reflected and SS-reflected cases. Fig. 4 shows axial power shapes for SS-reflected APR1400-VLB core loaded with CSBA and Er-doped GT. In Fig. 3, it has been shown that the boron concentration remains below ~600 ppm during most of cycle operation even in cases without Er-doped GTs. According to a recent study, MTC of APR1400-VLB core with 600 ppm at BOC is evaluated to be less than -20 pcm/°C, and it is expected that APR1400-VLB is capable of passive frequency control (PFC) operation during the most of operation cycle.

3. Optimization of APR1400-VLB

3.1 Design of additional burnable absorber

Application of cutback design in Er-doped GT (guide thimble) may have manufacturing problem and material property of the mixture has not been studied fully yet. Thus, other types and material of burnable absorber are examined in this study. To evaluate the effect on cycle length and maximum CBC, gadolinium bearing BigT (Burnable absorber integrated guide thimble, See Fig. 5) [5] and erbium bearing BigT are compared with Er-doped GT with and without cutback. Table II shows additional BA configurations for comparison.



Initial Location	Reloaded Location	Initial Location	Reloaded Location
I5	D2	F6	-
I6	-	D4	H8
I8	-	E5	I9 (Center)
H6	-	I1	B4
H7	-	G1	H3
G7	C3	F2	H5
I3	I4	E2	G6
F3	H2	E3	F5
H4	H1	D3	E4
G3	G4	I2	I7
G5	F1	I5	D2
F4	G2		

Fig. 1. Loading pattern for 24-month APR1400-VLB

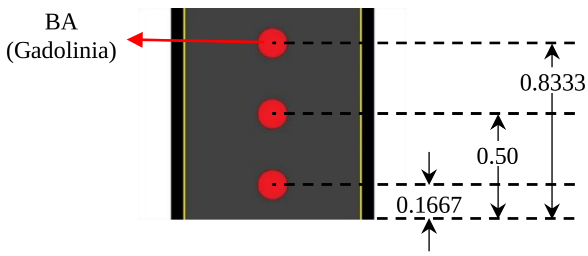


Fig. 2. 3-ball CSBA fuel pellet

The CBCs for various types of GT-contained BAs are shown in Fig. 6 and Table III. In point of reactivity swing, BigT-Gd case 1 is preferred since it shows lowest CBC and longest cycle length which is loaded with more Gd compared to case 0.

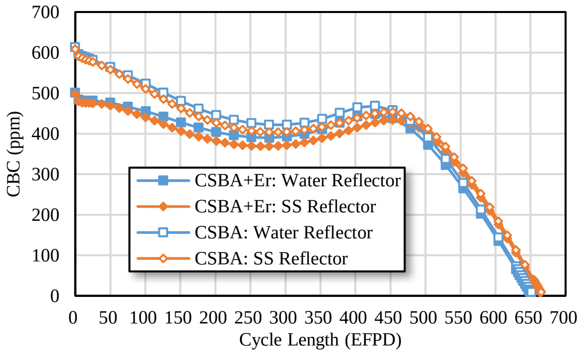


Fig. 3. CBC vs. cycle length for CSBA-loaded APR1400-VLB core with or without Er-doped GT

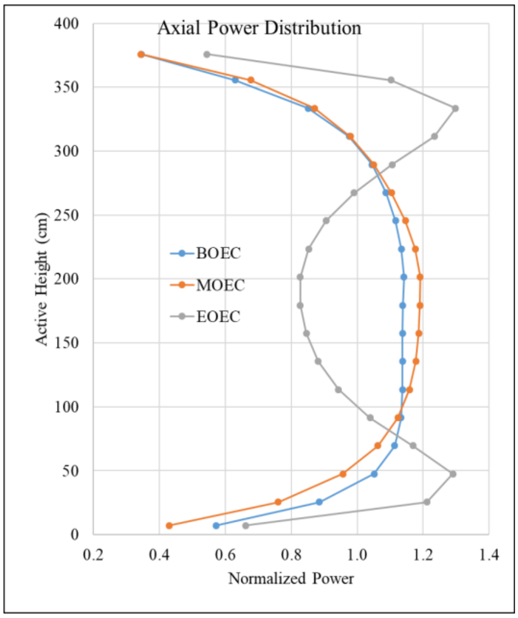


Fig. 4. Axial power distribution of SS-reflected APR1400-VLB core loaded with CSBA and Er-doped GT

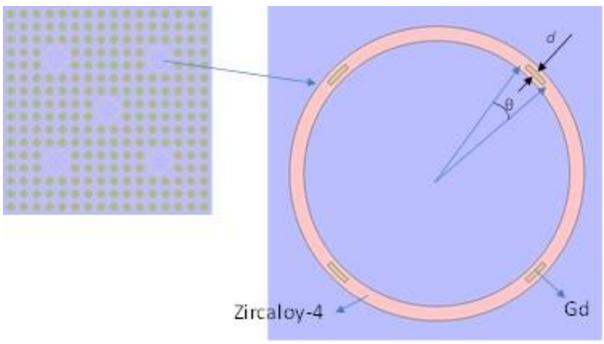


Fig. 5 Concept of BigT-fAHR (Burnable absorber integrated guide thimble – fixed azimuthally heterogeneous ring)

3.2 Axial power shape analysis with design modification of cutback

The axial power shapes at BOC, MOC, and EOC of APR1400-VLB equilibrium cycle are compared in Fig. 7

for Gd-bearing BigT designs with different cutback lengths. It can be shown that the saddle shape at EOC is less severe for large cutback case due to the rapid depletion at top and bottom of the core.

Table II. Er-doped GT vs. BigT design

Case	**Design**	**Cutback length**
CSBA Only	Without GT modification	14.5 cm
Er-doped (case 0)	3wt% Er doped in GT	14.5 cm
Er-doped (case 1)	3wt% Er doped in GT	0.0 cm
BigT-Gd (case 0)	θ = 5, d = 0.04 cm	14.5 cm
BigT-Gd (case 1)	θ = 7, d = 0.04 cm	14.5 cm
BigT-Er	θ = 90, d = 0.0025 cm	14.5 cm

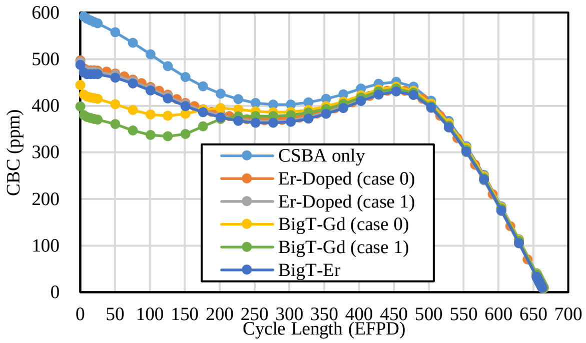


Fig. 6. CBC vs. cycle length for various additional BA designs

Table III. Maximum CBC and cycle length for various type of additional BA

Case	**Maximum CBC (ppm)**	**Cycle Length (EFPD)**
CSBA Only	609	667
Er-Doped (case 0)	497	665
Er-Doped (case 1)	494	665
BigT-Gd (case 0)	444	666
BigT-Gd (case 1)	399	666
BigT-Er	487	665

The cycle length as well as axial power shape are affected by uranium enrichment in cutback region. The boron letdown and power distributions are calculated by changing cutback region enrichment with fixed cutback length (14.5 cm). Fig. 8 compares boron concentration vs. cycle length for 3.0 wt%, 2.5 wt%, 5.0 wt%, and 4.0 wt% cutback. The difference of cycle lengths due to 2.5 wt% cutback and 5.0 wt% cutback is calculated as 15 EFPDs. It should be noted that only CSBA is loaded and other BA type such as Er-doped GT or BigT is not loaded in this calculation.

Fig. 9 shows axial power shapes with 5.0 wt% cutback. Even though the axial power distributions are less symmetric compared to the axial power shapes with 3.0 wt% cutback in Fig. 7, APR1400-VLB with 5.0 wt% cutback is preferred because a clearly longer cycle length is available. The shifted power distributions at BOC and EOC can be fixed by adjusting axial CSBA loading.

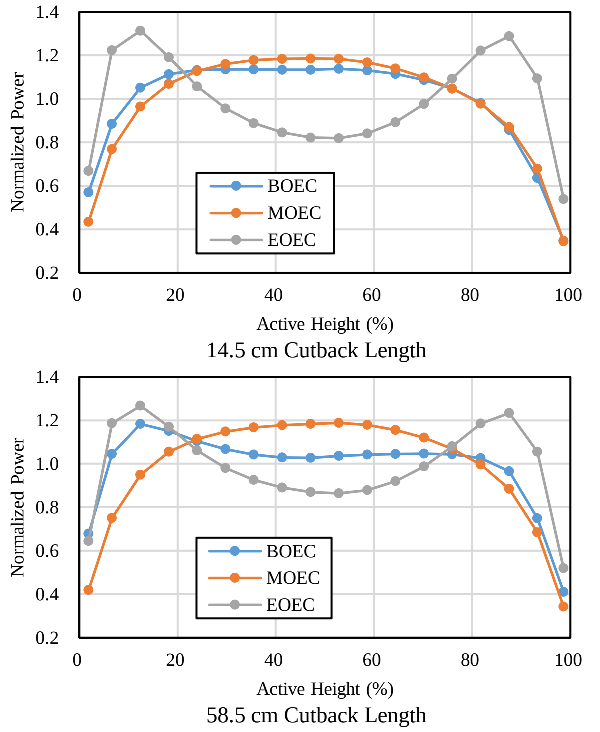


Fig. 7. Comparison of axial power shapes for APR1400-VLB core loaded with CSBA and BigT

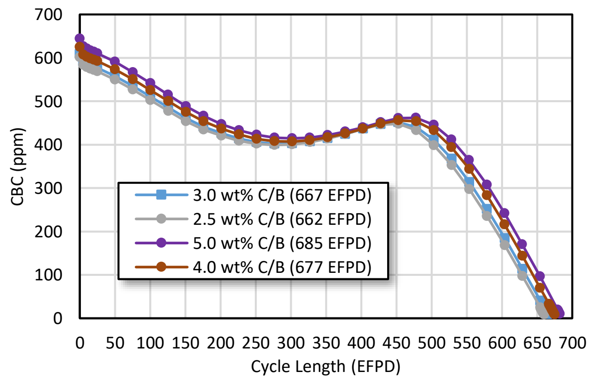


Fig. 8. Cycle length comparison with different cutback enrichment

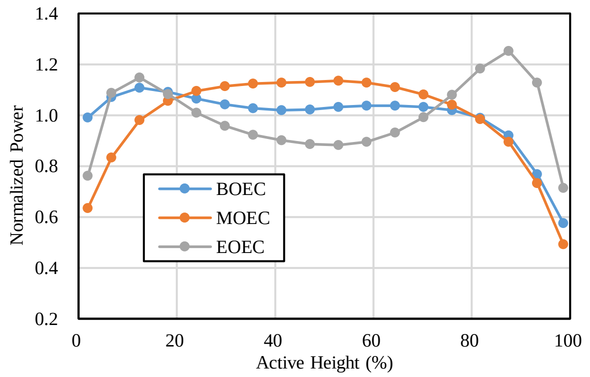


Fig. 9.Axial power shapes with 5.0 wt% cutback enrichment

3.3 Flexible fuel management scheme

With fuel management scheme that replaces 136 FAs during overhaul, 31 once burned FAs are discharged for every cycle. Since spent fuels discharged with insufficient burnup cannot be stored in spent fuel pool region II, discharged fuels with one cycle operation most likely not be stored in region II. To reduce the amount of under-depleted spent fuels, fuel management scheme which aims to reload as many fuels twice is preferred.

In this study, the flexibility in cycle operation has been surveyed by changing the fuel shuffling scheme with different number of feed FAs. The fuel shuffling schemes for 132-feed and 121-feed loading patterns are shown in Fig. 10.

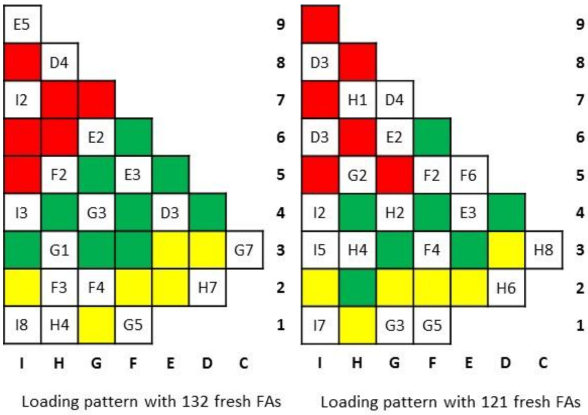


Fig. 10. Fuel shuffling scheme with 132- and 121- feed FAs

The basic evaluation results of boron concentration and cycle length are compared in Fig. 11 for loading patterns with 132 feed FAs and 121 feed FAs. It should be noted that the loading of CSBA are slightly reduced to reduce the residual reactivity in later 2 cases.

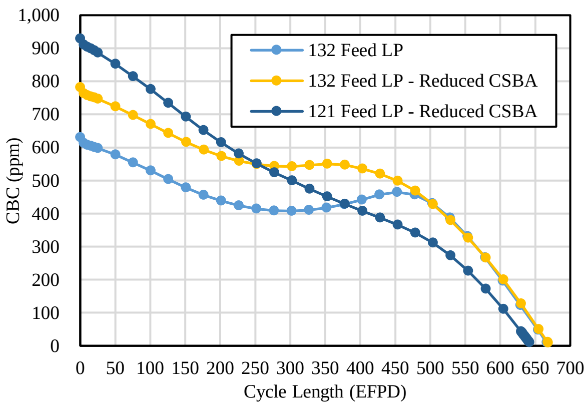


Fig. 11. Comparison of CBC and cycle length for LPs with 132- and 121- feed FAs

Even allowing the additional BAs are not included in the calculation, boron concentrations are too high for LPs with 132 and 121 feed FAs since the amount of CSBA loadings are decreased compared to LPs with 136 feed FAs. To enable PFC operation, the maximum CBC should be reduced by optimization of CSBA and additional BA designs.

4. Conclusions and Future Works

The physics characteristics and core performances were analyzed for various configurations of APR1400-VLB core. This optimization study has focused on the manufacturing feasibility of CSBA and additional BA designs and improvement of axial power distribution during cycle. For flexibility in operational cycle length and fuel management of feed and spent fuel, alternative loading patterns of APR1400-VLB has been sought.

It has been shown that the flattening axial power distribution at BOC by increasing cutback region enrichment helps to suppress the saddle-like power shape at EOC. For additional BA design, Gd-bearing BigT showed better performance in point of CBC. Since the BA configurations and core LPs with 132 or 121 feed FAs are not optimized yet, the CBC and power distributions are not acceptable in this stage. The maximum assembly burnup also should be evaluated and verified to satisfy corresponding limit by optimizing fuel shuffling scheme.

Further optimization in CSBA design and cutback length will be done to reduce the maximum CBC and to improve axial power shape. Also, LP optimization will be performed to reduce radial power peak and to lower maximum assembly burnup.

ACKNOWLEDGMENT

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