Cutback sensitivity test for boron-free small modular PWR

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Abstract. A soluble boron-free small modular pressurized water reactor (SMPWR) uses burnable absorbers (BA) instead of soluble boron to reduce excess reactivity. As a consequence, the fuel cycle length can be shortened by the residual penalty of BA. This paper performs cutback sensitivity tests to extend the cycle length. The influence of the height of the cutback, of the ^{235}U enrichment rate, and of the BA material on the power peaking factor (Fq), the axial offset (AO) and the fuel cycle length is analyzed with the reactor core design system, CASMO-4E/SIMULATE-3 code system.

1. Introduction

Soluble boron-free operation of small modular pressurized water reactor (SMPWR) has some advantages: reduction of the plant size owing to the removal of the chemical volume control system (CVCS), reduction of liquid radioactive waste, no corrosion issue due to boric acid [1]. However, large amounts of burnable absorber (BA) must be loaded in the core so as to reduce excess reactivity. As a consequence, the fuel cycle length can be shortened by the residual penalty of BA. This paper performs cutback sensitivity tests at the top and bottom regions of the core to extend the cycle length.

The influence of the height of the cutback, of the ^{235}U enrichment rate and of the BA material on the power peaking factor (Fq), the axial offset (AO) and the fuel cycle length has been analyzed. The Studsvik's reactor core design CASMO-4E/SIMULATE-3 code system is used for these simulations [2-4].

2. Reference SMPWR Design Parameters

Core design parameters of reference SMPWR are summarized in Table 1. The thermal power is 200 MW, and the power density is 58.4 kW/L. The base model of a fuel assembly (FA) is 17 pins by 17 pins, Westinghouse type. The fuel material is uranium oxide. The BA design uses new type of BA, R-BA, which is a thin Zr-^{167}Er layer coated inside the cladding, as shown in Figure 1 [5]. The target reactivity swing is below 1,000 pcm to secure enough shutdown margin and to secure stable control of excessive reactivity by control rods.

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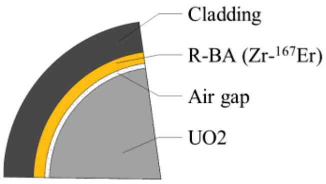

Figure 1. R-BA Cross Section View.

Table 1. Core Design Parameters of reference SMPWR.

Parameters	Target Value
Thermal power	200 MW
Power density	58.4 kW/L
Fuel cycle length	36 months
Fuel material	UO_2
BA material	R-BA with Zr-^{167}Er
Fuel enrichment	4.90 w/o ^{235}U
Number of FAs	37
Active core height	2.0 m
Reactivity($\Delta\rho$) Swing[a]	< 1,000 pcm
Boron concentration	0 ppm
3D pin peaking factor [b]	< 4.4
Axial Offset [b]	-0.4 < AO < +0.4

[a] ((max k_{eff} -1) / max k_{eff}) × 10^5 [pcm], [b] [6]

The two-batch loading pattern with 37 FAs is shown in Figure 2. This configuration uses 12 FAs of Type 01 and 25 FAs of Type 02. The specification of R-BA for each FA type is different: Type 01 FA uses 1 mm of ^{167}Er 5 w/o R-BA for 88 pins whereas Type 02 FA uses 2 mm of ^{167}Er 15 w/o R-BA for 216 pins, as shown in Figure 3. The reactivity swing of this core is 548 pcm and the cycle length reaches 798 effective full power days (EFPD, 26.6 months). The fuel cycle length of the reference core is shorter than the target value.

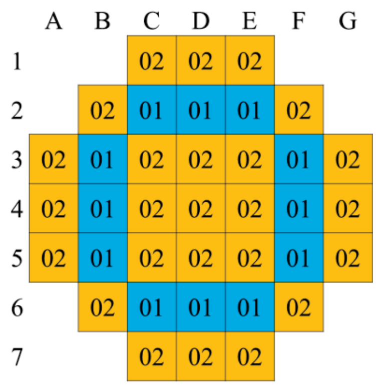

Figure 2. Two-batch Loading Pattern for SMPWR.

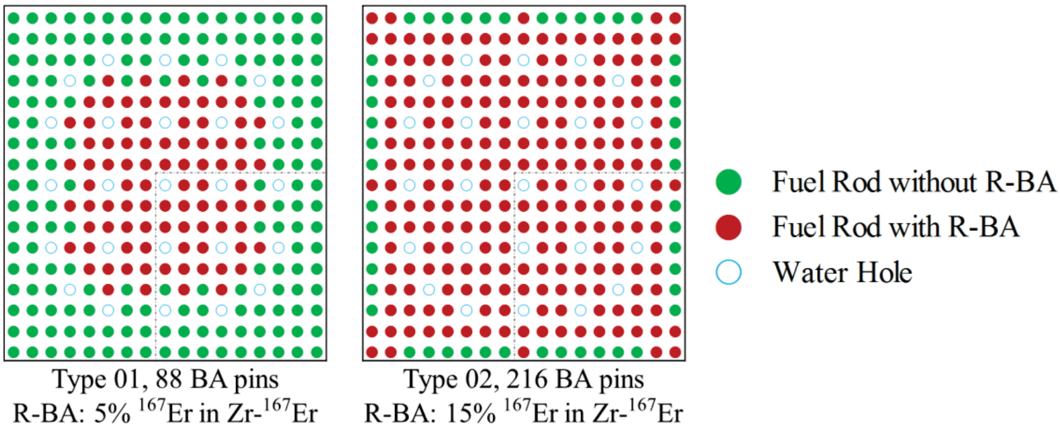

Figure 3. Fuel Assembly Pattern for Type 01 and Type 02.

3. Cutback Sensitivity Test

3.1 Description of Cutback Sensitivity Test

The R-BA is loaded from the top to the bottom in the reference core as shown in Figure 4. The cutback sensitivity test is performed at the top and bottom regions. The relative power is low at the top and bottom regions; thus those regions may not need to load large amount of BA.

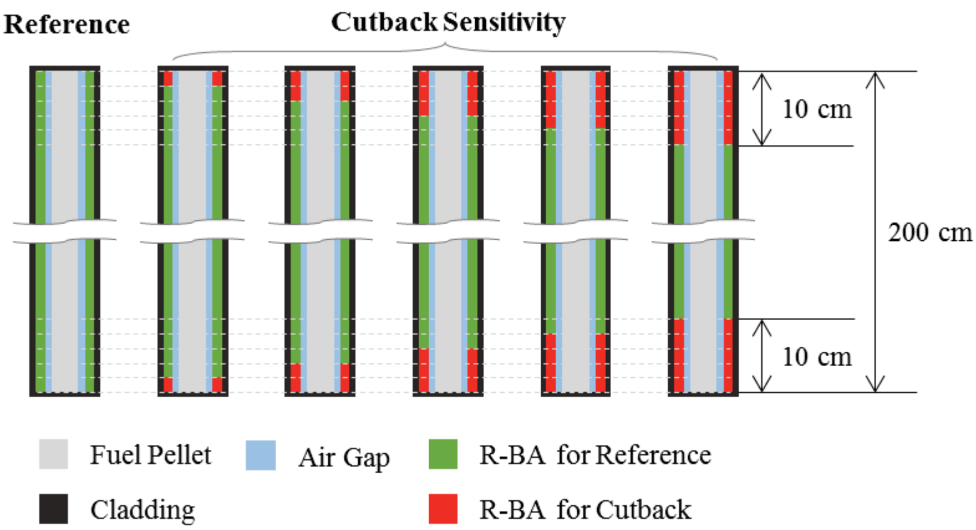

Figure 4. Axial View of BA Rods for Test Cases.

The test cases are summarized in Table 2. There is no cutback (0 cm cutback) in the reference core. The height of cutback was then changed from 2 cm to 10 cm by 2 cm step from both the top and the bottom, as shown in Figure 4. For each non-zero cutback, two sensitivity tests were carried out:

- First, no BA material was used in the cutback regions; the ^{235}U enrichment rate in the cutback regions was changed from 2.2 w/o to 4.9 w/o by 0.5 w/o steps.
- Second, different BA materials were tested in the cutback regions; the ^{235}U enrichment rate was fixed to 4.9 w/o ^{235}U.

In the 2nd sensitivity test, 2 different BA materials were tested, one after the other. The first BA material tested in the cutback regions is Zr-B instead of Zr-^{167}Er. The B content in Zr-B was changed from 5 w/o to 10 w/o by 5 w/o step. The second BA material tested is Zr-Gd instead of Zr-^{167}Er. The Gd content in Zr-Gd was changed from 5 w/o to 20 w/o by 5 w/o step. The content range of BA material in Zr-BA is determined by their phase diagrams [7-9].

Table 2. Cases description for Cutback Height and Material.

	Cases Description					
Height of Cutback [cm]	2.00	4.00	6.00	8.00	10.0	
^{235}U Enrichment rate (no BA) [w/o ^{235}U]	2.20	3.00	3.50	4.00	4.50	4.90
BA Content of Zr-B in BA (^{235}U enrich. rate = 4.9 w/o) [w/o]	5.00	10.0				
BA Content of Zr-Gd in BA (^{235}U enrich. rate = 4.9 w/o) [w/o]	5.00	10.0	15.0	20.0		

3.2 First Study: Fuel Enrichment variation without BA

The fuel cycle length and the reactivity swing as a function of cutback height and fuel enrichment in the cutback regions are presented in Figure 5. The higher the cutback height is, the longer the fuel cycle length is, due to the absence of BA in the cutback regions.

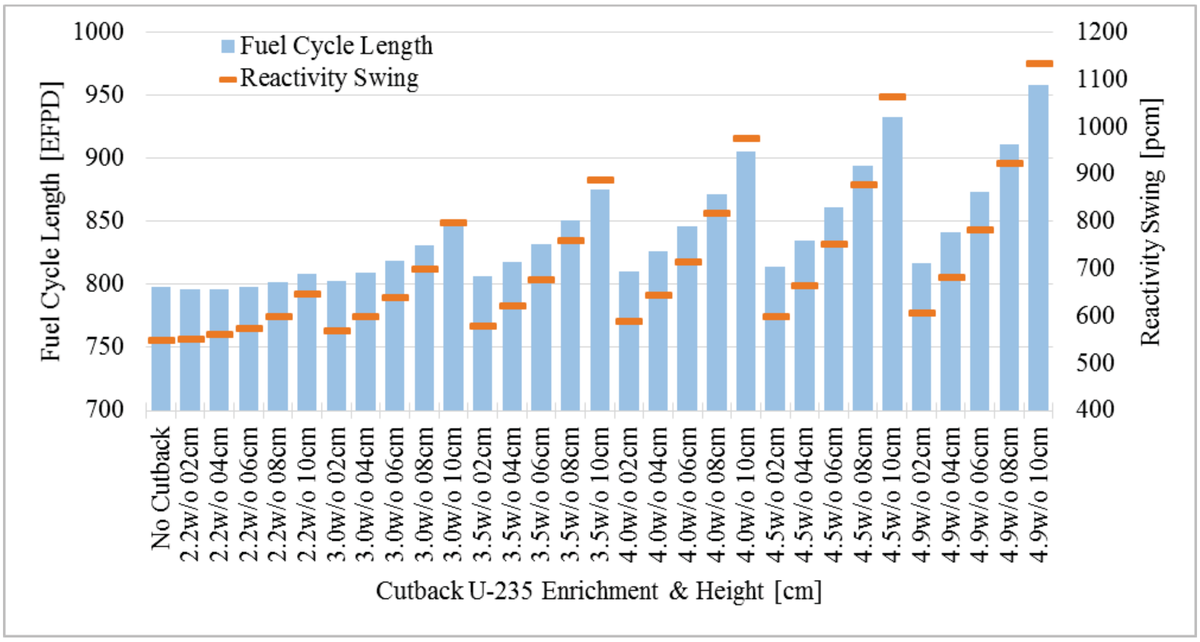

Figure 5. Fuel cycle length and reactivity swing as a function of fuel enrichment in the cutback regions.

3.3 Second Study: BA Material

The fuel cycle length and the reactivity swing variations, depending on the BA content in Zr-B or Zr-Gd cutback regions, are presented in Figure 6. Using Zr-Gd is better than using Zr-B. Indeed, the higher the B content in Zr-B is, the shorter the fuel cycle length is. On the other hand, the higher the height of Zr-Gd is, the longer the fuel cycle length is.

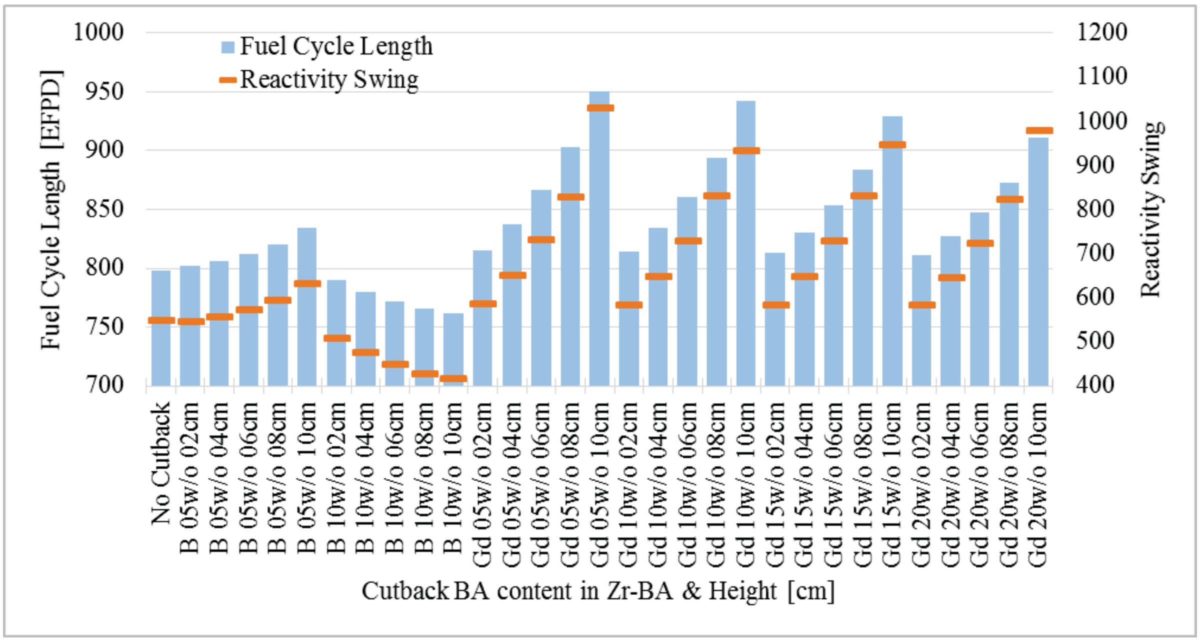

Figure 6. Fuel cycle length and reactivity swing change according to BA content.

Three cases of interest are presented in Table 3. Indeed, for those cases, the cycle length is increased by more than 140 EFPD compared to the reference cycle length. The cutback height for the three cases equals 10 cm and this makes the fuel cycle length longer. The cutback with 4.9 w/o ^{235}U without BA gives the longest cycle length, but the initial excess reactivity is higher than for the cases with Zr-Gd in cutback regions, as shown in Figure 7. The cutback with Zr-Gd makes the initial excess reactivity low, thus it is good for securing shutdown margin at the beginning of cycle (BOC). In the three cases, the axial offset and the power peaking factor are within target values (-0.4<AO<+0.4 and Fq<4.4 respectively), as shown in Figure 8 and 9. The cutback with Gd 10w/o in Zr-Gd is the best test case, because the reactivity swing of the two other cases is higher than the 1000-pcm reactivity swing target value.

Table 3. Cutback Sensitivity Test Results.

Test cases, Height	Cycle Length [EFPD]	Δρ Swing [pcm]
Reference	798	548
Gd 5w/o in Zr-Gd, 10cm	951	1029
Gd 10w/o in Zr-Gd, 10cm	942	934
4.9 w/o ^{235}U without BA, 10cm	959	1132

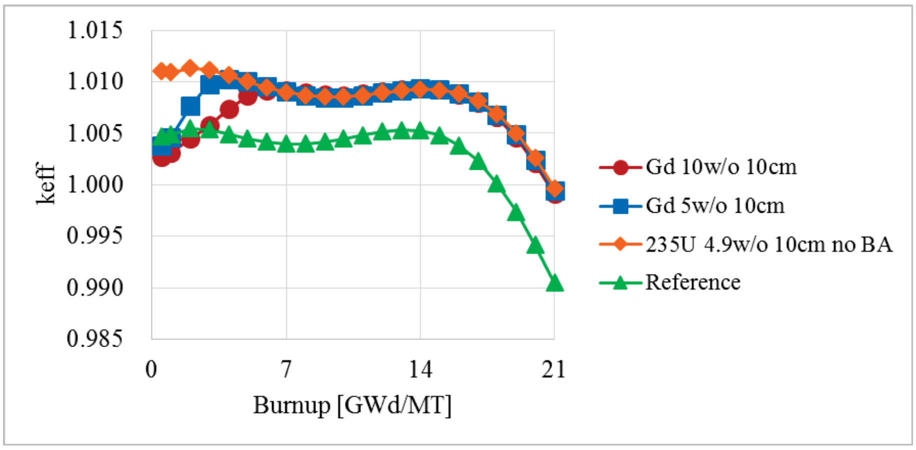

Figure 7. k_{eff} change behavior as burnup

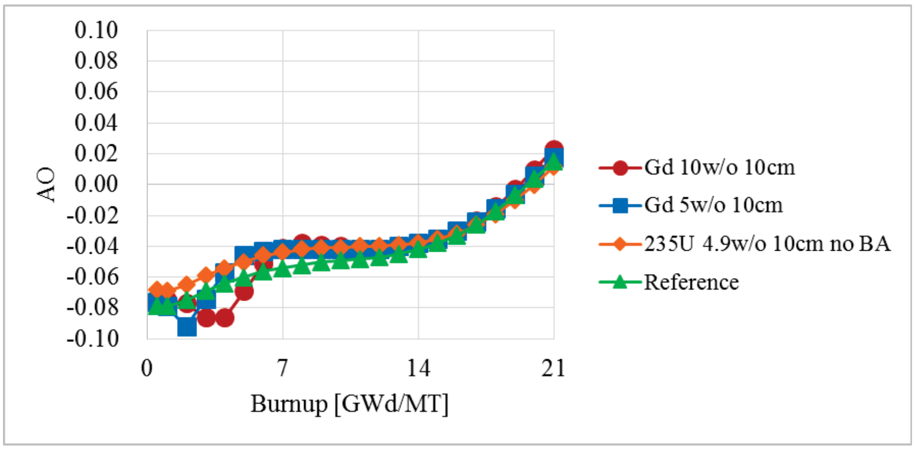

Figure 8. Axial offset change as burnup.

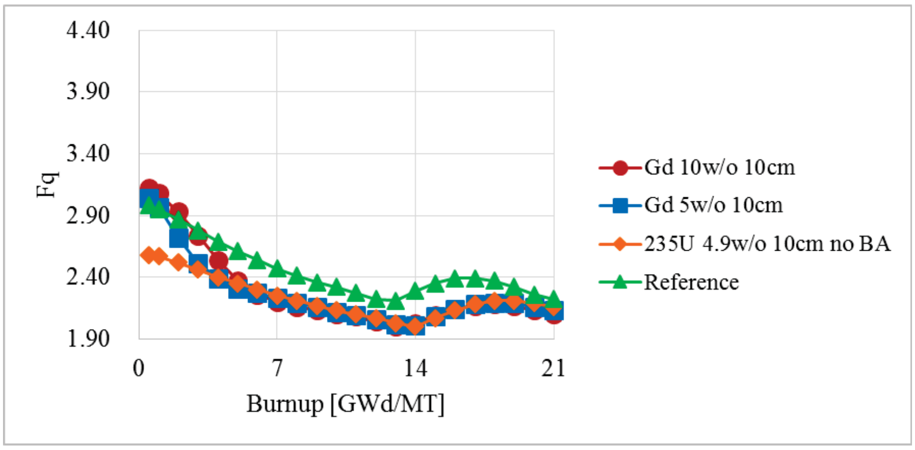

Figure 9. 3D pin peaking factor change as burnup.

4. **Conclusions**

This paper conducted cutback sensitivity tests in SMPWR to extend the cycle length. The cutback region may not need to load considerable amount of BA due to low relative power. At the bottom and top of the core pins, different heights of cutback were tested, along with different fuel enrichment rates and different BA materials (Zr-B or Zr-Gd). The reference core has no cutback region and uses only ^{167}Er-Zr as BA material, the cycle length of the reference core being 798 EFPD. An optimal cutback region of 10 cm height with natural Gd 10% in Zr-Gd was found, for which the cycle length increases to 942 EFPD. The core with this optimal cutback is satisfied with the design limits, which are the axial offset and the 3D pin peaking factor, over the operation time and the maximum excess reactivity is within 1000 pcm of target value. This is a 4.8-month increase of the reactor cycle length compared with the reference core.

References

[1] Choe J, Lee D and Shin H C 2016 *Preliminary Design of Boron-Free Small Modular Pressurized Water Reactor*, PHYSOR 2016 Sun Valley ID

[2] Rhodes J, Lee D and Smith K 2009 CASMO-4E: Extended capability CASMO-4 user's manual *Studsvik Scandpower*

[3] T. Bahadir 1999 CMS-LINK USer's Manual (Waltham: Studsvik Scandpower)

[4] BLJ Covington 2009 SIMULATE-3: Advanced Three-Dimensional Two-Group Reactor Analysis Code User's Manual (Waltham: Studsvik Scandpower)

[5] Choe J, Lee D and Shin H C 2016 New Burnable Absorber for Long-Cycle Low Boron Operation of PWRs *Annals of Nuclear Energy* **88** 272

[6] Mart J R 2013 *Feasibility Study on a Soluble Boron-Free Small Modular Reactor* (Oregon: Oregon State University)

[7] Franke P and Neuschütz D 2007 Thermodynamic Properties of Inorganic Materials *Springer Berlin Heidelberg*

[8] Mattern N *et al.* 2012 Experimental and thermodynamic assessment of the Gd–Zr system *Calphad: Computer Coupling of Phase Diagrams and Thermochemistry* **39** 27-32

[9] Brachet J C, Masclet C T, Hamon D, Guilbert T, Trego G, Jourdan J, Stern A, and Raepsaet C 2011 Oxygen, Hydrogen and Main Alloying Chemical Elements Partitioning Upon Alpha←→Beta Phase Transformation in Zirconium Alloys **172** 753