Impact of Erbia in Long Cycle Operation of PWR

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1. Introduction

There are two primary utility requirements for GEN III+ Pressurized Water Reactors (PWR) [1]: the first one is a long-cycle operation and the second one is low-boron operation. Extending the cycle length can not only increase the energy production, but also bring down outage costs by reducing the number of refueling outages during the lifetime of a plant. However, more fresh fuel must be loaded for long cycle operation and this might cause a positive moderator temperature coefficient (MTC) at beginning of cycle (BOC).

Therefore, in this paper, we design a core suitable for long cycle operation and we perform sensitivity tests of MTC on the content of erbia (Er_2O_3) in fuel rods. The correlations between the erbia content and MTC, peaking factor, critical boron concentration (CBC) and fuel cycle length are analyzed. CASMO-4E/SIMULATE-3, which is Studsvik's reactor core design code system, has been used for these simulations [3-5].

2. Design long-cycle PWR with Erbia

2.1 24-month Cycle Equilibrium Core

An equilibrium core with 24-month cycle length was designed as a reference core. This reference core was designed for 24-month cycle length including overhaul time. The quarter loading pattern (LP) of this core is as shown in Fig. 1. This LP follows checker board pattern using once burned fuels and fresh fuels so as to fulfill core design parameters. The reference core is composed of 177 fuel assemblies. "PLUS7" type fuel assemblies are used for this core. Each fuel assembly consists of a 16 x 16 array of 236 fuel rods and 5 guide tubes. Fuel assembly data is detailed in Table II. Gadolinia (Gd_2O_3) is used as burnable absorber (BA) only in the reference core.

The reference core performance results are summarized in Table I. This core uses 4.95 w/o ^{235}U in UO_2 fuels, 4.45 w/o ^{235}U in UO_2 in fuel zoning and 105 fresh fuel assemblies for an extended cycle length. The core design parameters, which are initial CBC, 3D pin peaking factor (Fq), maximum pin burnup and MTC at hot zero power (HZP) BOC, MTC at hot full power (HFP) BOC, middle of cycle (MOC) and End of Cycle (EOC), are all within design limits. Since the core parameters satisfy the design limits, the reference core is well suited for 24-month long cycle operation.

	H	J	K	L	M	N	P	R
8	Q7	J-09	Q5	K-08	Q5	M-08	Q4	P-08
9	G-09	Q4	L-09	Q5	N-09	Q5	R-09	Q6
10	Q5	J-11	Q5	Q5	P-12	Q5	Q3	Q6
11	H-10	Q5	Q5	K-10	Q6	P-10	M-10	
12	Q5	J-13	M-14	Q6	Q4	Q4	Q4	
13	H-12	Q5	Q5	K-14	Q4	M-12		
14	Q4	J-15	Q3	K-12	Q4			
15	H-14	Q6	Q6					

Fresh fuel
Once burned fuel

Fig. 1. Loading pattern of the reference core.

Table I: Summary of core results for the reference core

Parameters	Values
Enrichment [w/o ^{235}U] (Normal/Fuel Zoning)	4.95/4.45
Number of Batch	2
Number of FA (Fresh/Once/Twice)	105/72/0
Initial CBC [ppm]	1693
Fuel Cycle Length [EFPD]	650.40
Fuel Cycle Length [EFPM]	21.68
Core Average Discharge Burnup [GWd/MT]	23.80
3D Pin Peaking Factor (Fq)	1.86
Max. Pin Burnup [GWd/MT]	59.91
MTC at HZP BOC [pcm/°F]	3.33
MTC at HFP BOC [pcm/°F]	-6.77
MTC at HFP MOC [pcm/°F]	-14.43
MTC at HFP EOC [pcm/°F]	-38.94

Table II: Summary of Fuel assemblies data for the reference core

Assembly Type	No. of Fuel assemblies in reference core	Fuel Enrichment (w/o ^{235}U)	No. of Fuel Rods per Assembly	No. of Gd Shim Rods per Assembly	Poison Enrichment (w/o Gd_2O_3)
Q3	8	4.95/4.45	176/52	8	8
Q4	28	4.95/4.45	172/52	12	8
Q5	44	4.95/4.45	168/52	16	8
Q6	24	4.95/4.45	164/52	20	8
Q7	1	2.2	236	-	-

2.2 Erbia Loading in Fuel Rods

To increase safety margin, making the MTC more negative is essential. The MTC at HFP should always be negative. The ^{167}Er isotope has huge resonances in the thermal energy region [2]. When the moderator temperature increases, the thermal flux spectrum becomes hardened and shifts to that resonance so that the neutron spectrum overlaps with the large absorption resonance of ^{167}Er [2]. The increased neutron absorption by ^{167}Er makes the MTC more negative [2]. This reasoning shows that ^{167}Er makes the MTC more negative. In this paper, natural Er is used to makes MTC more negative because ^{167}Er and natural Er have similar absorption cross sections. Erbia is loaded in normal and zoning fuel regions. Different enrichments, namely 0.05w/o, 0.10 w/o and 0.20 w/o Er_2O_3 in Er_2O_3-UO_2, are used for sensitivity test.

Initial CBC and fuel cycle length are showed in Table III. Initial CBC and fuel cycle length decrease as Er_2O_3 enrichment increases. However, the decreases remain small in values. Er can help making MTC more negative without causing a large decrease of initial CBC and fuel cycle length. Fig. 2 shows boron letdown curve for different erbia enrichments. The Fq changes during operation and changes for different erbia enrichments, but it remains at all times within the design limit (Fq,max=2.568) as shown in Fig. 3.

Erbia enrichment sensitivity test results are shown in Table IV and Fig. 4. We notice that MTC is enhanced as erbia enrichment increases. These results show that natural Er can be used to make MTC more negative.

Table III: CBC and Fuel Cycle Length Comparison

Test Cases	Initial CBC [ppm]	Fuel Cycle Length [EFPD]
Reference	1693	650.40
Er_0.05w/o	1602	649.30
Er_0.10w/o	1514	645.00
Er_0.20w/o	1365	645.40

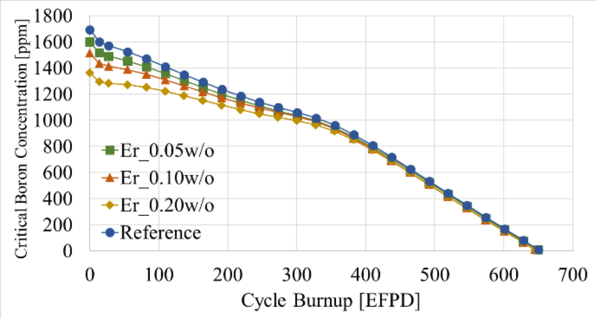

Fig. 2. Boron letdown curve Comparison.

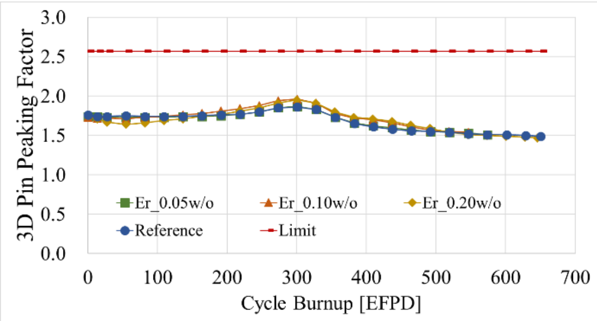

Fig. 3. 3D Pin Peaking Factor (Fq) Comparison.

Table IV: MTC at HZP BOC Comparison

Test Cases	Value [pcm/°F]
Reference	3.33
Er_0.05w/o	2.02
Er_0.10w/o	0.71
Er_0.20w/o	-1.66

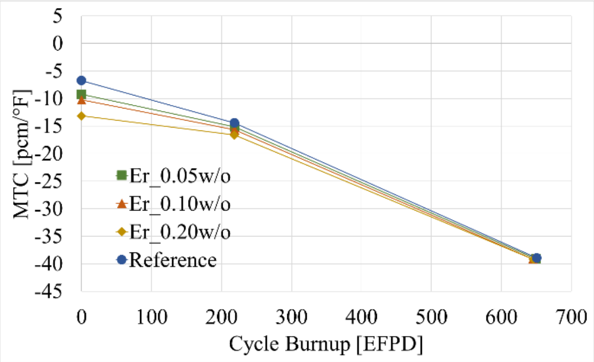

Fig. 4. MTC at HFP Comparison.

3. Conclusions

In this paper, we designed a core suitable for long cycle operation and we conducted sensitivity tests of MTC on the content of erbia in fuel rods. Erbia is used in normal and zoning fuel region. The correlation between the erbia content and MTC, peaking factor and CBC was analyzed.

The more the Er_2O_3 enrichment increases, the more the MTC is enhanced. However, although Er enrichment increases, initial CBC and fuel cycle length do not change remarkably. Er presents the right property of reducing MTC without causing a large change to initial CBC and fuel cycle length.

In conclusion, using the properties of Er, MTC can be enhanced and the safety margins can be increased for long cycle operation of cores.

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