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24-Month Operating Cycle Containing Gadolinium Integral Burnable Absorbers for NPP Krško

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ABSTRACT

A few years ago Westinghouse innovations in PWR technology resulted in a proposal for a new type of integral fuel burnable absorbers containing Gadolinium. Preliminary designs of loading patterns for NPP Krško were made for 18 month fuel cycles with standard VANTAGE+ fuel type containing Integral Fuel Burnable Absorbers (IFBA) with enriched Boron, as well as newly proposed Gadolinium based absorbers. In this paper we investigate the possibility to design 24 month cycle for the NPP Krško with VANTAGE+ fuel type and Gadolinium based integral absorbers. The key fuel cycle parameters are compared to the one based on IFBAs. The analysis is performed by the latest version of FUMACS code package capable of simulating Gadolinium based integral fuel burnable absorbers.

1 INTRODUCTION

At the moment, the Nuclear Power Plant (NPP) Krško is running on 18-month cycle, although studies, like Bilić et al. [1], have been conducted almost fifteen years ago examining the possibility to implement 24-month cycle. Those studies, as well as current NPP Krško operational experience, are mostly based on standard Westinghouse fuel (Standard, Vantage5, Vantage+) and integral fuel burnable absorbers containing natural or enriched Boron (IFBA). The exceptions are a few cycles in which burnable poison rods (BPR) and KWU type of fuel have been used.

However, a few years ago Westinghouse innovations in PWR technology resulted in a proposal for a new type of integral fuel burnable absorbers containing Gadolinium. Preliminary designs of loading patterns for NPP Krško were made for 18 month fuel cycles with standard, VANTAGE+, fuel type containing IFBAs with enriched Boron, as well as newly proposed Gadolinium based absorbers [2].

In general, longer operating cycles should lead to reduction of total electricity generation costs by decrease of outage frequency and improvement of capacity factor. On the other hand, longer cycles require higher enrichment of fresh fuel containing large quantities of burnable absorbers, what leads to increase of fuel fabrication costs. Prior to analysing economic impacts of longer cycle, one has to analyse whether such a cycle would satisfy safety limits. Therefore, in this paper we investigate the possibility to design 24-month cycle for the NPP Krško with VANTAGE+ fuel type and Gadolinium based integral absorbers. The key 24-month fuel cycle parameters of the proposed design are compared to the one based on VANTAGE+ fuel type containing IFBAs with enriched Boron. The design is performed by FUMACS-FEEC 2008 code package.

A short description of the FUMACS-FEEC 2008 code package is given in Section 2. Design of the Gadolinium based 24-month equilibrium cycle is conducted in Section 3, while the comparison of the 24-month cycles based on IFBAs containing enriched Boron and Gadolinium is performed in Section 4. Conclusion is given in Section 5, and used references are listed at the end of the manuscript.

2 FUMACS-FEEC 2008 CODE PACKAGE

The first version of the FUMACS code package was developed at "Ruđer Bošković" Institute in the year 1991 for in-core fuel management analysis of the NPP Krško core and it was designed as a stand-alone application for PC DOS environment [3]. It consisted of the PRELEO pre-processing code (preparation of ready-to-execute PSU-LEOPARD/RBI input data files), PSU-LEOPARD code (generation of a cross sections library for various fuel types, represented by polynomial coefficients depending on burnup and Boron concentration), and the MCRAC code (global analysis of PWR core using a library of cross sections generated by PSU-LEOPARD/RBI).

Throughout the years all of these codes were constantly improved and modified, with the addition of new options and calculational modules, to reflect improvements and innovations in PWR technologies. NPP Krško uprate and modernization process which took place in the year 2000, required major modifications of the code package, finally resulting in the new version of the FUMACS code package developed in the year 2001, marked as FUMACS/FEEC 2001, and built for Windows platforms [4]. In that version the first graphical user interface (GUI) was introduced in the code package and marked as FUMACS-G [5]. In the year 2005, FUMACS/FEEC 2005 version was developed with new fully automated calculational module that enabled core modeling with different integral fuel burnable absorber loadings containing enriched Boron [6]. With this new feature, long-term planning and depletion modeling of extended operating cycles has been enabled. To make the FUMACS-G, i.e., GUI, as user friendly as possible, the initial FUMACS/FEEC 2005 code package was improved with implementation of new GUI automated procedures, at the end resulting in simplification of different user actions. To reflect Westinghouse innovations, discussed in previous section, and to prepare the code package for possible implementation of NGF fuel type as well as Gadolinium based burnable absorbers in standard NPP Krško operation, the third major modification of FUMACS code package took place in the year 2008 resulting in FUMACS-FEEC 2008 code package version [7]. Upgraded version of the FUMACS code package has been verified and validated on 3 NPP Krško preliminary designed cycles using standard and NGF fuel assemblies containing enriched Boron and Gadolinium. The main goal has been to show the acceptance of the upgraded FUMACS code package in preliminary analysis for global core calculation in order to reach the predefined quality assurance requirements. Verification and validation procedure has shown satisfying deviations of the estimates of key technical and safety parameters [8].

3 24-MONTH EQUILIBRIUM CYCLE WITH GADOLINIUM

The design of the Gadolinium based 24-month equilibrium cycle started with NPP Krško preliminary designed cycle using standard fuel assemblies containing Gadolinium – Cycle 25 B [2]. All together, three transient cycles have been analysed prior to reaching desired 24-month equilibrium cycle: cycle 26 as an 18-month cycle, and cycles 27 and 28 as 24-month cycles.

Targeted length of Cycle 29 was set to 25000 MWd/tU, resulting from the assumptions of 0.9 capacity factor and a 30 days outage period.

In the Cycle 29 (Gadolinium based 24-month equilibrium cycle) 4 different fuel assembly regions are used (29A, 29B, 30A, and 30B). There are 72 fresh fuel assemblies (FA) in a split-feed configuration from regions 30A and 30B with nominal fuel enrichment 4.750 w/o U-235 (region 30A) and 4.950 w/o U-235 (region 30B). In total 1312 Gadolinium rods, with different Gd contents are used. The details are provided in Table 1, where the type of absorber is represented by the number of rods containing Gadolinium and Gadolinium content.

Table 1 Types of Gadolinium burnable absorbers used in equilibrium cycle

Type	No. of FA from region 30 A (4.75 w/o U-235)	No. of FA from region 30 B (4.95 w/o U-235)
24 rods with 6% Gd	-	4
24 rods with 4% Gd	16	-
20 rods with 4% Gd	-	24
16 rods with 4% Gd	-	12
12 rods with 4% Gd	-	8
8 rods with 4% Gd	-	8
Total FA and Gd rods	16 / 384	56 / 928

The loading pattern for the equilibrium cycle and assemblywise power and burnup distribution for the end of the cycle (EOC) are given in Figure 1 and Figure 2, respectively.

Figure 1: Gadolinium based equilibrium cycle loading pattern

Gadolinium based equilibrium cycle stepwise power peaking factor ($F_{\Delta H}$) and critical Boron concentration are given in Table 2. Both, critical Boron concentration as well as power peaking factor, are within safety margins. Obtained cycle length was 24500 MWd/tU with capacity factor of 0.89, while the corresponding discharged burnup was 41158 MWd/tU.

1 29B GC30 0.938 0.963 55334.	2 30A GD01 1.146 1.184 29758.	3 29B GC29 1.000 1.032 50836.	4 30A GD02 1.180 1.222 31109.	5 29B GC21 1.024 1.057 50891.	6 30B GD21 1.106 1.283 25163.	7 29A GC01 0.530 0.784 40006.
8 30A GD03 1.146 1.184 29758.	9 29B GC23 0.989 1.021 50776.	10 30A GD04 1.167 1.227 31022.	11 29B GC26 1.050 1.097 49517.	12 30B GD22 1.228 1.297 31442.	13 30B GD23 1.078 1.285 24820.	14 29A GC04 0.487 0.806 40294.
15 29B GC32 1.000 1.032 50838.	16 30A GD05 1.166 1.227 31023.	17 29B GC34 1.025 1.076 52166.	18 30B GD24 1.249 1.293 33097.	19 30B GD25 1.216 1.315 30487.	20 30B GD26 0.972 1.294 21540.	
21 30A GD06 1.180 1.222 31109.	22 29B GC33 1.049 1.097 49519.	23 30B GD27 1.249 1.292 33097.	24 30B GD28 1.251 1.327 30679.	25 30B GD29 1.073 1.358 24346.	26 29B GC25 0.557 0.926 41570.	
27 29B GC35 1.024 1.056 50899.	28 30B GD30 1.228 1.297 31442.	29 30B GD31 1.216 1.315 30487	30 30B GD32 1.073 1.358 24346.	31 29B GC28 0.612 0.973 42900.		
32 30B GD33 1.105 1.282 25163.	33 30B GD34 1.078 1.285 24819.	34 30B GD35 0.972 1.293 21540.	35 29B GC31 0.557 0.926 41571.		Location Region FA ID Assembly Power Maximum Power Cumulated Burnup	
36 29A GC03 0.530 0.784 40008.	37 29A GC05 0.486 0.805 40296.					

Figure 2: Gadolinium based equilibrium cycle EOC assemblywise power and burnup distribution

Table 2 Stepwise power peaking factor ($F_{\Delta H}$) and critical Boron concentration for Gadolinium based equilibrium cycle

tep	B urnup	BC (ppm)	ΔH
	0	21	
	.	02.	.436
	1	15	
	50.	97.	.417
	1	15	
	000.	00.	.429
	2	16	
	000.	09.	.439
	4	17	
	000.	58.	.437
	6	18	
	000.	07.	.437
	8	17	
	000.	70.	.445
	1	16	
	0000.	63.	.450
	1	14	
	2000.	90.	.447
	1	10	
0	6000.	38.	.455
	2	53	

1	0000.	1.	.415
	2	-4.	
2	4500.		.358

4 COMPARISON OF GADOLINIUM AND BORON BASED CYCLES

In the previous section we have shown that Gadolinium based 24-month equilibrium cycle can be designed to satisfy safety requirements. In this section we compare Gadolinium and IFBA based 24-month equilibrium cycles.

For IFBA based equilibrium cycle we used identical fresh fuel split feed configuration as in Gadolinium case. Therefore, regions 30A and 30B with nominal fuel enrichment 4.750 w/o U-235 (region 30A) and 4.950 w/o U-235 (region 30B) were used. In total 7744 IFBAs containing enriched Boron were used (148 IFBA × 16 FA = 2368 IFBAs from region 30A; 48 IFBA × 8 FA + 64 IFBA × 8 FA + 92 IFBA × 12 FA + 116 IFBA × 24 FA + 148U IFBA × 4 FA = 5376 IFBAs from region 30B).

The loading pattern for the IFBA based equilibrium cycle and assemblywise power and burnup distribution for the end of the cycle are given in Figure 3 and Figure 4, respectively.

Figure 3: IFBA based equilibrium cycle loading pattern

IFBA based equilibrium cycle stepwise power peaking factor ($F_{\Delta H}$) and critical Boron concentration are given in Table 3. Both, critical Boron concentration, as well as power peaking factor, are within safety margins. Obtained cycle length was slightly over 24500 MWd/tU, with capacity factor of 0.89, while the corresponding discharged burnup was 41151 MWd/tU.

Loading pattern arrangement applicable for Gadolinium, as well as IFBA based equilibrium cycle is given in Figure 5.

Graphical representations of stepwise critical Boron concentration and power peaking factor for Gadolinium based equilibrium 24-month cycle compared to IFBA based equilibrium cycle are depicted on Figure 6 and Figure 7, respectively. There are slight differences between these two types of equilibrium cycles. Boron concentration for IFBA based cycle is slightly higher in the burnup interval ranging from 150 MWd/tU to 6000 MWd/tU, and slightly lower in the burnup interval ranging from 6000 MWd/tU to 20000 MWd/tU. Power peaking factor shows similar behaviour except that the intervals are moved towards higher values. These differences can be attributed to different characteristics of used burnable absorbers.

1 29B GC30 0.968 0.994 55218.	2 30A GD01 1.187 1.221 29650.	3 29B GC29 1.019 1.047 50882.	4 30A GD02 1.201 1.236 30943.	5 29B GC21 1.023 1.059 50753.	6 30B GD21 1.089 1.273 25090.	7 29A GC01 0.523 0.771 40001.
8 30A GD03 1.187 1.221 29650.	9 29B GC23 1.013 1.041 50622.	10 30A GD04 1.194 1.241 30901.	11 29B GC26 1.057 1.099 49317.	12 30B GD22 1.231 1.304 31319.	13 30B GD23 1.061 1.278 24743.	14 29A GC04 0.479 0.786 40190.
15 29B GC32 1.019 1.047 50885.	16 30A GD05 1.194 1.241 30902.	17 29B GC34 1.032 1.081 52109.	18 30B GD24 1.251 1.292 33244.	19 30B GD25 1.214 1.321 30431.	20 30B GD26 0.951 1.285 21424.	
21 30A GD06 1.201 1.236 30944.	22 29B GC33 1.056 1.099 49321.	23 30B GD27 1.251 1.292 33244.	24 30B GD28 1.243 1.322 31362.	25 30B GD29 1.058 1.360 24529.	26 29B GC25 0.546 0.912 41540.	
27 29B GC35 1.022 1.059 50761.	28 30B GD30 1.231 1.303 31318.	29 30B GD31 1.214 1.321 30430.	30 30B GD32 1.058 1.360 24528.	31 29B GC28 0.597 0.951 43622.		
32 30B GD33 1.089 1.272 25087.	33 30B GD34 1.061 1.278 24740.	34 30B GD35 0.951 1.285 21423.	35 29B GC31 0.546 0.911 41543.			
36 29A GC03 0.523 0.770 40000.	37 29A GC05 0.478 0.785 40246.					

Location Region	FA ID
Assembly Power	
Maximum Power	
Cumulated Burnup	

Figure 4: IFBA based equilibrium cycle EOC assemblywise power and burnup distribution

Table 3 Stepwise power peaking factor ($F_{\Delta H}$) and critical Boron concentration for IFBA based equilibrium cycle

tep	B urnup	BC (ppm)	ΔH
	0	20	
	.	63.	.431
	1	15	
	50.	92.	.414
	1	16	
	000.	97.	.433
	2	17	

	000.	91.	.438
	4	18	
	000.	75.	.448
	6	18	
	000.	48.	.457
	8	17	
	000.	40.	.459
	1	15	
	0000.	69.	.457
	1	13	
	2000.	66.	.446
	1	93	
0	6000.	1.	.412
	2	50	
1	0000.	5.	.385
	2	33.	
2	4500.		.360

The difference between discharge burnup for two types of cycles is negligible (41158 MWd/tU for Gadolinium based equilibrium cycle compared to 41151 MWd/tU for IFBA based equilibrium cycle).

IFBA based equilibrium 24-moth cycle can be slightly longer than Gadolinium based cycle. Although we compared discharge burnup for cycle length of 24500 MWd/tU it can be observed in Table 2 and Table 3 that EOC soluble Boron concentration (24500 MWd/tU) for Gadolinium based cycle is -4 ppm, while for the IFBA based cycle it is 33 ppm. That indicates that IFBA based cycle can be extended for a couple of hundreds of MWd/tU, which would also effect discharge burnup.

EOC position	BOC position
H-9	H-13
I-8	M-8
J-10	K-11
G-8	G-13
H-7	M-7
L-7	K-7
G-12	G-11
K-10	G-9
K-10	I-7
H-12	H-8
L-8	I-9
I-12	H-10
L-9	J-8
I-11	J-12
K-9	L-10
K-8	G-7

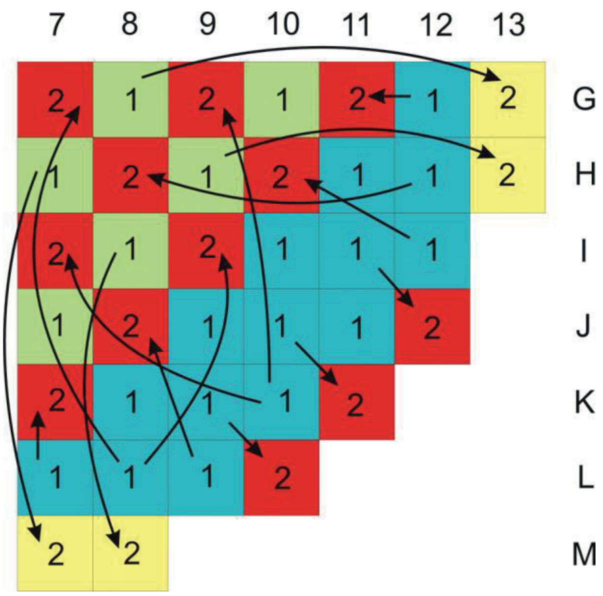

Figure 5: Equilibrium cycle loading pattern arrangement

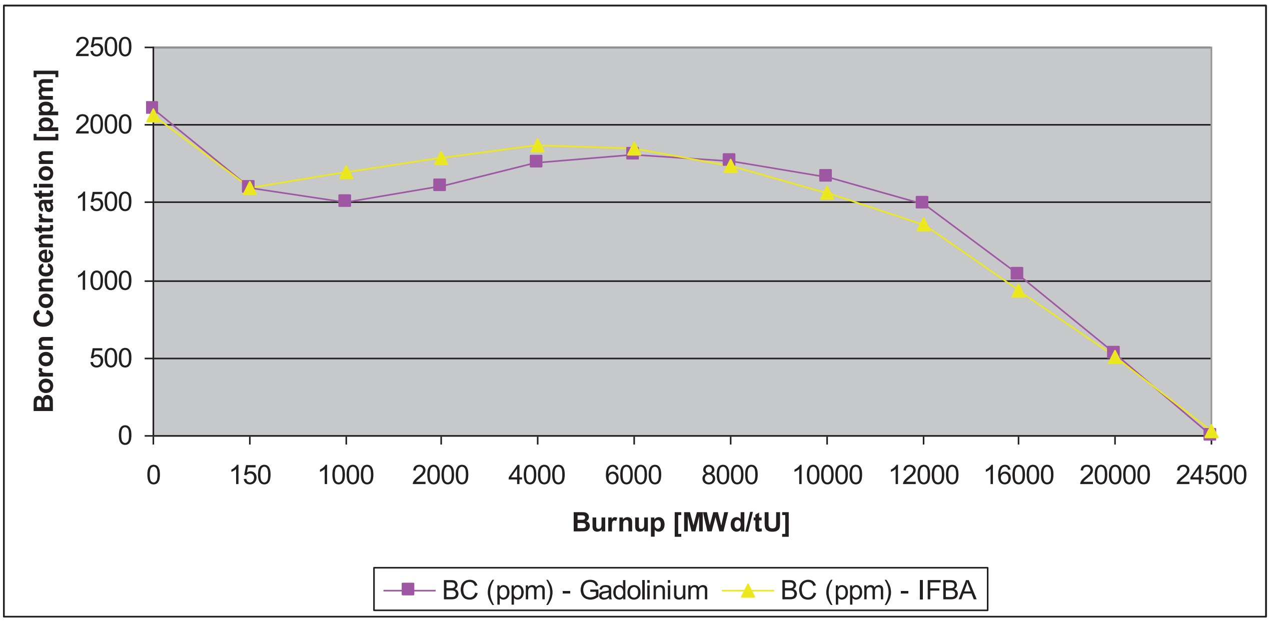

Figure 6: Stepwise critical Boron concentration for Gadolinium and IFBA based 24-month equilibrium cycles

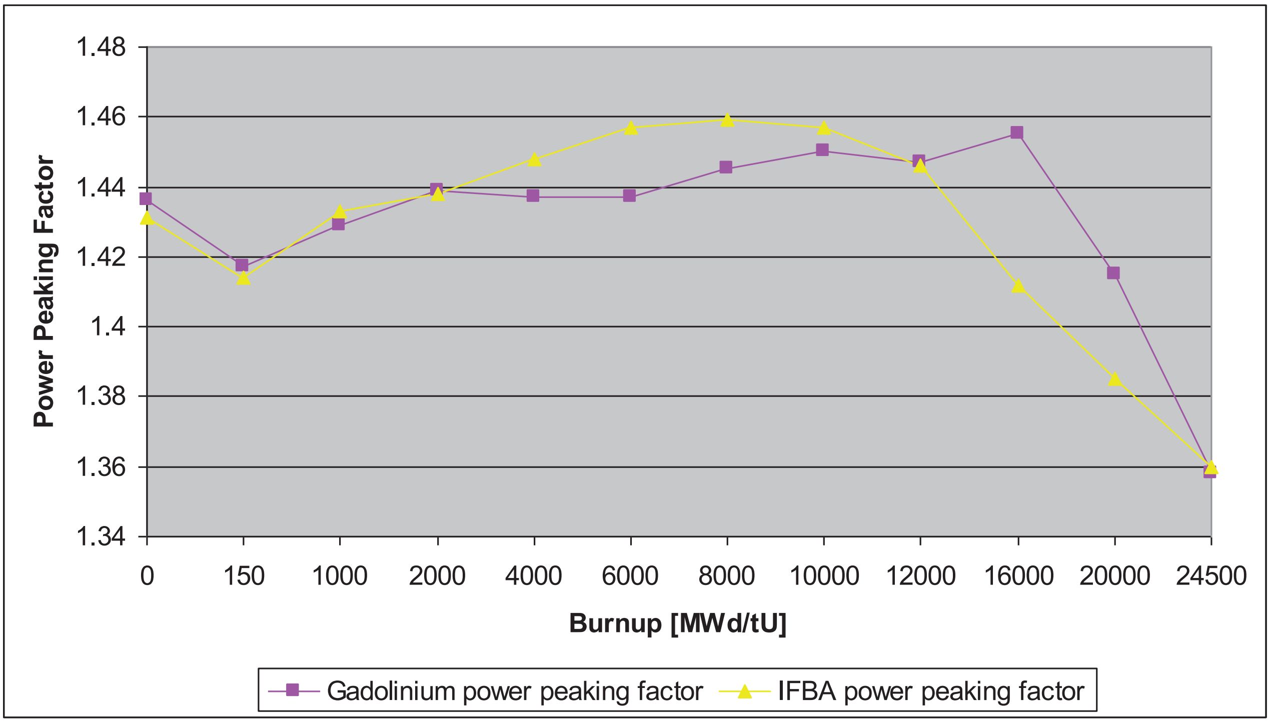

Figure 7: Stepwise power peaking factor for Gadolinium and IFBA based 24-month equilibrium cycles

5 CONCLUSION

In this paper we investigate the possibility to design 24-month equilibrium cycle for the NPP Krško with VANTAGE+ fuel type and Gadolinium based integral absorbers using FUMACS-FEEC 2008 code package. We showed that it is possible to design desired loading pattern and maintain safety parameters within prescribed limits. Obtained cycle length was 24500 MWd/tU with capacity factor of 0.89, while the corresponding discharged burnup was 41158 MWd/tU.