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Feasibility study of 24-month cycle using enriched Gadolinium as burnable poison for OPR1000

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1. Introduction

Reload core design and economic analyses show that nuclear power plants can derive significant benefits by increasing cycle length and discharge burnup of their fuel above the currently licensed value. However, optimum cycle length and discharge burnup levels may not be achievable without exceeding the current 5 wt% limit on enrichment [1]. A few utilities have various fuel cycle strategies from 12-month cycle to 24-month cycle to select optimum core cycle even if internal or external nuclear environments are changed. And it is necessary to technically prepare utility requirements document (URD) including core design of 24-month cycle to get the design certificate (DC) from NRC and export NPP abroad.

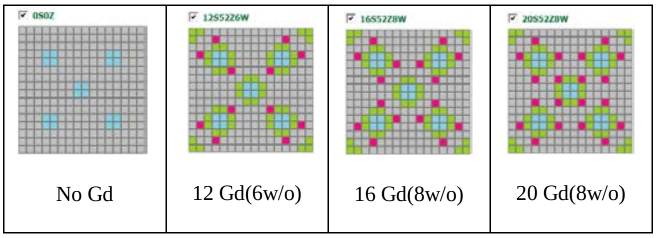
Extended cycle length is an effective means of reducing plant outage costs if improved capacity factor benefits can offset the increased fuel costs. In this study we analyzed a nuclear fuel design and core loading patterns for 24-month cycle under the constraint of a 5 wt% U-235 enrichment limit. Most PWR nuclear power plants operate for 18-month cycle including refueling outages in KHNP and OPR1000 reactor types were selected for this study.

To satisfy moderator temperature coefficient (MTC) limit of Technical Specification as well as extension of cycle length we used method of enriched Gadolinium. Also we studied two types of loading patterns using 92 and 101 fresh fuel assembly core respectively.

2. Core design and result of 24-month cycle

2.1 Characteristics of Gadolinium

The reactor core is composed of 177 fuel assemblies. Each fuel assembly consists of a 16X16 array of 236 fuel rod and 5 guide tubes [2].



No Gd | 12 Gd(6w/o) | 16 Gd(8w/o) | 20 Gd(8w/o)

Fig. 1 Burnable Poison Rod Arrangement

Gadolinium oxide, also known as Gadolinia (Gd_2O_3) is currently used as burnable poison for OPR1000. Seven Gadolinium isotopes naturally exist on earth. From these only two isotopes, the Gd-155 and Gd-157 have extremely high thermal neutron absorption cross sections.

Burnable poisons containing gadolinium have the undesirable effect of reducing the thermal conductivity of UO_2-Gd_2O_3 fuel and thus leading to higher temperature profiles in the fuel. In order to avoid such hot spots the currently available PWR rods use lower U-235 enrichment in all fuel pellets containing gadolinium. The use of gadolinium enriched in the most important isotopes, Gd-155 and Gd-157, to absorb neutrons, may permit to reduce the content of Gadolinia in the pellets and thus to improve the thermal conductivity of the fuel rods [3].

2.2 Current experience of 24-month cycle

Currently, 30 of 37 BWRs and only 7 of 69 PWRs operate with 24-month refueling intervals in US. Generally, PWRs have higher power density than BWRs and high power density leads to large batch size and high enrichment needs. And PWRs 24-month cycles may require more than 1/2 core load [4].

Table 1 Power density of PWRs and BWRs

Plant	Type	MWth	# of Ass'y	kW/kg
WH 17OFA	PWR	3,587	193	44.3
WH 17RFA	PWR	3,411	193	38.6
CE 16	PWR	3,438	217	36.2
CE 14	PWR	2,738	217	36.2
B&W 15	PWR	2,568	177	31.0
OPR1000	**PWR**	**2,815**	**177**	**36.9**
US BWR	**BWR**	**3,458**	**764**	**25.1**

2.3 Uranium and Gadolinium Enrichment

The upper U-235 enrichment design limit is 4.95 wt%, which accounts for 0.05 wt% fabrication tolerance. The enrichment of fuel assembly 52 zoning surrounding the guide tubes was designed in 4.45 wt% and the enrichment of fuel assembly axial blanket was designed in 3.2 wt% considering cycle energy requirements.

Table 2 Comparison of Uranium enrichment

	Uranium enrichment [wt%]	
	18-month cycle (New fuel : ~69 Ass'y)	24-month cycle (New fuel : ~101 Ass'y)
High enriched rod	4.65	4.95
Low enriched rod	4.1	4.45
Axial blanket	2.2	3.2

To meet moderator temperature coefficient (MTC) limit of Technical Specification we used enriched Gadolinium instead of natural Gadolinium.

Table 3 Isotopic content and cross section of Gadolinium

Isotope	Natural Gd	Enriched Gd	σ
Gd-152	0.2	0.2	1056
Gd-154	2.15	2.15	84.99
Gd-155	**14.73**	**20.0**	**60,889**
Gd-156	20.47	20.47	2.188
Gd-157	**15.68**	**30.0**	**25,4078**
Gd-158	24.87	5.28	2.496
Gd-160	21.9	21.9	0.7961
Sum	100	100	

Table 4 Comparison of Gadolinium enrichment

	Gadolinium enrichment [wt%]	
	18-month cycle (New fuel : ~69 Ass'y)	24-month cycle (New fuel : ~101 Ass'y)
Enrichment of Gadolinium	•Natural Gadolinium	•Enriched Gadolinium -Gd-155 : 20 wt% -Gd-157 : 30 wt%

2.4 Calculation Tools

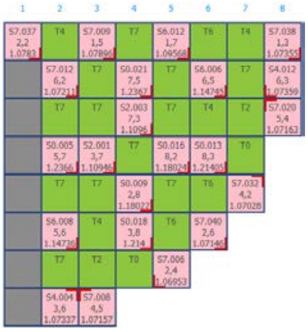
Two principal computer codes, PARAGON and ANC, was used in the nuclear design of 24-month cycle. PARAGON is a two-dimensional, multi-group transport theory code which utilizes a 70 energy-group cross-section library. ANC is an advanced nodal code capable of two-dimensional and three-dimensional calculations [2].

2.5 Loading patterns of 24-month cycle

The reload batch size depends on cycle length and U-235 enrichment of the fresh fuel assemblies. While an extended cycle will require a large batch size, this quantity can be reduced somewhat with higher enrichment. Therefore the batch size of the 24-month core can be roughly estimated considering of current 18-month cycle core [5].

2.5.1 Loading pattern 1(92 fresh fuel)

Low leakage loading pattern (L3P) is very effective method if we consider of neutron economy. If too many fresh fuel assemblies are adopted in the 24-month core, it is impossible to search for effective low leakage loading pattern. Therefore we searched for 24-month cycle with 92 fresh fuel assemblies.



	1	2	3	4	5	6	7	8
1	S7.037 2,2 1.0783	T4	S7.009 1,5 1.07896	T7	S6.012 1,7 1.09568	T6	T4	S7.038 1,3 1.07355
2		S7.012 6,2 1.07211	T7	S0.021 7,5 1.2367	T7	S6.006 6,5 1.14745	T7	S4.012 6,3 1.07359
3		T7	T7	S2.003 7,3 1.1096	T7	T4	T2	S7.020 5,4 1.07163
4		S0.005 5,7 1.2366	S2.001 3,7 1.10946	T7	S0.016 8,2 1.18024	S0.013 8,3 1.21405	T0	
5		T7	T7	S0.009 2,8 1.18022	T7	T6	S7.032 4,2 1.07028	
6		S6.008 5,6 1.14736	T4	S0.018 3,8 1.214	T6	S7.040 2,6 1.07146		
7		T7	T2	T0	S7.006 2,4 1.06953			
8		S4.004 3,6 1.07337	S7.008 4,5 1.07157					

Fig 2 Loading pattern 1 (92 fresh fuel)

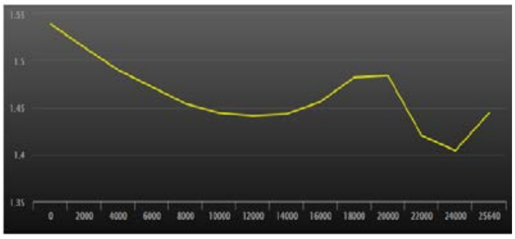


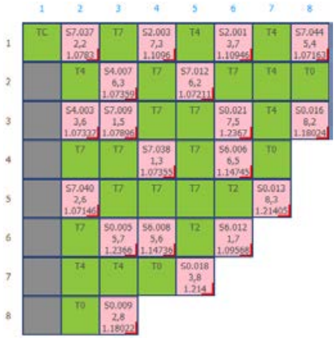
Fig. 3 Burnup vs. Fxy Trend (92 fresh fuel)

Table 5 Summary of loading pattern 1 (92 fresh fuel)

Parameters	Value	Design Limit
Cycle length (MWD/MTU)	25,640 (693 EFPD)	-
ppm (@BOC)	1,664	-
Max. Fxy	1.539	< 1.60
Max. Pin Burnup (MWD/MTU)	60,949	< 60,000 < 62,000(studying)
MTC(HZP, pcm/°C)	7.86	< 9
MTC(HFP, pcm/°C)	-64.8	> -68

2.5.2 Loading pattern 2 (101 fresh fuel)

It needs to be minimized moderator temperature coefficient conservatively at beginning of cycle by reducing critical boron concentration. For this purpose we increased new fuel assemblies and didn't follow a little the rule of low leakage loading pattern method. Finally, we searched for 24-month cycle with 101 fresh fuel assemblies.



	1	2	3	4	5	6	7	8
1	TC	S7.037 2,2 1.0783	T7	S2.003 7,3 1.1096	T4	S2.001 3,7 1.10946	T4	S7.044 5,4 1.07163
2		T4	S4.007 6,3 1.07359	T7	S7.012 6,2 1.07211	T7	T4	T0
3		S4.003 3,6 1.07337	S7.009 1,5 1.07896	T7	T7	S0.021 7,5 1.2367	T4	S0.016 8,2 1.18024
4		T7	T7	S7.038 1,3 1.07355	T7	S6.006 6,5 1.14745	T0	
5		S7.040 2,6 1.07146	T7	T7	T7	T2	S0.013 8,3 1.21405	
6		T7	S0.005 5,7 1.2366	S6.008 5,6 1.14736	T2	S6.012 1,7 1.09568		
7		T4	T4	T0	S0.018 3,8 1.214			
8		T0	S0.009 2,8 1.18022					

Fig. 4 Loading pattern 2 (101 fresh fuel)

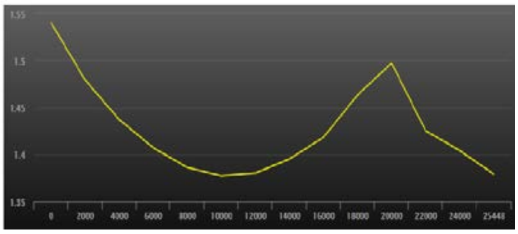


Fig. 5 Burnup vs. Fxy Trend (101 fresh fuel)

Table 6 Summary of loading pattern 2 (101 fresh fuel)

Parameters	Value	Design Limit
Cycle length (MWD/MTU)	25,448 (688 EFPD)	-
ppm (@BOC)	1,547	-
Max. Fxy	1.55	< 1.60
Max. Pin Burnup (MWD/MTU)	60,333	< 60,000 < 62,000(studying)
MTC(HZP, pcm/˚C)	3.941	< 9
MTC(HFP, pcm/˚C)	-63.9	> -68

3. Conclusions

The analysis of these preliminary loading patterns for 24-month cycles shows that it is possible to design the 24-month cycle cores for OPR1000. The burnup, power distribution, and power peaking factors generated with the preliminary loading patterns indicate that these parameters will not interrupt the design and operation of 24-month cycle.

Most PWRs operate with 18-month cycle because of more favorable economics and only a few of PWRs operate with 24-month refueling intervals. Achieving 24-month cycles in PWRs is still challenging because of higher power density than BWRs.

In addition, it should be necessarily reviewed changes in Technical Specification surveillance intervals to accommodate a 24-month fuel cycle [6].

The choice of optimum cycle length will depend on outage costs as well as the value of the additional energy produced by 24-month cycle. The costly enrichment process is still a disadvantage, but it might be reduced in the near future by applying a new laser technology.

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