PHYSOR 2004 – The Physics of Fuel Cycles and Advanced Nuclear Systems: Global Developments Chicago, Illinois, April 25-29, 2004, on CD-ROM, American Nuclear Society, Lagrange Park, IL. (2004)

Enriched Gadolinium as Burnable Absorber for PWR

Klaes-Håkan Bejmer*[1] and Ola Seveborn[2]

[1]Vattenfall Bränsle AB, S-162 87 Stockholm, Sweden

[2]Sernanders väg 5-518, S-752 61 Uppsala, Sweden

Abstract

This paper is a summary of a master of thesis work in reactor physics made by Ola Seveborn. The work was done at Vattenfall Bränsle AB and Ola was guided through the work by the corresponding author of this paper.

The results presented are calculations for Ringhals 3, which is a Westinhouse 3-loop PWR within the Vattenfall Group. The fuel is characterized by 17x17 assemblies of AFA type containing 3.80-3.95 w/o ^{235}U and 8 rods containing 2 w/o Gadolinium with an enrichment of 70 w/o ^{157}Gd. The calculations were performed with the Studsvik-Scandpower code package based on the CASMO-4 lattice code and the SIMULATE-3 nodal code.

The results are compared to the corresponding calculations for fuel with 5 w/o gadolinium with natural isotopic constitution. The depletion of the cores was done separately for the reference and enriched case.

The results show that the gains in average for the five cycles studied are about 70 EFPH per cycle. This is an effect of the lower gadolinium content needed. Also less parasitic absorption of enriched gadolinium in the end of the fuel life contributes to the increased cycle lengths. The abruptly increased reactivity and internal power peaking factor around 10 MWd/kgU do not affect the core design negatively.

1. Introduction

Gadolinium contains seven isotopes, only ^{155}Gd and ^{157}Gd are useful due to their very high absorption cross sections, Table1. The other isotopes, which constitute 70% of the total amount, have small cross sections and are primarily responsible for the undesirable small absorption in the end of the fuel life. In order to decrease this parasitic absorption in the end and emphasize the absorption in beginning of the life it is possible to use Gadolinium enriched in ^{155}Gd or ^{157}Gd. [1-7]

Already in 1986 Hassan, Hove and Spetz discussed the advantages of enriched gadolinium.[1] In another paper Helmersson and Keith conclude that fuel with enriched ^{157}Gd decreases the parasitic absorption of neutrons by more than a factor of three. [1-2] Furthermore they claim that fuel with enriched ^{157}Gd need less than half the gadolinium content and consequently the fuel will contain more enriched uranium and hence the thermal characteristics of the fuel can be improved.

The benefits of the reactivity and power peaking factor control of the core stands against the enrichment costs of gadolinium. Traditionally, isotope separation has

* Corresponding author, Tel. +46 8 73 90 312, Fax: +46 8 17 86 40, E-mail: klaes-hakan.bejmer@vattenfall.com

been performed through the techniques of gaseous diffusion and gas centrifuge. However in the past decade also the laser technique has been used in the separation process. This new technique might decrease the separation costs and make enriched gadolinium for nuclear reactor fuel very interesting.

Table 1. *Isotopic content and cross sections of gadolinium. [8-9]*

Isotope	Natural Gd	Enriched Gd, 70 w/o ^{157}Gd	$\sigma_{n,\gamma}$ (barn)
152	0,20	0,071	1 056
153	0,00	0,00	-
154	2,15	0,747	84,99
155	14,73	5,160	60 889
156	20,47	7,219	2,188
157	15,68	70,00	254 078
158	24,87	8,883	2,496
159	0,00	0,00	-
160	21,90	7,920	0,7961
Summa	100,00	100,00	

This paper presents results of calculations for PWR fuel with 70 w/o ^{157}Gd with isotopic content shown in Table 1. In the first part of the results figures of the neutron multiplication factor and the internal power peaking factor are shown and discussed. In the second part, the core radial power peaking factor and cycle length are given for 5 different cycles.

2. Characteristics of the Analyzed Fuel

The calculations are done for 17x17 fuel assemblies of AFA-type with 3,80-3,95 w/o ^{235}U supplied by Framatome/ANP. Fuel rod data, enrichment and density of the burnable absorber (BA) for assemblies loaded in the analyzed cycles are presented in Table 2. The BA assemblies contain 8 BA rods. The BA rods with identity Y contain no BA in the end zones (30 cm in top and bottom). For clarity, except for the enrichment of ^{157}Gd, only the BA density is different from the reference fuel.

The assemblies are designed for Ringhals 3, which is a Westinghouse 3-loop PWR, owned and operated by Ringhals AB, a company within the Vattenfall Group.

Fuel lattice and core calculations are performed with the Studsvik-Scandpowers code package, based on the CASMO-4 lattice code and the SIMULATE-3 nodal code. The package has been routinely used for PWR in-core fuel management work at Vattenfall since the late eighties.

Table 2. *Fuel rod data of 17x17 assemblies loaded in analyzed cycles.*

Identity	BA density, ref. case (w/o Gd_2O_3)	BA density, 70 w/o ^{157}Gd (w/o Gd_2O_3)	^{235}U enrichm. (no BA) (w/o UO_2)	^{235}U enrichm. (BA rods) (w/o UO_2)
U	5,0	2,0	3,80	0,22
V, W, X	5,0	2,0	3,80	2,50
Y	6,0	2,5	3,95	2,50

3. Analyzed Cores

The reference case is the operated fuel core sequences for the period 1999-2004 (cycle 17-21). The depletion of the cores for the period was done separately for the reference and the enriched case. The fuel with enriched gadolinium together with old standard fuel were depleted in accordance with the operation of cycle 17, and for cycle 18 the core was redesigned with a new batch of enriched gadolinium fuel and depleted, and again redesigned and depleted for in total five cycles. Due to different loading patterns and depletion characteristics of the fuel, different full power cycle lengths were obtained for the reference and enriched cases. This effect was corrected for by different coast down period lengths. Thus the total energy produced in each cycle is the same.

4. Results of k_∞ and the Peaking Factor (F_{int})

Tables 3-4 present the reactivity of fuel assemblies with 0-5 w/o gadolinium densities at zero and 35 MWd/kgU depletion points. The reactivity for fuel with natural gadolinium isotopes decreases at both zero and 35 MWd/kgU, see Table3. The reactivity differences between BA fuel and fuel without BA at 35 MWd/kgU are –759 to -780 pcm.

For enriched gadolinium, Table 4, the reactivity at zero depletion also decreases, however at 35 MWd/kgU the reactivity instead increases for 0-5 w/o gadolinium. The reactivity difference between BA fuel and fuel without BA at 35 MWd/kgU is here –721 to -586 pcm.

Table 3. *The effect of natural gadolinium on the reactivity.*

Gd-density (w/o)	k_∞ at 0 MWd/kgU	k_∞ at 35 MWd/kgU	$\Delta k_\infty \left(= k_\infty - k_\infty^{BA-fr}\right)$ at 35 MWd/kgU (pcm)
0,0	1,28126	0,96636	0
1,0	1,21137	0,95877	-759
2,0	1,202	0,95867	-769
3,0	1,1966	0,95861	-775
4,0	1,19271	0,95858	-778
5,0	1,18961	0,95856	-780

Table 4. *The effect of 70 w/o ^{157}Gd on the reactivity.*

Gd density (w/o)	k_∞ at 0 MWd/kgU	k_∞ at 35 MWd/kgU	$\Delta k_\infty \left(= k_\infty - k_\infty^{BA-fr}\right)$ at 35 MWd/kgU (pcm)
0,0	1,28126	0,96636	0
1,0	1,19679	0,95915	-721
2,0	1,18925	0,95943	-693
3,0	1,18475	0,95974	-662
4,0	1,18145	0,9601	-626
5,0	1,17874	0,9605	-586

Figure1 shows k_∞ as a function of depletion for 1-5 w/o gadolinium and 70 w/o ^{157}Gd. The curves are compared to fuel without Gd and with natural Gd of 5 w/o. The curve with 2 w/o Gd is close to the reference case except around depletion 10 MWd/kgU where the deviation is nearly 800 pcm, see Figure 2.

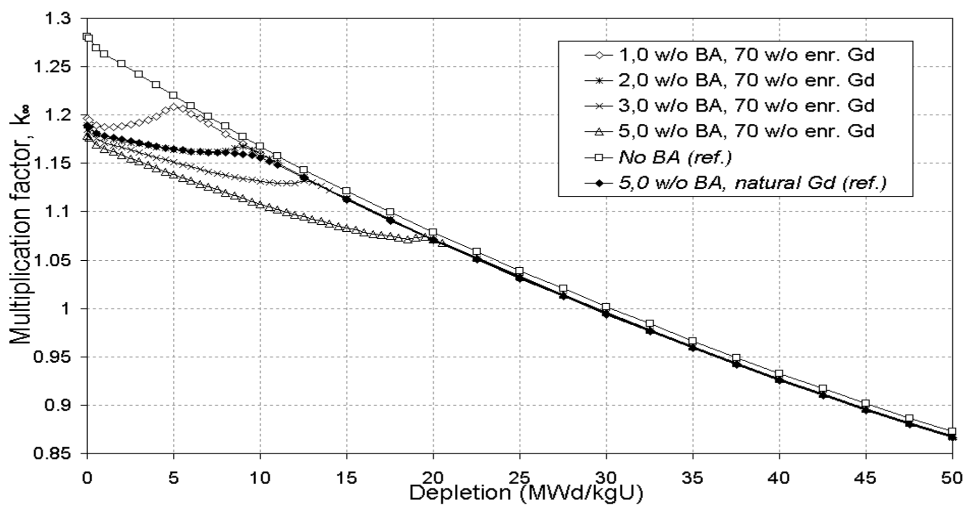

Figure 1. *The effect of 70 w/o ^{157}Gd on the neutron multiplication factor.*

Figure 3 shows the internal power peaking factor for different Gd densities. The significant peaks, appearing at higher depletions for higher Gd densities, are an effect of the Gd depletion. The peaks of the enriched cases are more significant compared to the reference peak, and especially the peak of the 2 w/o Gd curve has about 4% higher maximum value and appears slightly before the peak of the reference curve.

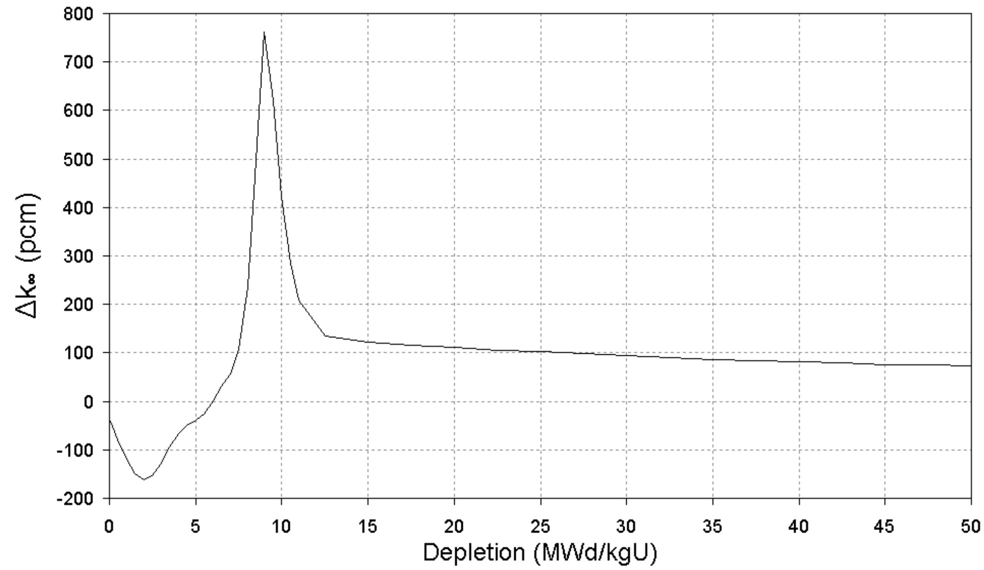

Figure 2. *Reactivity difference between fuel with 70 w/o ^{157}Gd of 2 w/o Gd and fuel with natural Gd of 5 w/o.*

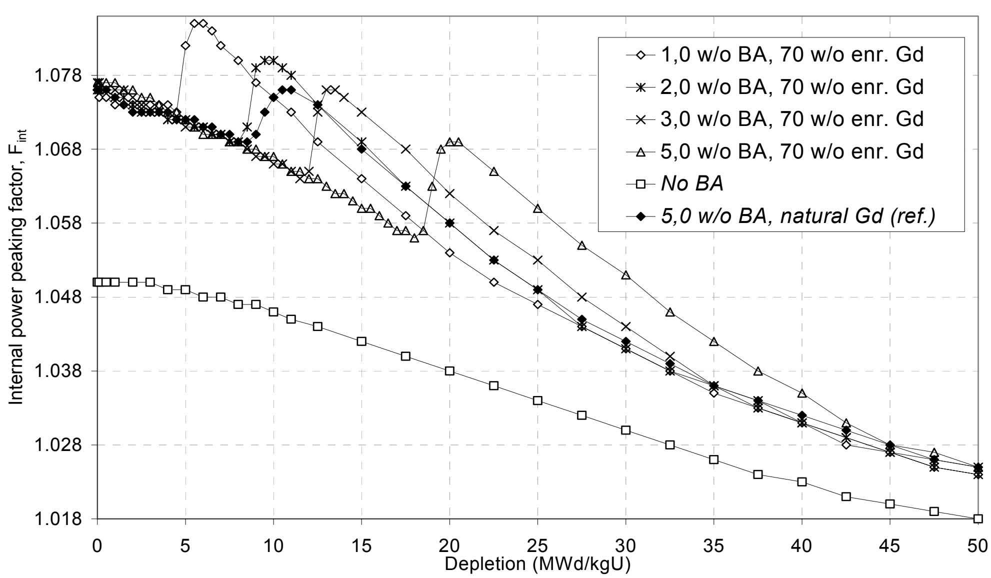

Figure 3. *The internal power peaking factor for fuel with 70 w/o ^{157}Gd at different Gd densities.*

5. Results on Core Level

In Figure 4 the core radial power peaking factor, $F_{\Delta H}$, is presented for cycle 17. The line with the square symbols represents the real core operated in 1999-2000. In the enriched Gd case, 16 assemblies with natural gadolinium of 5 w/o are replaced by 16 assemblies with 70 w/o ^{157}Gd of 2 w/o density. The core is completely redesigned and the results show that $F_{\Delta H}$ is above the reference curve and slightly touch the limit in the beginning of the core cycle, but is below the reference curve rest of the cycle.

The optimization of the five cycles (17-21) was done with focus on full power cycle lengths (EOFP). For cycle 17 the core with the reference fuel reached 9.139 MWd/kgU and the core with enriched Gd fuel 9.294 MWd/kgU, which means 1.6% better fuel utilization with enriched Gd fuel.

The results show that the EOFP length is longer than the original, as operated, cycle length for all the five cycles. However, for cycle 20, Figure 5, the difference in EOFP length is below 0.2%.

The result, show that $F_{\Delta H}$ has the same character for all analyzed cycles as in Figure 4. However, for cycles 20 and 21 $F_{\Delta H}$ for the enriched Gd case is above the reference case line.

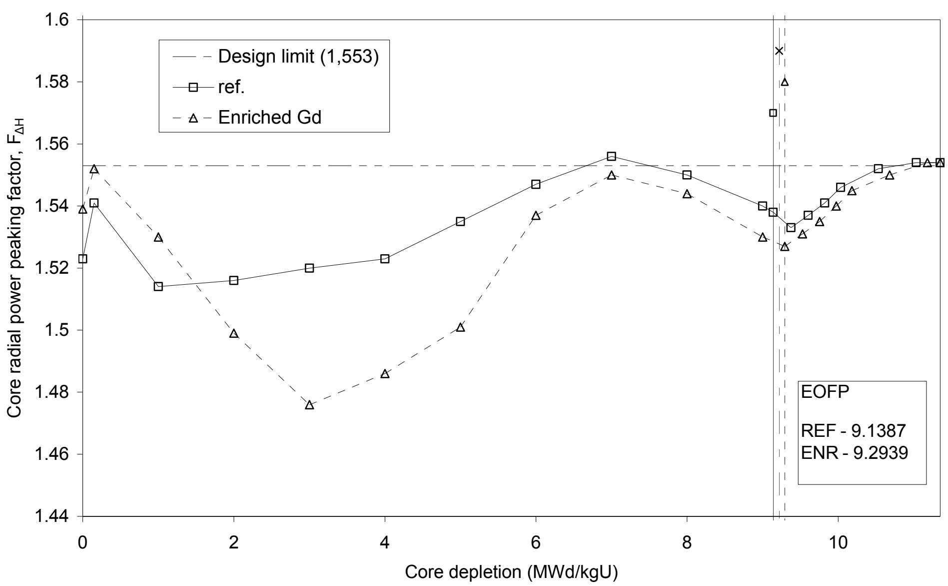

Figure 4. *The core radial power peaking factor for cycle 17. "ref" stands for the core containing fuel with natural gadolinium of 5 w/o. "Enriched Gd" is the core containing fuel with 70 w/o ^{157}Gd of 2 w/o.*

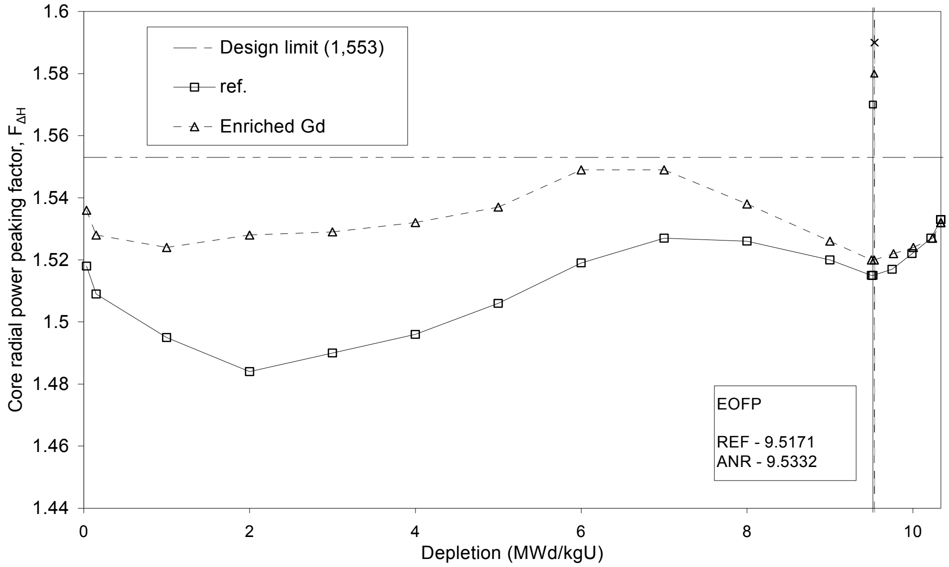

Figure 5. *The core radial power peaking factor for cycle 20. "ref" stands for the core containing fuel with natural gadolinium of 5 w/o. "Enriched Gd" is the core containing fuel with 70 w/o ^{157}Gd of 2 w/o.*

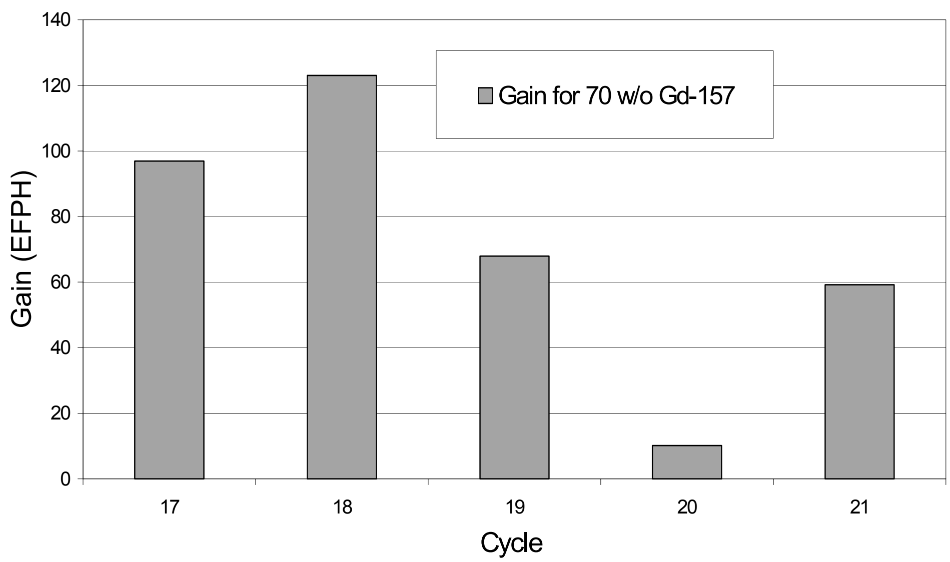

Figure 6. *Gain in full power cycle length (EOFP). The gain is defined as the difference between EOFP lengths for the core with enriched gadolinium fuel and core with fuel of natural gadolinium.*

6. Discussions

In order to discuss the results of the study it can be convenient to raise some questions in this matter.

Does it make sense to enrich certain gadolinium isotopes ?

We show in the paper that there is a gain in fuel efficiency if we use Gd enriched in ^{157}Gd as BA. However, it is also seen from Figure 2 and 3 at about 10 MWd/kgU the enriched Gd case has a large reactivity peak and a significant internal power peaking factor, which are effects from the abrupt depletion of the enriched Gd. In order to smooth the internal power peaking factors of the gadolinium fuel one could also enrich both ^{155}Gd and ^{157}Gd. [5] However, the improved neutron economy must be put against the enrichment costs of gadolinium.

Is the "degree" of optimization the same for all the redesigned cores as compared to the real operated ones ?

It is difficult to answer because it is not the same person who has designed the reference cores and the enriched ones. The original operated cores were designed by people with more than 5-6 year experiences and probably with more focus on the optimization, while the cores with enriched fuel was designed by a student doing his thesis work. Therefore the "degree" of optimization is probably somewhat higher for the original operated cores.

What might be the explanation behind the positive results for the enriched cases?

The improved neutron economy comes from the fact that the gadolinium will be more efficiently used, smaller amount of low absorbing isotopes will be left over in the gadolinium fuel. Moreover, a much lower density of gadolinium can be used, which improves the thermal characteristics of the BA rods. Thus improving the heat conduction properties of the BA rods may also allow a higher enrichment of ^{235}U in these rods than assumed in Table 2. This could lead to a further increase in fuel efficiency, however, this design change was not studied here.

7. Conclusions

The following advantages for enriched gadolinium fuel compared to fuel of natural gadolinium are observed:

- At 35 MWd/kgU, the reactivity for natural gadolinium decreases while for enriched fuel of 70 w/o ^{157}Gd it increases for 1 to 5 w/o Gd.
- The 70 w/o ^{157}Gd of 2 w/o Gd fit rather well to both the reactivity and the power peaking factor of natural Gd of 5 w/o.
- Enriched gadolinium is more effective as burnable absorber because less than half of the gadolinium density need to be used.
- Gain of about 70 EFPH per cycle compared to the reference cycles is observed and is the result of the improved neutron economy of the cores.

However, the costly enrichment process is still a disadvantage, but it might be reduced in the near future by applying a new laser technology.

Acknowledgements
The author expresses his great thanks to Prof. Tomas Lefvert and Ewa Kurcyuz for their assistance in preparation of this paper.

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