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PWR FUEL OF HIGH ENRICHMENT WITH ERBIA AND ENRICHED GADOLINIA

Klaes-Håkan Bejmer[*] **and Christian Malm**
Vattenfall Nuclear Fuel AB
S-162 87 Stockholm, Sweden
klaes-hakan.bejmer@vattenfall.com; christian.malm@vattenfall.com

ABSTRACT

Today standard PWR fuel is licensed for operation up to 65-70 MWd/kgU, which in most cases corresponds to an enrichment of more than 5 w/o ^{235}U. Due to criticality safety reason of storage and transportation, only fuel up to 5 w/o ^{235}U enrichment is so far used. New fuel storage installations and transportation casks are necessary investments before the reactivity level of the fresh fuel can be significantly increased. These investments and corresponding licensing work takes time, and in the meantime a solution that requires burnable poisons in all pellets of the fresh high-enriched fuel might be used. By using very small amounts of burnable absorber in every pellet the initial reactivity can be reduced to today´s levels. This study presents core calculations with fuel assemblies enriched to almost 6 w/o ^{235}U mixed with a small amount of erbia. Some of the assemblies also contain gadolinia. The results are compared to a reference case containing assemblies with 4.95 w/o ^{235}U without erbia, utilizing only gadolinia as burnable poison. The comparison shows that the number of fresh fuel assemblies can be reduced by 21% (which increases the batch burnup by 24%) by utilizing the erbia fuel concept. However, increased cost of uranium due to higher enrichment is not fully compensated for by the cost gain due to the reduction of the number assemblies. Hence, the fuel cycle cost becomes slightly higher for the high enrichment erbia case than for the reference case.

Key Words: PWR, High Enrichment, Erbia, Gadolinia.

1. INTRODUCTION

Over the past years, the average enrichment levels used in the Swedish nuclear power plants have slowly increased in order to improve the fuel economy. For the PWRs the fuel cycle cost analyses indicate that the optimal average enrichment is above 5 w/o ^{235}U. However, there are issues worth to analyze before significant enrichment increase may be implemented.

Firstly, we know that the number of spent fuel assemblies will be reduced when increasing the discharge burnup for each fuel assembly. But, does a significant increase of the uranium enrichment also give a positive fuel economy outcome, especially taking into account the Swedish conditions with annual cycle lengths and back end costs independent of the number of disposed fuel assemblies? Furthermore, it is also necessary to analyze how the high-enriched fuel affects the in-core fuel management scheme. Is it possible to retain both good safety margins and good neutron economy?

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[*] Also employed by; Division of Applied Nuclear Physics, Department of Physics and Astronomy, Uppsala University, SE-751 20 Uppsala, Sweden

Secondly, a lot of licensing work and investments in new fuel storage installation and transportations casks are necessary before the reactivity level of the fresh fuel may be increased significantly above the levels corresponding to 5 w/o ^{235}U. This work takes time, meanwhile a solution that utilizes burnable poisons (BA) in all pellets of the fresh high-enriched fuel might be used. By having a very small amount of BA in every pellet of the fuel, the initial reactivity can be reduced to the same levels as today.

This study presents core design calculations for Ringhals Unit 3, which is a Westinghouse 3-loop PWR owned by Ringhals AB, a company within the Vattenfall group**.** In the study the cores are loaded with 17x17 fuel assemblies enriched to almost 6 w/o ^{235}U mixed with erbia in all pellets. In order to keep annual cycle lengths with regard to safety limits the fuel must be combined with assemblies also containing gadolinia. The gadolinia in these assemblies is enriched to 70 w/o ^{157}Gd. The results from this case, named ERSHB, are compared with two other cases with uranium enrichment below 5 w/o and without erbia, REF (reference case) with natural gadolinia and axial blankets, and ENGD with enriched gadolinia and axial blankets. The ENGD case was presented in 2006 [1] and will therefore not be discussed more in this paper.

It can be noticed that ERSHB contains no axial blankets. It is known that fuel with low enriched end zones improves the fuel economy, however the gain is very small and so far Vattenfall thus has not introduced axial blankets in the fuel [2].

The study was performed utilizing Studsvik Scandpower Core Management System based on 2D lattice code CASMO-4 and 3D nodal core simulator SIMULATE-3.

At least three other studies concerning fuel with enrichments above 5 w/o ^{235}U, [3-5], addresses the same subject. In [3], N. Sugimura et al used erbia in all pellets in order to reduce the reactivity in the super high burnup fuel. It was concluded that for 18.5 EFPM (effective full power month) cycle length the number of feed fuel assemblies could be reduced by approximately 20% with this concept.

In section 2 the characteristics of erbia and gadolinia is discussed. In section 3 the operating parameters, core design parameters, core management scheme, fuel design segments and the calculation software are presented. The results, section 4, contain reactivity comparisons, cycle length, power peaking factors, isothermal temperature coefficient, fuel assembly statistics, batch exposure data and fuel saving comparison. Discussions and conclusions are presented in section 5 and 6. Finally, acronyms which are not explained in the text are listed and explained in Appendix.

2. CHARACTERISTICS OF ERBIA AND GADOLINIA

Gadolinia is a strong absorber in the neutron thermal region. This means that a small amount of gadolinia causes a large reactivity decrease in the very beginning of the fuel life, but as a result of the fast burnup the effect of the absorber is small later in its fuel life. Erbia is a weaker absorber in the neutron thermal region, hence the reactivity decreases less than for gadolinia. However on the other hand it keeps the reactivity low longer. Furthermore it has a significant resonance peak around 1 eV, which helps to keep the temperature coefficient (ITC) negative in the beginning of the core operation cycle.

Gadolinia contains seven isotopes, only ^{155}Gd and ^{157}Gd are useful due to theirs very high absorption cross section. The other isotopes, which constitute 70% of the total amount, have small cross sections and are primarily responsible for the small but undesirable absorption during the last part of the fuel life. In order to decrease this parasitic absorption and emphasize the absorption in the beginning of the life it is possible to use gadolinia enriched in ^{155}Gd or ^{157}Gd. In [1] K-H Bejmer shows that by using enriched gadolinia (70% of ^{157}Gd) less than half the gadolinia is needed and consequently these BA rods are allowed to contain more enriched uranium.

To simulate alternative compositions of gadolinia and erbia isotopes in CASMO it is necessary to specify the relative weight number (weight fraction or weight percent) of each isotopes of the fuel, [6]. It is worth mentioning that the component weight percents for the different burnable absorbers are slightly different depending on from which source they come. The data used here, Tab.1, are taken from [7] for gadolinia and from [3] for erbia. They differ from the default component weight percents used by CASMO but the impact of the differences on the results is small.

Table 1. Weight percents for different isotopes of the BA [7 and 3]

Isotope	Natural Gd and Er	Enriched Gd 70 w/o ^{157}Gd
Gd-152	0.20	0.07
153	0	0
154	2.15	0.77
155	14.73	5.24
156	20.47	7.28
157	15.68	70.00
158	24.87	8.85
159	0	0
160	21.90	7.79
Sum	100.00	100.00
Er-162	0.14	
164	1.61	
166	33.60	
167	22.95	
168	26.80	
170	14.90	
Sum	100.00	

3. METHOD

3.1 Core Management

In order to simulate a realistic operation for the Vattenfall PWRs the cycle lengths are varied between 9 and 15 months [1]. The simulation is done for Ringhals 3 with the operating and design data presented in Tab.2 below. The cycle lengths are chosen to cover different limiting variations and cycle-to-cycle transitions. A cycle sequence typical for the Swedish PWRs, 9-12-15-12-15-12 (months), is used, Tab.3. The coast down lengths are added to cover total cycle lengths from 7 400 to 10 900 EFPH (Effective Full Power Hours).

Table 2. Operating parameters. $F_{\Delta H,}$ design limit = 1.75/(1.04*1.03)=1,63

Core Thermal Power, MWt	3152
ITC BOC HZP, pcm/^{o}C	<0
$F_{\Delta H}$, operating limit	<1.75
F_Q operating limit	<2.50

The calculation starts at cycle 1 (true cycle 31) of Ringhals 3, and follows by 4 more transition cycles with fresh fuel of higher and higher enrichment (in small steps up to 4.95 w/o) without erbia and enriched gadolinia. For cycle 6 the core with the depleted fuel was ready for the three cases, REF, ENGD and ERSHB, with each case separately depleted in accordance to the operation data. For cycle 7 the core was redesigned with a new batch of ERSHB fuel and depleted, and again redesigned and depleted for in total 10 cycles. The same procedure was done for REF and ENGD cases.

In the transition cycles the enrichment level of the fresh fuel increases from today's 4,30 w/o up to 4,70 w/o ^{235}U. In these cycles the fuel has neither axial blankets, nor enriched gadolinia nor erbia. The transition cycles are followed by ten cycles with 4,95 w/o ^{235}U for REF and ENGD and 5,94 w/o ^{235}U for ERSHB.

The enrichment levels of the transition cycles are designed to fit the reactivity curve of the fuel representing REF and ENGD. For the higher enrichment level of ERSHB the step from 4,70 to 5,94 w/o ^{235}U is very high, which means that it was difficult to keep the power peaking factors below acceptable values the first cycle, however after 2-3 cycles this high enrichment step did not affect the peaking values, and it became easier to design the cores.

Table 3. Cycle lengths specifications. The number in parenthesis is the true cycle number. The first 5 cycles represent transition cycles with REF fuel only.

Cycle number	Cycle length to EOFP	Coast down length
1 (cycle 32)	8 400	500
2	6 400	0
3	10 400	500
4	8 400	1000
5	10 400	0
6	6 400	1000
7	8 400	100
8	10 400	500
9	8 400	500
10	10 400	100
11(cycle 42)	8 400	500
12	6 400	1000
13	8 400	500
14	10 400	500
15 (cycle 46)	8 400	500

3.2 Fuel Design

The calculations were performed for 17x17 fuel assemblies of HTP design supplied by AREVA. Fuel enrichments and gadolinia designs are presented in Tab. 4 and Fig.1. In order to use similar loading patterns for all three cases (ENGD, ERSHB and REF) designs with 0,2 w/o Er_2O_3 in all pellets for ERSHB were chosen. Enriched gadolinia for the gadolinia assemblies of both ERSHB and ENGD was used. A gadolinia enrichment level of 70 w/o ^{157}Gd was chosen, which is realistic level of production.

In order to compensate for the decrease in heat conductivity compared to pellets without gadolinia, the uranium enrichment of the gadolinia pellets is normally reduced. Therefore, the average assembly enrichment varies slightly due to the gadolinia density and the number of gadolinia pins used for the fuel in each specific cycle.

3.3 Calculation code package

Fuel lattice and core calculations are performed with the Studsvik-Scandpowers code package, based on 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.

- CASMO-4 version 2.05.06_MROD neutron library e4lb170, [6]
- CMSLINK ver. 1.19.16 and SIMULATE-3 ver. 5.08.08_VAT_6, [8-9]

4. RESULTS

4.1 Fuel Reactivity

Figure 2 shows the infinite multiplication factor (k_{inf}) for the 6 different fuel segments with and without burnable absorbers, described in Fig.1 and Tab.4. The burnable absorption content is chosen to match the reactivity of the fuel segments for ENGD and ERSHB to the reactivity of the reference fuel, REF. Due to the absorption of neutrons, but also the fact that these BA segments have reduced enrichment levels the reactivity of segment FS-5 (ERSHB) is lower than the reactivity of FS-1 (REF) from BOL to 5 MWd/kgU. For higher burnup levels FS-5 declines above FS-1's because of FS-5's higher enrichment level. Notice how well the k-infinity curve for FS-6 and FS-4 match FS-5 and FS-1 respectively when most of the gadolinia has been depleted. It is also worth mentioning that the reactivity of the high enrichment fuel segment, i.e."600", without erbia and gadolinia is flatter than the reactivity of FS-1.

Table 4. Uranium enrichments, gadolinia, erbia and stack pellet column density for the different axial zones defined in Fig. 1 below.

Segment	Enrichment (^{235}U), w/o UO_2	Natural w/o Gd_2O_3	Natural w/o Er_2O_3	Enrichment (^{157}Gd) w/o Gd_2O_3	Density g/cm^3
FS-1	4.95				10.38
FS-2	2.60				10.38
FS-3	3.47	6.00 (8-20 fuel pins)			10.15
FS-4	4.33			2.50 (8-20 fuel pins)	10.28
FS-5	5.94		0.20 (all pellets)		10.37
FS-6	5.19		0.20 (all pellets)	2.50 (8 fuel pins)	10.28

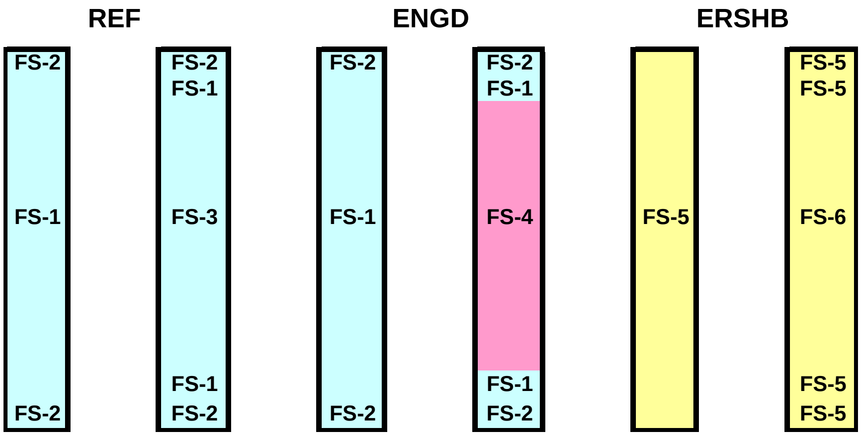


Figure 1. Axial zones of different fuel pin enrichment for the three cases. The fuel pins for each case represent the Gd-free pin(left) and the Gd pin(right).

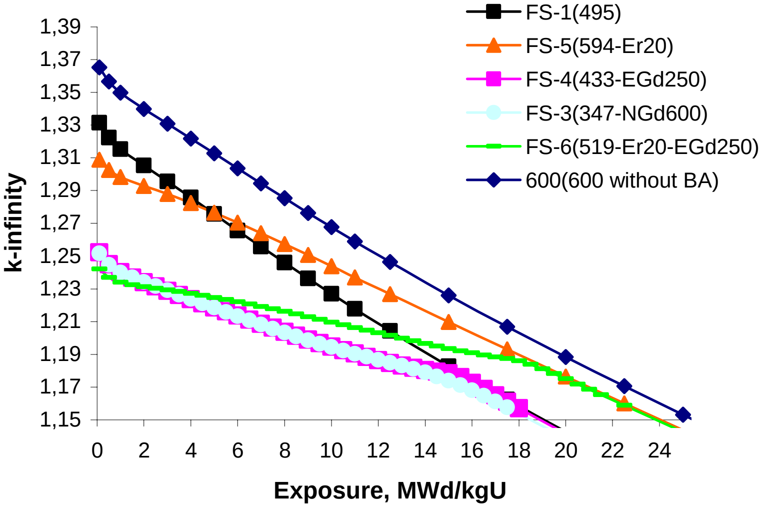


Figure 2. "FS-1" and "600" contain no burnable absorber. "FS-6" contains both erbia and enriched gadolinia. The uranium enrichment and BA content is presented in parenthesis above, see also Fig.1 and Tab.4. FS-3 match FS-4 very well.

4.2 Core Design

4.2.1 Cycle Length

Although the method itself implies that the cycle length for the three cases should be identical, there are small deviations because of the difficulties to exactly match the cycle lengths, Tab.5. The integrated cycle length of the ten cycles is, however, almost identical for the three cases.

4.2.2 Power Peaking Factor

The design limit 1.63 of the pin power peaking factor $F_{\Delta H}$ is violated twice for ENGD and ERSHB cases, see Tab.5. In cycle 6 $F_{\Delta H}$ for ERSHB is significantly violated. This is the first cycle loaded with the erbia fuel design and it is known to be very difficult to design a low leakage loading pattern with fresh assemblies that have such a large enrichment increase compared to the batch enrichment the cycle before.

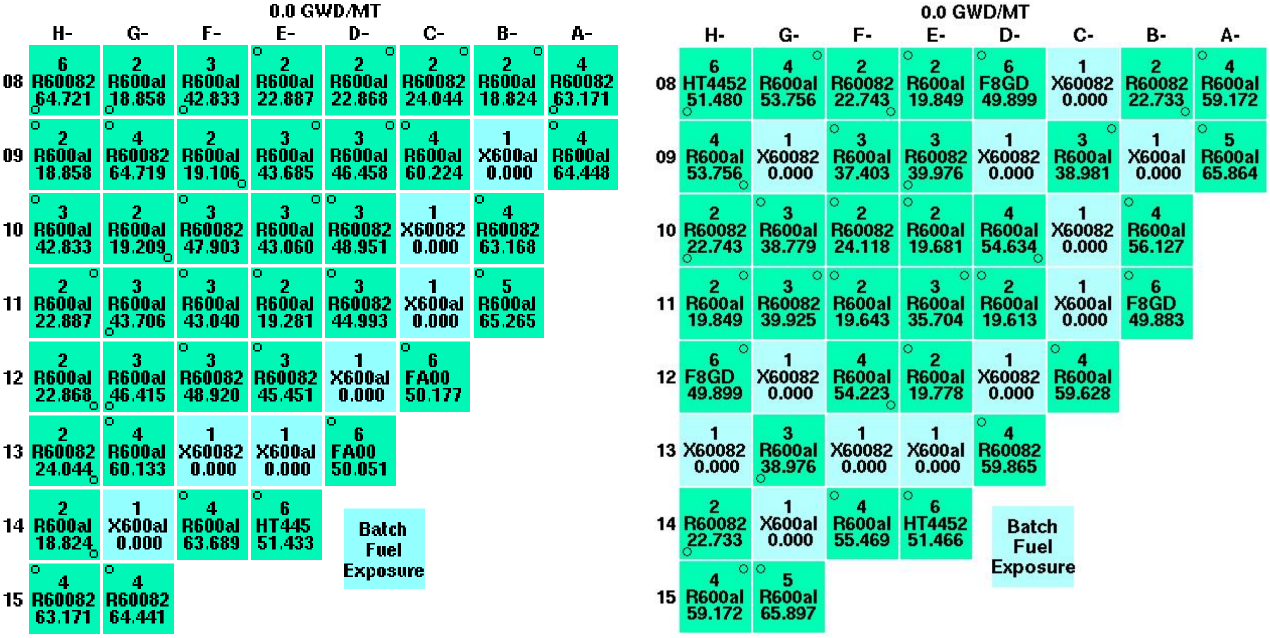
The average margin to the $F_{\Delta H}$ limit of 1.63 for the three cases is 0.6 % for ERSHB, 1.1% for REF and 1.8 % for ENGD. The ITC margin is larger for ERSHB compared to ENGD and REF. It should be noted that in all pellets of ERSHB there is a small amount of erbia, which worsen the heat conductivity and hence slightly decreases the F_Q margin. However, it is of less importance in these cases due to the large margin ($F_Q < 2.5$) for this parameter.

Table 5. Summary of the core design characteristics. "Av.BAT.Exp" means discharge exposure for fuel assemblies batch first loaded in cycle "i".

Cycle	Cycle Length			max F_{DH}			max F_{Q}			ITC at BOC		
	REF	ENGD	ERSHB	REF	ENGD	ERSHB	REF	ENGD	ERSHB	REF	ENGD	ERSHB
C6	6393	6412	6493	1.572	1.572	1.675	1.978	1.979	1.979	-7.6	-7.6	-10.8
C7	8307	8352	8444	1.630	1.634	1.620	2.126	2.129	1.924	-0.7	-0.7	-9.3
C8	10226	10422	10341	1.609	1.582	1.632	1.957	1.934	1.981	-0.6	-0.3	-4.6
C9	8081	8312	8454	1.626	1.616	1.629	2.088	2.079	1.917	-3.1	-2.3	-9.0
C10	10481	10458	10407	1.606	1.602	1.611	2.028	2.029	2.000	-0.1	-0.9	-2.8
C11	8918	8808	8578	1.628	1.565	1.607	2.069	1.993	1.921	-0.5	-0.6	-6.3
C12	6331	6316	6669	1.624	1.594	1.614	2.039	1.996	1.931	-9.7	-10.4	-14.9
C13	8275	8212	8485	1.624	1.631	1.604	2.094	2.112	1.913	-1.3	-1.4	-8.7
C14	10828	10865	10322	1.593	1.588	1.599	1.987	2.002	1.943	-0.2	-0.4	-5.0
C15	8634	8619	8282	1.606	1.618	1.61	2.022	2.056	1.919	-0.2	-0.4	-8.3
Tot.	86474	86776	86475									

Cycle	Total number FA			Number FA with Gad			Enrichment FA/FABA			Av.Bat.Exp.MWd/kgU		
	REF	ENGD	ERSHB	REF	ENGD	ERSHB	REF	ENGD	ERSHB	REF	ENGD	ERSHB
C6	32	32	28	8	8	12	4.75/4.71	4.75/4.73	5.94/5.92	55.08	55.13	67.57
C7	44	44	40	12	12	20	/4.71	/4.73		57.22	57.44	69.71
C8	52	52	40	44	44	20	/4.68	/4.72		55.34	57.01	67.81
C9	44	44	36	20	20	20	4.71	/4.73		56.10	55.96	69.74
C10	60	60	44	40	40	16	/4.67	/4.72		56.08	56.61	70.06
C11	44	40	32	24	16	4	/4.69	/4.73		54.37	57.00	69.05
C12	32	32	28	12	12	8	/4.71	/4.73				71.13
C13	44	44	36	20	20	16	/4.71	/4.73				69.56
C14	60	60	44	40	40	28	/4.66	/4.71				69.86
C15	44	40	32	24	24	12	/4.71	/4.73				
Tot.	456	448	360	244	236	156						

The amount of work put into the core design was approximately equal for the three cases. Except the first core design for ERSHB, the cores with a short operating cycle length were more difficult to design than the long ones. All of the cores have successfully applied low leakage loading patterns, which means that the least reactive fuel was placed in the periphery of the core. Two typical loading patterns, one for a short cycle 12 and one for a long cycle 14, are presented in Fig.3.



0.0 GWD/MT

	H-	G-	F-	E-	D-	C-	B-	A-
08	6 R60082 64.721	2 R600al 18.858	3 R600al 42.833	2 R600al 22.887	2 R600al 22.868	2 R60082 24.044	2 R600al 18.824	4 R60082 63.171
09	2 R600al 18.858	4 R60082 64.719	2 R600al 19.106	3 R600al 43.685	3 R600al 46.458	4 R600al 60.224	1 X600al 0.000	4 R600al 64.448
10	3 R600al 42.833	2 R600al 19.209	3 R60082 47.903	3 R600al 43.060	3 R60082 48.951	1 X60082 0.000	4 R60082 63.168	
11	2 R600al 22.887	3 R600al 43.706	3 R600al 43.040	2 R600al 19.281	3 R60082 44.993	1 X600al 0.000	5 R600al 65.265	
12	2 R600al 22.868	3 R600al 46.415	3 R60082 48.920	3 R60082 45.451	1 X600al 0.000	6 FA00 50.177		
13	2 R60082 24.044	4 R600al 60.133	1 X60082 0.000	1 X600al 0.000	6 FA00 50.051			
14	2 R600al 18.824	1 X600al 0.000	4 R600al 63.689	6 HT445 51.433				
15	4 R60082 63.171	4 R60082 64.441						

Batch
Fuel
Exposure

0.0 GWD/MT

	H-	G-	F-	E-	D-	C-	B-	A-
08	6 HT4452 51.480	4 R600al 53.756	2 R60082 22.743	2 R600al 19.849	6 F8GD 49.899	1 X60082 0.000	2 R60082 22.733	4 R600al 59.172
09	4 R600al 53.756	1 X60082 0.000	3 R600al 37.403	3 R60082 39.976	1 X60082 0.000	3 R600al 38.981	1 X600al 0.000	5 R600al 65.864
10	2 R60082 22.743	3 R600al 38.779	2 R60082 24.118	2 R600al 19.681	4 R600al 54.634	1 X60082 0.000	4 R600al 56.127	
11	2 R600al 19.849	3 R60082 39.925	2 R600al 19.643	3 R600al 35.704	2 R600al 19.613	1 X600al 0.000	6 F8GD 49.883	
12	6 F8GD 49.899	1 X60082 0.000	4 R600al 54.223	2 R600al 19.778	1 X60082 0.000	4 R600al 59.628		
13	1 X60082 0.000	3 R600al 38.976	1 X60082 0.000	1 X600al 0.000	4 R60082 59.865			
14	2 R60082 22.733	1 X600al 0.000	4 R600al 55.469	6 HT4452 51.466				
15	4 R600al 59.172	5 R600al 65.897						

Batch
Fuel
Exposure

Figure 3. Loading pattern for cycle 12 (left, 6669 EFPH) and cycle 14(right, 10322 EFPH). The least reactive fuel assemblies are put in the periphery (LLLP). The light grey colour represents fresh fuel assemblies.

4.3 Fuel Statistics

In Tab.5 the number of fresh fuel assemblies, number of BA assemblies, enrichments of the fresh fuel and its average batch discharge exposure are presented for different cycles. It can be noticed that REF use 456 assemblies in total for the 10 cycles while ERSHB use 360 only, which is a reduction of 21% compared to REF. This is an effect of the higher enrichment for ERSHB. The average batch exposure for ERSHB is 24% higher than for REF.

The number of assemblies containing gadolinia is less for ERSHB than for the other two cases. The reduction here is more than 34%. This is a consequence of the presence of erbia in every pellets of the fuel. Furthermore, in order to get a negative ITC, 8-20 fuel pins containing gadolinia were necessary for REF and ENGD, while ERSHB only required 8 fuel pins per assembly with gadolinia, see also the node statistics in Appendix.

4.4 Fuel saving comparison

The Fuel Cycle Cost (FCC) for the different cases can be described by the formulas;

$$FCC(e) = FC_u(e) / (E_{bu}(e)*\eta*24)\text{..........}(1)$$

$$FC_u(e) = C_{feed}*F(e) + C_{swu}*S(e) + C_{mfg} + (C_{be})\text{..........}(2)$$

where;
FCC(e) Fuel Cycle Cost in units of SEK/MWh$_e$,
FC$_u$(e) is the total cost per kgU,
E$_{bu}$(e) is the average discharge burnup, MWd/kgU,
η is the efficiency between thermal and electrical power (~35%),
C$_{feed}$ is the feed uranium cost, SEK per kgU (C$_{feed}$ = C$_{nat}$ + C$_{conv}$),
C$_{swu}$ is the enrichment cost, SEK per separative work unit (SWU),
C$_{mfg}$ is the manufacturing cost, SEK/kgU,
C$_{be}$ is the back-end cost, SEK/kgU,
F(e) is the feed uranium factor and finally
S(e) is the SWU factor.

Both FC$_u$(e) and E$_{bu}$(e) in Eq. 1 increase with the enrichment (e), F is almost linear with e while S increases more and more (nonlinear) with e. The other factors in Eq. 2 are here constant.

By calculating FC$_u$, using data for each case, a relative comparison with REF can be done, which is presented in Tab.6 below.

Looking at E$_{bu}$, for fuel inserted in the first six cycles, Tab.5, it can be noticed that the burnup increases as much as 24 % for ERSHB in comparison to REF

As mentioned above, FC$_u$, the specific fuel cost per kgU, increases even more, 27%, with current prices for the cost parameters. This explains partly the results for the FCC in Tab.6, where there is a 2% cost increase for ERSHB in comparison to REF.

4.4.1 Back end costs included

In the calculations above the back end costs, C$_{be}$, were excluded. In Sweden there is a fee proportional to the electricity generated from nuclear power that is supposed to cover all back end costs. There is no direct dependency of the fee on burnup and the amount of fuel for final storage. In reality there may be a dependency, as the amount of fuel will decrease with increased burnup. This might in turn affect the final cost in the long term, as the number of disposal canisters will decrease.

To study how the influence of this burnup dependency of the back end costs would affect the relative cost between the cases, a sensitivity study was performed, where a constant value of C$_{be}$ was applied. C$_{be}$ was calculated by dividing the cost for a final storage canister by the amount of fuel, kgU, per canister. Thus, a variable cost for the back end in SEK/kgU was obtained excluding the fixed costs such as for constructing the final storage facilities, overhead etc. Using this hypothetical model the incitement of higher burnup would be stronger and consequently ERSHB would obviously be more competitive.

However, when the burnup is increased as much as 24 % the residual power of the fuel assemblies increases. This would have to be taken into consideration when loading the canisters for final storage. Each canister is designed for maximum 1.7 kW in residual power. To cope with this limitation, going to higher burnup, the number of fuel assemblies loaded in the canisters may have to be reduced. This would in turn also affect the back end costs, as the number of canisters would not decrease as much as in the previous case.

To obtain a burnup dependant $C_{be(bu)}$, as a rough estimation C_{be} was multiplied by the factor 1.24 for ERSHB (corresponding to the increase of E_{bu}) while no change in C_{be} was applied for the other two cases. The cost was thus assumed to increase proportionally to the burnup, Tab.6.
As shown in the Tab.6, the conclusion is now once again, that there is no benefit for ERSHB.

4.4.2 Consideration to a discounted interest cost of the fuel

Increasing the enrichment for ERSHB is an investment. Discounting the fuel costs and the revenues in form of energy to the same point in time one can calculate the discounted FCC. A real interest rate of 6% was applied in this investment calculus.

The results, Tab.6, show that accounting for the interest costs makes the ERSHB case still less profitable with respect to FCC.

Table 6. Relative FCC without back end cost, with constant back end, with back end depending on burnup and finally FCC with a discounted interest and no back end cost.

Case	E_{bu} [%]	FCC [%]	FCC, C_{be} (%)	FCC, $C_{be(bu)}$ (%)	FCC interest(%)
REF	REF	REF	REF	REF	REF
ENGD	1.4	-0.9	1,0	-1,0	-0.8
ERSHB	24.3	2.1	0.3	2,0	4.7

5. DISCUSSIONS

The reactivity levels calculated by CASMO, Fig.2, indicate that it might not be necessary to install new fuel racks and transport facilities in order to license the facilities for the higher uranium enrichment. Other calculations applied to Ringhals 3 fuel pool verify that fuel assemblies without Gd, in REF and ERSHB cases, have almost identical reactivity level. However, the current acceptable reactivity criteria for the Ringhals 3 pool does not even accept fuel of 4.95 w/o uranium enrichment. But with a very small amount of erbia (0.1 w/o) in all pellets for REF fulfills the today reactivity criteria level.

The fact that the absorption cross section for thermal neutrons is much smaller for erbia than gadolinia means that ERSHB must use approximately 33% more BA in total than REF, see Appendix . Firstly, this fact slightly decreases the fuel reactivity due to undesirable small absorption in the end of the fuel life. Secondly, it makes the neutron spectrum during the whole cycle slightly harder, which increases the conversion ratio. This effect, however, is small but might partly compensate the reactivity loss due to the extra BA.

The next item, that may need an explanation, is that despite the fact that the ERSHB results show a reduction of the number fuel assemblies of approximately 20%, the analysis shows no profit. The reason is that due to the enrichment increase the feed and SWU factors, Eq.2, increase more than 30%. The manufacturing cost reduction (-20%) and the increased discharged burnup (24%) do not fully compensate for the cost increase for feed and SWU.

However, if the back end cost C_{be} (last parameter in Eq.2), would be higher, the increase of the feed and SWU costs would at some point be fully compensated for, and ERSHB would then be profitable. The back end costs in Sweden are handled as a fee proportional to the electricity generated from nuclear power and consequently do not encourage reactor operation with higher enriched fuel. Not even taking the hypothetical burnup dependent back end model used above into account will fully compensate for the increase of the costs for enriched uranium.

The situation is different in e.g. Germany, where to our knowledge, the utilities pay a fixed fee per fuel assembly to cover *all* back end costs, in contrast to our hypothetical model. This gives a stronger incitement for going to higher burnup and explains the difference in economically optimal enrichment/burnup as compared to Sweden. This fact also explains why the back end costs in Germany are almost 3 times higher than the fictional figures used in this study for Swedish circumstances. In the model assumed here, one part is largely independent of the amount of disposal material and the other varies with it.

If we instead apply the German model to this study we find that the relative FCC is reduced by 2% for the scenario with constant back end costs. This means that in this case ERSHB would be profitable.

Also, if the price of enriched uranium (F and S) were less than half of the current market price assumed in this study, ERSHB would be profitable.

6. CONCLUSIONS

By using a small amount of erbia (0.2 w/o) in all pellets of uranium fuel enriched to 6 w/o ^{235}U, the reactivity of the fuel in its first part of its life is reduced to a level below the reactivity of erbia free fuel with an enrichment of 5 w/o. The results, Fig.2, indicate that the erbia concentration can even be lower. Nevertheless, the maximal reactivity of the 6 w/o enriched fuel is lower than the reactivity of the standard fuel. This indicates that erbia is an excellent reactivity suppressor.

The fact that the absorption cross section of erbia has a resonance around 1 eV makes even a small amount of erbia effective in order to keep the isothermal temperature coefficient (ITC) below zero. As a consequence the ERSHB case has large ITC margin and contains less gadolinia pins as compared to REF and ENGD.

The total amount of fresh fuel assemblies used for 10 cycles is reduced by 21% by using 6 w/o enriched fuel compared to 5 w/o enriched fuel. The batch exposure is increased by 24% in average with 6 w/o enriched fuel.

For the studied cycles, the assumed operational data and the Swedish back end model it is not profitable to increase the uranium enrichment to 6 w/o ^{235}U. However, with a different back end model or large changes in the price of enriched uranium, ERSHB may be competitive.

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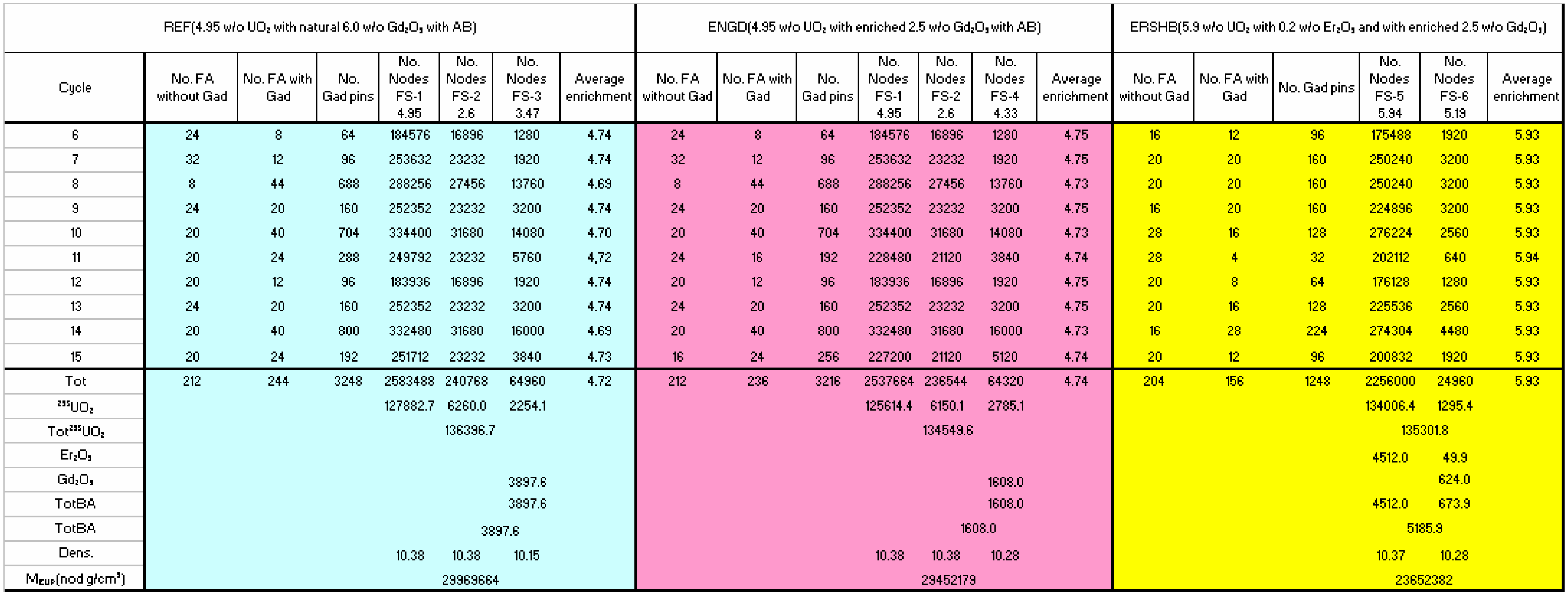
APPENDIX

ACRONYMS

ERSHB – Erbium super high burnup case , REF – Reference case, ENGD – Enriched gadolinia case, ITC – Isothermal temperature coefficient, BOC – Beginning of reactor cycle, HZP – Hot zero power condition, $F_{\Delta H}$ – 2D power peaking factor, F_Q – 3D power peaking factor, EOFP – End of full power, FA – Fuel assembly, BAT – Fuel batch, EFPH – Effective full power hours

FUEL STATISTICS

Fuel statistics; Using ERSHB the number of fuel assemblies are reduced by 21%. The mass of $^{235}UO_2$ is almost the same for the three cases. ERSHB uses 33% more BA than REF, but only 17% of the amount of gadolinia used by REF. "nds" is number of nodes.



	REF(4.95 w/o UO_2 with natural 6.0 w/o Gd_2O_3 with AB)							ENGD(4.95 w/o UO_2 with enriched 2.5 w/o Gd_2O_3 with AB)							ERSHB(5.9 w/o UO_2 with 0.2 w/o Er_2O_3 and with enriched 2.5 w/o Gd_2O_3)					
Cycle	No. FA without Gad	No. FA with Gad	No. Gad pins	No. Nodes FS-1 4.95	No. Nodes FS-2 2.6	No. Nodes FS-3 3.47	Average enrichment	No. FA without Gad	No. FA with Gad	No. Gad pins	No. Nodes FS-1 4.95	No. Nodes FS-2 2.6	No. Nodes FS-4 4.33	Average enrichment	No. FA without Gad	No. FA with Gad	No. Gad pins	No. Nodes FS-5 5.94	No. Nodes FS-6 5.19	Average enrichment
6	24	8	64	184576	16896	1280	4.74	24	8	64	184576	16896	1280	4.75	16	12	96	175488	1920	5.93
7	32	12	96	253632	23232	1920	4.74	32	12	96	253632	23232	1920	4.75	20	20	160	250240	3200	5.93
8	8	44	688	288256	27456	13760	4.69	8	44	688	288256	27456	13760	4.73	20	20	160	250240	3200	5.93
9	24	20	160	252352	23232	3200	4.74	24	20	160	252352	23232	3200	4.75	16	20	160	224896	3200	5.93
10	20	40	704	334400	31680	14080	4.70	20	40	704	334400	31680	14080	4.73	28	16	128	276224	2560	5.93
11	20	24	288	249792	23232	5760	4,72	24	16	192	228480	21120	3840	4.74	28	4	32	202112	640	5.94
12	20	12	96	183936	16896	1920	4.74	20	12	96	183936	16896	1920	4.75	20	8	64	176128	1280	5.93
13	24	20	160	252352	23232	3200	4.74	24	20	160	252352	23232	3200	4.75	20	16	128	225536	2560	5.93
14	20	40	800	332480	31680	16000	4.69	20	40	800	332480	31680	16000	4.73	16	28	224	274304	4480	5.93
15	20	24	192	251712	23232	3840	4.73	16	24	256	227200	21120	5120	4.74	20	12	96	200832	1920	5.93
Tot	212	244	3248	2583488	240768	64960	4.72	212	236	3216	2537664	236544	64320	4.74	204	156	1248	2256000	24960	5.93
$^{235}UO_2$				127882.7	6260.0	2254.1					125614.4	6150.1	2785.1					134006.4	1295.4	
Tot$^{235}UO_2$					136396.7							134549.6						135301.8		
Er_2O_3																		4512.0	49.9	
Gd_2O_3						3897.6							1608.0						624.0	
TotBA						3897.6							1608.0					4512.0	673.9	
TotBA					3897.6							1608.0						5185.9		
Dens.				10.38	10.38	10.15					10.38	10.38	10.28					10.37	10.28	
M_{EUR}(nod g/cm^3)					29969664							29452179						23652382		