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MULTICYCLE LOADING PATTERN SEARCHES FOR END-OF-LIFE SCENARIOS WITH ROSA

H.P.M. Gibcus[1], F.C.M. Verhagen[1], J.T. van Bloois[2]
1. NRG
P.O. Box 9034, 6800 ES Arnhem, The Netherlands;
2. N.V. EPZ
P.O. Box 130,4380 AC Vlissingen, The Netherlands;
E-mail: gibcus@nrg.eu

Abstract: The Borssele PWR in The Netherlands plans to close down by the end of 2033 after 60 years of operation. A study searching for the optimum loading patterns covering the last four years of operation (2030-2033) is carried out. This search resulted in four different End-of-Life scenarios all starting at the same calculated equilibrium cycle in 2030. All scenarios meet the requirements of the operator, both standard safety-related as well as the End-of-Life specific ones. The first scenario is a continuation of the equilibrium cycle and is used as a reference. The other three demonstrate optimized loading patterns that differ in number of feeds, enrichment of feeds, natural cyclelength, coast, and stretch-in strategy. In every scenario the major shortcoming of the previous scenario is dealt with. With respect to the total costs scenario 4 appears to be the most promising with a saving of 1 M€ compared the reference scenario even when the Back End costs of 4 extra feeds in the reference scenario is not taken into account.

Keywords: ROSA, multicycle loading pattern, loading pattern optimization, EOL scenarios, core design, fuel management

1. INTRODUCTION

The Borssele PWR (KCB) in The Netherlands plans to close down by the end of 2033 after 60 years of operation. This paper presents a study searching for the optimum loading patterns covering the last four years of operation (2030-2033). The main reason for this study was to find scenario's that enable transport of all used assemblies from the site as soon as possible after closure of the plant and to determine the optimum type of transportation cask suited for this job.

2. ROSA CODE SYSTEM

ROSA, NRG's loading pattern optimization code system for PWRs, is used to find the loading patterns for different End-of-Life (EOL) scenario's that meet all the constraints of the operator and are also economically attractive.

The ROSA code system (Verhagen, 2003, Wakker, 2005) has been developed at NRG for PWR core design and utilizes Simulated Annealing as optimization technique in combination with a very fast and accurate 3-D core simulator code. With this code millions of loading patterns can be evaluated on a workstation or PC in a day including cycle depletion. The code can be switched between manual and automatic mode. In addition to single cycle also equilibrium cycle optimization is possible. Apart from using previous cycle burnup, also the impact of short or long previous cycle burnup (the burnup window) can be evaluated. For all these burnup states the impact of the Rod Insertion Limit (RIL) can also be evaluated.

A powerful graphical user interface (GUI) allows the user to interact with the optimization process by changing optimization targets during the run or perform manual movements. The GUI of ROSA is shown in Figure 1.

The code starts by evaluating an initially provided loading pattern. In automatic mode loading patterns candidates ae generated by randomly exchanging fuel assemblies, rotating burned fuel assemblies, and/or changing the composition of fresh fuel assemblies by changing the enrichment and/or poison loading.

Next, the generated loading pattern is checked against flexible user-defined rules, needed to apply logistic constraints (e.g. position lock the central assembly) and/or a a-priori knowledge (e.g. no feed fuel on the core periphery).

When a loading pattern satisfies the user defined rules, neutronics calculations are performed in quarter core geometry with rotational boundary conditions and typically 12-18 axial nodes. A 1½ group 3-D coarse mesh kernel method, coupled with a 2-D fine mesh method (3x3 or 4x4 nodes per assembly) is used. Two pinpower reconstruction methods are available: pin by pin or 8x8 per assembly. About 10 or 20 burnup steps per cycle are normally used. Typical accuracy compared to license code results is within ±0.02 for normalized assembly powers, ±0.03 for maximum FdH, and ±2 days for natural cycle length. Typical full cycle evaluation takes 10 to 100 ms CPU time per loading pattern on a 3.2 GHz PC with Cygwin, depending on core-size, axial mesh, pinpower reconstruction, number of burnup steps, selected parameters, and the previously evaluated loading pattern. About 60 parameters can be optimized simultaneously, amongst others: peaking factors, natural cycle length, burnup limits, economics/fuel costs, shutdown margin, MTC, burnups, octant symmetry, quadrant tilt, and CIPS- and PCI-criteria.

Acceptance of a candidate loading pattern depends on the results of the activated optimization parameters, compared to the results of the previously accepted loading pattern, and the so-called annealing temperature of each parameter. If all parameters improve the candidate loading is always accepted. Worsening of certain parameter results may be acceptable, depending on annealing temperatures. If the pattern is accepted, the results are displayed, if not a new pattern is generated.

During a run temperatures are automatically lowered to converge towards a “frozen” solution.

If all the targets have been reached the optimization is finished. However, ROSA has the capability to do an optimization at different levels. For each level specific parameters and targets can be defined. When all targets have been reached for the current level, the level of the optimization run is increased, and optimization continues with additional parameters. When the highest level has been reached the optimization is completely finished.

In automatic mode an effective calculation time in the order of 1 ms CPU time per evaluated loading pattern is usually achieved, due to a high fraction of rejected cases with parameter violations early in the cycle. Therefore about 100 million loading patterns can be evaluated in a day.

In interactive mode a new loading pattern is generated by manually exchanging two fuel assemblies of or by rotating a burned fuel assembly or by changing the composition of a fresh fuel assembly (e.g. by changing the enrichment and/or poison loading). The new loading pattern is evaluated with respect to neutronics, and always accepted and displayed.

ROSA has proven to be a valuable tool to utilities for over almost two decades by improving their fuel management economics in a highly constrained environment (Jones, 2003, Verhagen, 2009). The code is continuously extended with new optimization parameters and rules. The last three releases of ROSA offer seven new parameters. Two of them can be used for AO control which is especially useful for the design of initial cycles of new plants. The third parameter is related to the burnup distribution of discharged fuel. The fourth parameter can be used to control the negative power jump of once burned fuel. The last release offers two DNBR-related parameters, which can be used to optimize the DNB-ratio for which the W3-correlation has been implemented. The seventh and last parameter can be used to maximize the rod power margin as a function of rod burnup.

3. BASIC FEATURES OF KCB

The Borssele PWR is characterized by a capacity of 485 MWe net (1366 MWth), an average rod power of 20.8 kW/m and an average coolant temperature of 304 °C. Its core consists of 121 fuel assemblies of the 15x15 type. The

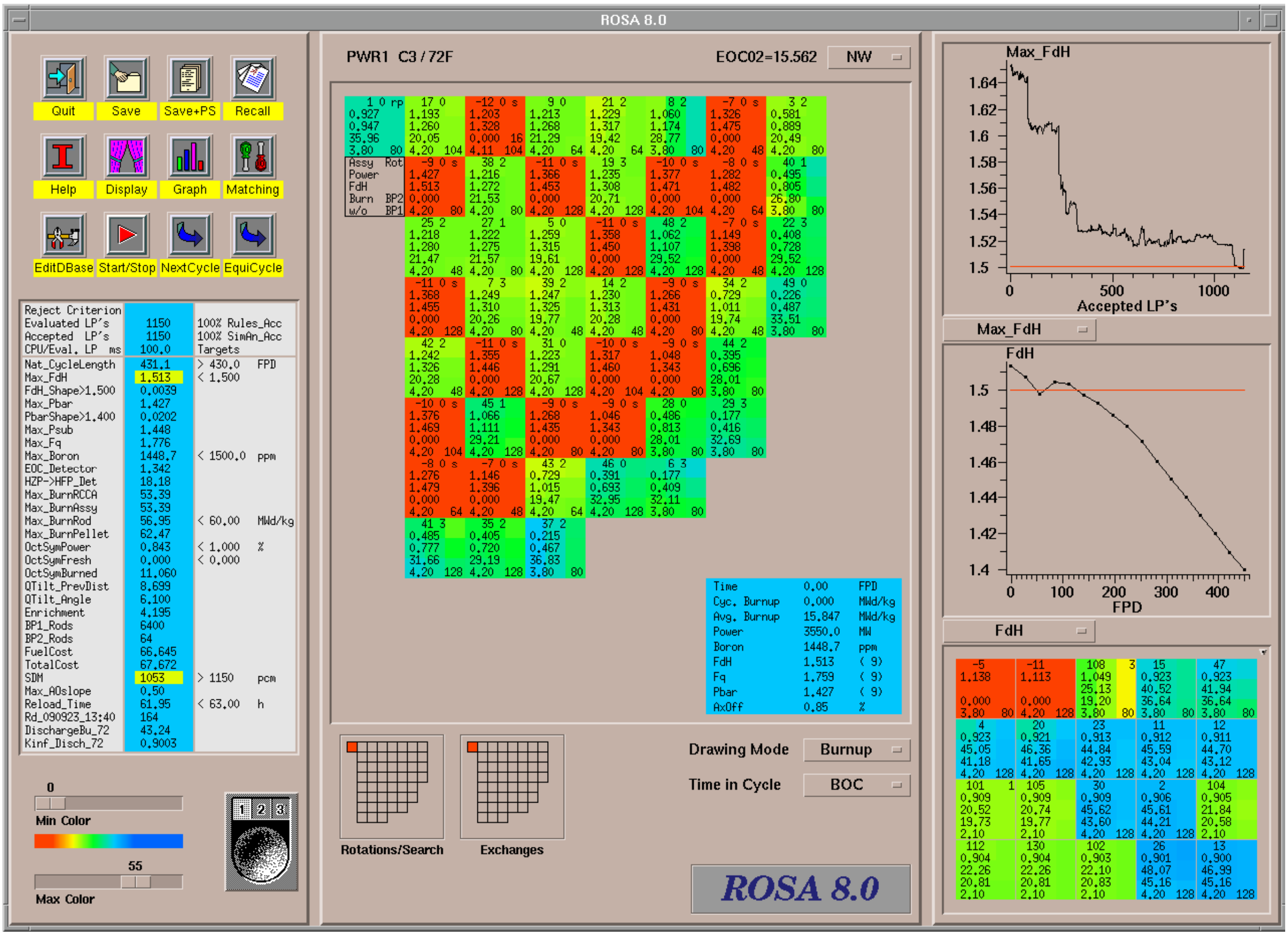

Fig. 1 ROSA graphical user interface

maximum enthalpy rise hot-channel factor should be less then 1.80. The reactor is operated in annual cycles with a typical number of 24 or 28 feeds of 4.4 w/o and approximately 350 efpd natural cycle length. During the coast the inlet temperature of the reactor is being kept at the full power value. The fuel assemblies all have one basic enrichment from bottom to top.

4. BOUNDARY CONDITIONS

All EOL scenarios start from the same equilibrium cycle C44. Table 1 shows the characteristics of cycle 44.

Table 1 Characteristics of cycle 44

Feeds	28
Enrichment (w/o U235)	4.4
Production (efpd)	350
Nat. cycle length (days)	337.5
Coast (efpd)	12.5
Max. FdH	1.746
Max. rod burnup (MWd/kgU)	59.8
Avg. discharge burnup (MWd/kgU)	52.6
Max. fuel assembly burnup (MWd/kgU)	55.4

Further the following criteria were issued by the operator of KCB:

- A maximum FdH of 1.75
- a negative temperature coefficient at hot full power of less then -20 pcm/K
- a maximum feed enrichment of 4.4 w/o U235 and no poison used
- A rod burnup limit of 68 MWd/kgU
- A fuel assembly burnup limit of 55 MWd/kgU for at least 4 out of 9 discharged fuel assemblies (transportation cask limit).
- A maximum fuel assembly burnup of 60 MWd/kgU (transportation cask limit).

5. RESULTS

Four EOL scenarios are presented. An overview of the different scenarios including all relevant cycle characteristics is given in Table 2. For 3 scenarios distinction is being made between two different last EOL cycles. They are referred to as A and B (e.g. scenario 1A and 1B).

The planned transportation cask dictates that not more 5 out of 9 discharged fuel assemblies have a burnup greater than 55 MWd/kgU. The total number of discharged fuel assemblies is shown in Table 2 in brackets next to the value for the average discharge burnup. The number of discharged fuel assemblies with a burnup greater than 55 MWd/kgU is shown next to the maximum fuel assembly burnup. If more then 5 out of 9 discharged fuel assemblies have a burnup greater than 55 MWd/kgU this value is colored red. In practice this means that not all discharged assemblies can be transported directly after the minimum cooling time of 4 year, typical for the planned transportation cask. These assemblies can however be transported easily together with the discharged fuel assemblies from the last cycle since almost all of them have a burnup less than 55 MWd/kgU.

Fuel costs as well as total cycle costs are determined for all cycles. The fuel costs are based on recent spot prices of 135 €/kgU and 120 €/SWU. For the fabrication costs of one fuel assembly a value of 150 k€ is used, while the costs of one efpd loss is set at 500 k€. Back End costs are not included in the fuel or total costs.

Both reference scenario and scenario 4 were recalculated with a whole core 3-D fine mesh version of the LWRSIM-P3.10 code package. The fine mesh model of the Borssele PWR consists of 3x3x30 nodes per fuel assembly. The calculated fine mesh natural cycle length differs 1.4 days at the most when compared to the results of ROSA.

The following paragraphs contain details with respect to the four different scenarios.

5.1 Reference scenario

The first scenario is a continuation of the equilibrium cycle and is used as a reference. It consists of four cycles (three annual and one nine-month cycle) with fixed feed enrichment and still use of feeds in the last short cycle. All four cycles only use fuel assemblies from the previous cycle except the central fuel assembly which is being taken from C44 for all four EOL cycles.

Two different last cycles are optimized, one with 20 feeds (scenario 1A) and one with 16 feeds (scenario 1B). Four extra feeds yields 3 extra efpd. But given the cost assumptions, this does not offset the extra fuel costs even without Back End costs.

5.2 Scenario 2

Basic idea for the subsequent scenarios is to stretch the first three cycles such that last very short cycle can operate without feeds.

In this scenario 16 twice burned were set aside during the cycles C45 up to C47 and reused in C48. Additional to these fuel assemblies C48 reuses 12 thrice burned fuel assemblies from C45 and 4 from C46 with a relatively low burnup.

The high FdH in C46 – C48 (1.768 – 1.778) is caused by the long cycle length starting from C45 causing bigger differences in burnup. Reduction of FdH to 1.75 using stretch-in would cause a loss of 3.6 efpd for these cycles. This loss in not accounted for in Table 2.

The energy production of scenario 2 is over 4 efpd below the production of scenario 1. Due to the saving of 4 feeds the total costs are however lower (despite the loss of efpd). The extra Back End costs of scenario 1 are in this comparison not taken into account, as well as loss of production in scenario 2 due to stretch-in. If stretch-in is taken into account the total costs of scenario 2 will increase by 1.8 M€ to a total of 82.4 M€.

Due to the increased cycle length the fuel assembly burnup is increased with respect to scenario 1.

5.3 Scenario 3

The third scenario differs from the second one by using feeds with a reduced enrichment in C47.

As in scenario 2, 16 twice burned fuel assemblies were set aside during the reloading of the cycles C45 up to C47 and reused in C48. Additional to these fuel assemblies C48 reuses 8 thrice burned fuel assemblies from C45 and 4 from C46 with a relatively low burnup.

Reuse of twice burned fuel assemblies from C44 results in a slightly lower FdH for C46 compared to scenario 2. In scenario 2 this reloading strategy would have resulted in even higher FdH in C47 (FdH > 1.78). Thanks to the use of feeds with a lower enrichment (4.0 w/o U235) in scenario 3 a value 1.750 for FdH was calculated.

On the other side the use of feeds with a lower enrichment results in a lower cycle length of C47 compared to scenario 2. This causes extra loss of efpd in C48. Compared to scenario 2 the coast loss for C48 increases by 5.6 efpd (scenario 3A). This loss could be reduced by allowing a higher FdH combined with a stretch-in (scenario 3B). The extra loss of 2.1 efpd due to the stretch-in is amply offset by the reduction of efpd loss in the coast (3.4 efpd less).

Loss of production due to stretch-in in C46 is not taken into account. If this loss of 1 efpd is taken into account the total costs of scenario 3 will increase by 0.5 M€ to a total of 81.2 M€.

The fuel assembly burnup of scenario 3 is somewhat lower compared to scenario 2. This is caused by the shorter cycle length of C47 in scenario 3.

5.4 Scenario 4

The last scenario is a variation to the third one and covers a search to solve an overshooting of FdH in C46 of scenario three by using a mixture of different feed enrichments. This was solved by using a mixture of 4.0 and 4.4 feeds in both cycles C46 and C47. The total number of feeds with a reduced enrichment of 4.0 is being kept identical to scenario 3 for comparison reasons. Comparable to scenario 3 again 2 options for the last cycle were optimized: one without (scenario 4A) and one with a stretch-in needed to reduce the high FdH to 1.75 (scenario 4B).

With respect to the total costs scenario 4B appears to be the most promising with a total value of M€ 80.6.

The Figs. 2-5 show in detail the loading pattern of the four cycles of the most promising scenario 4B at BOC.

6. FUTURE DEVELOPMENT OF ROSA

Due to ROSA's high speed it was possible to perform a thorough search into many different branches of the presented multicycle scenarios. However one shortcoming should be mentioned: ROSA automatically finds the optimum loading pattern for one specific cycle, but it has no possibilities to automatically find an optimized series of cycles (other than an optimum equilibrium cycle). All the changes you can make when you go to the next cycle (e.g. the number of feeds, the enrichment and/or poison allowed, cyclelength, coast, etc), you have to make yourself. In practice this means that whenever you decide to make a change in one of the first cycles of a series of cycles you have to adjust all following cycles in your series in order to meet all the requirements. This way of working may become inoperable if too many changes can or should be made every time you go to a next cycle.

Apart from designing EOL scenarios, multicycle optimization is of particular interest for designing the first cores of new plants and for transients from one equilibrium cycle to another (due to e.g. changes in fuel enrichment, poison content, cyclelength, etc).

It is therefore that NRG has planned to develop an automatic multicycle optimization routine for the ROSA code system.

7. CONCLUSIONS

Four different EOL-scenarios for the Borssele PWR are presented. The first scenario is used as a reference. The scenarios 2, 3, and 4 all end up with an increased EOC burnup compared to the reference scenario. However this increase does not have an impact on the transport period needed after closure of the plant. Furthermore the scenarios 2, 3, and 4 result in a saving of 4 feeds against a loss of 4 to 9 efpd compared to the reference scenario. This loss is easily compensated by the cost savings due to the reduced number of feeds needed. A high FdH in the last 3 out of 4 cycles, the major shortcoming of scenario 2 could be lowered significantly by using a reduced feed enrichment in the last but one cycle of scenario 3. An even better result could be reached by using a mixture of different feed enrichments in the both the last but one and third last cycle of scenario 4. By allowing a high value of FdH in the last cycle in combination with a stretch-in the overall costs could be reduced even further.

The ROSA code system has proven to be a very valuable asset in finding optimum loading patterns for different EOL-multicycle scenarios. However going from one cycle to the next still requires a lot of manual actions and decisions to be made. To improve the multicycle capabilities of ROSA NRG has planned to develop an automatic multicycle optimization routine for the ROSA code system.

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Table 2 Overview of the different scenarios including all relevant cycle characteristics.

Cycle		Scenario						
		1A	1B	2	3A	3B	4A	4B
45	Feeds (#) x Enrichment (w/o U235)	28x4.4		32x4.4				
	Production (days/efpd)	353.2 / 351.0		403.7 / 400.0				
	Nat. cycle length (days)	335.6		368.8				
	Coast (efpd)	15.4		31.2				
	Coast loss (days)	0.4	= 1A	2.0	= 2	= 2	= 2	= 2
	FdH	1.749		1.753				
	Max. rod burnup (MWd/kgU)	61.1		61.4				
	Avg. discharge burnup (MWd/kgU)	53.9 (29)		55.6 (17)				
	Max. fuel ass. burnup (MWd/kgU)	57.1 (4>55)		57.3 (8>55)				
	Fuel cost / Total cost (M€)	22.07 / 22.30		25.23 / 26.23				
46	Feeds (#) x Enrichment (w/o U235)	28x4.4		32x4.4	32x4.4		8x4.0 + 24x4.4	
	Production (days/efpd)	348.9 / 347.0		399.0 / 395.0	403.7 / 400.0		399.8 / 395.0	
	Nat. cycle length (days)	337.4		361.8	368.7		357.2	
	Coast (efpd)	9.6		33.2	31.3		37.8	
	Coast loss (days)	0.2	= 1A	2.3	2.0	= 3A	3.1	= 4A
	FdH	1.745		**1.777**	**1.771**		1.751	
	Max. rod burnup (MWd/kgU)	59.3		60.7	61.2		60.4	
	Avg. discharge burnup (MWd/kgU)	53.1 (29)		55.1 (25)	55.3 (21)	55.0 (25)	54.4 (33)	
	Max. fuel ass. burnup (MWd/kgU)	55.4 (4>55)		56.4 (**17**>55)	56.6 (**13**>55)		56.6 (13>55)	
	Fuel cost / Total cost (M€)	22.07 / 22.16		25.23 / 26.37	25.23 / 26.23		24.67 / 26.22	
47	Feeds (#) x Enrichment (w/o U235)	28x4.4		32x4.4	32x4.0		24x4.0 + 8x4.4	
	Production (days/efpd)	352.9 / 351.0		398.8 / 395.0	374.4 / 370.0		369.9 / 365.0	
	Nat. cycle length (days)	340.5		363.1	334.6		327.2	
	Coast (efpd)	10.5		31.9	35.4		37.8	
	Coast loss (days)	0.2	= 1A	2.1	2.7	= 3A	3.2	= 4A
	FdH	1.744		**1.778**	1.750		1.749	
	Max. rod burnup (MWd/kgU)	59.4		61.5	60.2		60.4	
	Avg. discharge burnup (MWd/kgU)	53.5 (21)	54.0 (17)	55.2 (33)	54.9 (25)	54.6 (29)	55.5 (25)	
	Max. fuel ass. burnup (MWd/kgU)	55.0 (4>55)		56.6 (21>55)	56.4 (8>55)		57.1 (**16**>55)	
	Fuel cost / Total cost (M€)	22.07 / 22.18		25.23 / 26.28	23.02 / 24.39		23.57 / 25.16	
48	Feeds (#) x Enrichment (w/o U235)	20x4.4	16x4.4	0	0	0	0	0
	Production (days/efpd)	262.2 / 260.0	262.1 / 255.7	115.5 / 110.3	135.2 / 124.4	135.3 / 125.8	143.8 / 133.4	143.7 / 135.9
	Stretch-in loss (efpd)	0.0	0.0	0.0	0.0	2.1	0.0	1.3
	Nat. cycle length (days)	244.7	210.3	70.6	66.3	78.8	75.8	91.9
	Coast (efpd)	15.3	45.4	39.7	58.1	47.0	57.6	44.0
	Coast loss (days)	0.4	4.7	3.5	9.1	5.7	8.7	4.8
	FdH	1.723	1.741	**1.768**	**1.757**	**1.810**	1.749	**1.800**
	Max. rod burnup (MWd/kgU)	58.1	58.6	57.7	57.7	57.4	58.3	58.5
	Avg. discharge burnup (MWd/kgU)	37.9 (121)	39.5 (121)	40.0 (121)	40.1 (121)	40.1 (121)	39.9 (121)	40.0 (121)
	Max. fuel ass. burnup (MWd/kgU)	54.5 (0>55)	54.5 (0>55)	54.0 (0>55)	54.4 (0>55)	54.2 (0>55)	55.1 (4>55)	55.0 (4>55)
	Fuel cost / Total cost (M€)	15.77 / 15.99	12.61 / 14.99	0.00 / 1.77	0.00 / 4.54	0.00 / 3.88	0.00 / 4.33	0.00 / 3.04
45-48	Total production (days/efpd)	1317.2 / 1309.	1317.1 / 1304.7	1317.0 / 1300.3	1317.0 / 1294.4	1317.1 / 1295.8	1317.2 / 1293.4	1317.1 / 1295.9
	Total feeds	104	100	96	96	96	96	96
	Total fuel cost / Total cost (M€)	82.0 / 82.6	78.8 / 81.6	75.7 / 80.6	73.5 / 81.4	73.5 / 80.7	73.5 / 81.9	73.5 / 80.6

Red colored values indicate that the corresponding limit is being exceeded. However appropriate measures are available (e.g. stretch-in for reducing FdH).

ROSA Summary Report for Reactor KCB1 C45 / 32F NW

Nat_CycleLength	368.8	Max_FdH	1.753	FdH_Shape>1.752	0.0001	Max_Pbar	1.497
Max_Fq	2.384	Max_Boron	1523.4	Max_MTC@HZP	2.2	Max_BurnAssy	57.33
Max_BurnRod	61.35	OctSymPower	1.410	OctSymFresh	0.000	OctSymBurned	1.071
Enrichment	4.400	FuelCost	25.226	TotalCost	26.226	SDM	2696
Reload_Time	37.72	DischargeBu_17	55.57	Kinf_Disch_17	0.8705	Kinf_OnceBu	1.1293

Begin of Cycle

11 9 21 0 0.668 0.755 43.29 4.40 0 5 0	4 0 15 3 0.773 0.999 45.24 4.40 0 11 8	0 0 6 3 1.237 1.520 16.63 4.40 0 16 16	21 40 26 1 1.389 1.645 14.51 4.40 0 0 24	0 10 17 2 1.347 1.545 17.59 4.40 0 5 13	-6 0 1.409 1.753 0.000 4.40 0	0 1 27 3 0.339 0.628 50.12 4.40 0 0 1
RCCA [cm] Assy Rot Pow FdH Burnup w/o BP1(/2) x Bu% (BP2)	7 -6 0 1.382 1.739 0.000 4.40 0	15 5 3 2 1.064 1.256 32.23 4.40 0 11 0	0 27 14 12 2 1.342 1.599 14.88 4.40 0 16 38	3 8 19 1 1.088 1.218 33.83 4.40 0 0 5	7 -6 0 1.208 1.613 0.000 4.40 0	0 3 30 2 0.259 0.585 50.90 4.40 0 1 4
	8 8 4 1 1.048 1.231 33.53 4.40 0 0 0	40 21 7 22 0 1.283 1.538 14.48 4.40 0 24 0	0 10 14 2 1.129 1.248 31.13 4.40 0 7 15	-6 0 1.497 1.752 0.000 4.40 0	0 7 11 2 0.513 0.912 44.95 4.40 0 6 11	
	0 16 14 28 2 1.333 1.588 14.87 4.40 0 27 38	0 7 9 2 1.127 1.245 31.10 4.40 0 10 15	12 10 7 25 0 1.287 1.411 17.62 4.40 0 5 0	-6 0 1.240 1.666 0.000 4.40 0	0 4 16 1 0.297 0.677 46.83 4.40 0 3 7	
	3 0 10 3 1.088 1.216 33.80 4.40 0 8 5	-6 0 1.496 1.752 0.000 4.40 0	-6 0 1.240 1.667 0.000 4.40 0	0 0 5 1 0.390 0.816 47.07 4.40 0 5 5		
	7 -6 0 1.208 1.613 0.000 4.40 0	0 6 24 2 0.513 0.912 44.95 4.40 0 7 11	0 3 20 3 0.297 0.677 46.80 4.40 0 4 7			
	0 1 23 2 0.259 0.584 50.92 4.40 0 3 4					

Time [FPD]	**0.00**
Cyc. Burnup	**0.000**
Avg. Burnup	**24.621**
Power [MW]	**1365.6**
Boron [ppm]	**1523.4**
FdH	**1.753 (6)**
Fq	**2.384 (6)**
Pbar	**1.497 (17)**
AxOff [%]	**1.43**

EOC44=12.330 MWd/kg Mass=38762 kgHM
2010-12-23_11:52:18 ROSA 7.9.2/12 © 2010 NRG Page 1

Fig. 2 First cycle of Borssele EOL scenario 4 at BOC

ROSA Summary Report for Reactor KCB1 C46 / 32F NW

Nat_CycleLength	357.2	Max_FdH	1.751	FdH_Shape>1.750	0.0003	Max_Pbar	1.473
Max_Fq	2.378	Max_Boron	1470.5	Max_MTC@HZP	1.2	Max_BurnAssy	56.61
Max_BurnRod	60.41	OctSymPower	1.854	OctSymFresh	0.000	OctSymBurned	6.050
Enrichment	4.300	FuelCost	24.674	TotalCost	26.219	SDM	2539
Reload_Time	38.83	DischargeBu_33	54.35	Kinf_Disch_33	0.8782	Kinf_OnceBu	1.1242

Begin of Cycle

5 11 4421 1 0.767 0.849 43.29 4.40 0 0 9	4 2 5 2 0.930 1.124 36.03 4.40 0 3 0	26 0 26 3 1.241 1.542 16.90 4.40 0 42 20	0 27 12 2 1.329 1.565 16.56 4.40 0 16 40	0 18 6 2 1.315 1.517 18.79 4.40 0 0 18	-6 0 1.413 1.751 0.000 4.40 0	0 2 23 2 0.339 0.629 51.44 4.40 0 0 3
RCCA [cm] Assy Rot Pow FdH Burnup w/o BP1(/2) x Bu% (BP2)	7 -6 0 1.430 1.741 0.000 4.40 0	9 0 19 1 1.014 1.209 33.53 4.40 0 11 4	0 26 14 22 2 1.286 1.533 16.89 4.40 0 20 42	0 9 10 0 1.089 1.229 33.62 4.40 0 4 11	7 -6 0 1.210 1.614 0.000 4.40 0	1 0 11 2 0.266 0.599 49.09 4.40 0 4 2
	4 8 21 1 0.991 1.180 35.27 4.40 0 0 7	13 8 7 4 3 0.991 1.215 33.80 4.40 0 7 0	4 13 25 1 1.291 1.481 19.94 4.40 0 0 12	-5 0 1.473 1.751 0.000 4.00 0	0 6 9 2 0.497 0.884 47.80 4.40 0 3 8	
	16 40 14 28 1 1.291 1.568 16.56 4.40 0 0 27	4 0 17 3 1.288 1.480 19.94 4.40 0 13 12	0 5 7 8 0 1.310 1.428 19.85 4.40 0 5 8	-6 0 1.277 1.725 0.000 4.40 0	0 4 14 1 0.293 0.664 48.89 4.40 0 0 5	
	0 3 3 0 1.081 1.220 34.52 4.40 0 6 9	-5 0 1.473 1.751 0.000 4.00 0	-6 0 1.277 1.725 0.000 4.40 0	0 6 16 0 0.403 0.855 47.07 4.40 0 4 9		
	7 -6 0 1.207 1.611 0.000 4.40 0	0 4 20 0 0.501 0.892 47.02 4.40 0 6 9	0 1 24 3 0.293 0.662 49.04 4.40 0 2 4			
	0 0 30 2 0.258 0.582 51.40 4.40 0 2 3					

Time [FPD]	**0.00**
Cyc. Burnup	**0.000**
Avg. Burnup	**24.952**
Power [MW]	**1365.6**
Boron [ppm]	**1470.5**
FdH	**1.751 (17)**
Fq	**2.378 (6)**
Pbar	**1.473 (25)**
AxOff [%]	**1.06**

EOC45=14.092 MWd/kg
2010-12-27_09:54:49

Mass=38762 kgHM
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Fig. 3 Second cycle of Borssele EOL scenario 4 at BOC

ROSA Summary Report for Reactor KCB1 C47 / 32F NW

Nat_CycleLength	327.2	Max_FdH	1.749	FdH_Shape>1.750	0.0000	Max_Pbar	1.486
Max_Fq	2.368	Max_Boron	1341.5	Max_MTC@HZP	-0.4	Max_BurnAssy	57.10
Max_BurnRod	60.43	OctSymPower	2.946	OctSymFresh	0.000	OctSymBurned	7.050
Enrichment	4.100	FuelCost	23.570	TotalCost	25.163	SDM	2668
Reload_Time	39.53	DischargeBu_25	55.46	Kinf_Disch_25	0.8715	Kinf_OnceBu	1.1237

Begin of Cycle

0 5 4421 2 0.781 0.865 43.29 4.40 0 9 11	7 0 5 2 0.953 1.166 36.73 4.40 0 7 0	27 0 28 3 1.301 1.624 16.37 4.40 0 40 17	0 20 26 2 1.378 1.643 16.96 4.40 0 27 44	0 18 6 2 1.363 1.572 18.64 4.40 0 0 18	-5 0 1.411 1.748 0.000 4.00 0	1 3 24 3 0.364 0.674 49.53 4.40 0 0 3
RCCA [cm] Assy Rot Pow FdH Burnup w/o BP1(/2) x Bu% (BP2)	7 -5 0 1.416 1.730 0.000 4.00 0	0 10 4 0 1.014 1.208 35.05 4.40 0 6 14	20 0 14 22 3 1.310 1.607 16.96 4.40 0 44 27	1 2 21 2 1.077 1.188 37.38 4.40 0 2 0	7 -6 0 1.254 1.673 0.000 4.40 0	0 1 2 2 0.277 0.618 50.00 4.40 0 1 1
	10 15 10 3 1.028 1.258 34.84 4.40 0 0 6	7 7 7 16 3 0.941 1.121 37.61 4.40 0 1 0	2 2 8 3 1.275 1.479 20.16 4.40 0 0 2	-5 0 1.486 1.749 0.000 4.00 0	0 4 11 0 0.500 0.889 48.74 4.40 0 2 5	
	0 27 14 12 2 1.330 1.617 16.40 4.40 0 17 40	14 14 25 0 1.226 1.447 19.33 4.00 0 4 0	14 14 7 17 1 1.226 1.359 19.32 4.00 0 0 4	-5 0 1.202 1.633 0.000 4.00 0	0 7 13 2 0.276 0.639 53.20 4.40 0 0 7	
	7 7 20 2 1.072 1.196 37.58 4.40 0 0 1	-5 0 1.483 1.747 0.000 4.00 0	-5 0 1.204 1.634 0.000 4.00 0	0 3 15 2 0.382 0.817 48.26 4.40 0 4 6		
	7 -6 0 1.251 1.672 0.000 4.40 0	0 2 9 3 0.503 0.890 48.38 4.40 0 5 6	0 2 14 1 0.287 0.662 49.83 4.40 0 3 4			
	0 1 27 2 0.266 0.598 53.00 4.40 0 2 3					

Time [FPD]	**0.00**
Cyc. Burnup	**0.000**
Avg. Burnup	**25.623**
Power [MW]	**1365.6**
Boron [ppm]	**1341.5**
FdH	**1.749 (17)**
Fq	**2.368 (6)**
Pbar	**1.486 (17)**
AxOff [%]	**0.82**

EOC46=13.916 MWd/kg Mass=38762 kgHM
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Fig. 4 Third cycle of Borssele EOL scenario 4 at BOC

ROSA Summary Report for Reactor KCB1 C48 / 0F NW

Nat_CycleLength	91.9	Max_FdH	1.800	FdH_Shape>1.800	0.0000	Max_Pbar	1.603
Max_Fq	2.235	Max_Boron	363.6	Max_MTC@HZP	-22.9	Max_BurnAssy	55.02
Max_BurnRod	58.51	OctSymPower	9.216	OctSymFresh	0.000	OctSymBurned	9.072
Enrichment	0.000	FuelCost	0.000	TotalCost	2.389	SDM	3029
Reload_Time	37.46	DischargeBu_121	40.03	Kinf_Disch_121	0.9629	Kinf_OnceBu	0.0000

Begin of Cycle

9 0 4421 3 1.104 1.200 43.29 4.40 0 11 5	7 0 21 3 1.233 1.461 34.82 4.00 0 7 1	16 9 4 2 1.359 1.634 34.48 4.40 0 7 0	17 13 4402 3 1.466 1.744 30.57 4.40 0 6 0	14 4 17 0 1.503 1.799 18.11 4.00 0 14 0	9 14 10 2 0.803 1.199 33.77 4.40 0 0 7	0 4 13 2 0.219 0.409 53.88 4.40 0 1 5
RCCA [cm] Assy Rot Pow FdH Burnup w/o BP1(/2) x Bu% (BP2)	2 2 7 8 3 1.518 1.799 18.39 4.00 0 0 2	8 0 3 0 1.391 1.619 33.38 4.40 0 13 6	0 8 14 4515 2 1.432 1.660 32.76 4.40 0 7 13	45 22 22 0 1.531 1.800 15.09 4.00 0 27 0	1 4 7 20 1 0.712 1.077 35.05 4.00 0 0 4	0 2 27 2 0.182 0.395 53.55 4.40 0 1 3
	0 7 5 0 1.352 1.541 35.65 4.40 0 0 7	14 8 7 4603 1 1.390 1.652 34.70 4.40 0 7 0	14 6 19 2 1.409 1.570 33.43 4.40 0 8 0	27 40 12 1 1.395 1.738 15.55 4.40 0 0 17	0 3 2 2 0.477 0.880 49.81 4.40 0 0 3	
	5 13 14 4619 0 1.408 1.644 34.56 4.40 0 0 9	14 13 25 0 1.603 1.800 18.10 4.00 0 4 0	27 0 7 28 3 1.481 1.798 15.53 4.40 0 41 17	0 1 16 1 0.781 1.225 36.43 4.40 0 3 3	0 3 11 2 0.257 0.603 51.15 4.40 0 2 2	
	45 27 26 0 1.484 1.765 15.12 4.00 0 22 0	17 17 6 1 1.260 1.590 17.12 4.00 0 0 0	0 6 14 1 0.640 1.071 48.65 4.40 0 3 8	0 0 24 2 0.294 0.667 51.30 4.40 0 5 5		
	3 0 7 9 1 0.597 0.944 48.71 4.40 0 8 6	0 0 15 2 0.423 0.812 50.39 4.40 0 4 4	0 1 4529 1 0.214 0.514 52.61 4.40 0 1 3			
	0 1 4518 3 0.162 0.360 52.62 4.40 0 1 3					

Time [FPD]	**0.00**
Cyc. Burnup	**0.000**
Avg. Burnup	**35.242**
Power [MW]	**1365.6**
Boron [ppm]	**363.6**
FdH	**1.800 (20)**
Fq	**2.235 (21)**
Pbar	**1.603 (20)**
AxOff [%]	**-2.87**

EOC47=12.859 MWd/kg
2010-12-27_17:16:13

Mass=38762 kgHM
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Fig. 5 Fourth and last cycle of Borssele EOL scenario 4 at BOC