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HIGHLY CONSTRAINED LOADING PATTERN SEARCHES WITH ROSA

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ABSTRACT

The core-loading pattern is decisive for fuel cycle economics, fuel safety parameters and economic planning for future cycles. ROSA, NRG's loading pattern optimization code system for PWRs, has proven to be a valuable tool to reactor operators for over a decade for improving their fuel management economics in a more and more constrained environment. ROSA uses simulated annealing as loading pattern optimization technique, in combination with an extremely fast 3-D neutronics code for loading pattern calculations. The code is continuously extended with new optimization parameters and rules. This paper outlines recent developments of the ROSA code system with regard to the reduction of CIPS-risk and fuel failures. Next to the developments a few practical cases are presented.

1. INTRODUCTION

The ROSA code system 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 including cycle depletion can be evaluated on a workstation or PC in a day. The code can be switched between manual and automatic mode. In addition to single cycle also equilibrium cycle optimization can be performed. With the latest version more than 50 parameters can be optimized simultaneously. Recently several parameters and rules options (loading pattern constraints) have been developed in cooperation with users to improve operational margins and to be able to further reduce fuel failures and reach the so called "Zero Ten" target (zero fuel failures by 2010).

2. ROSA CODE SYSTEM OVERVIEW

The ROSA code system[1,2] has been developed at NRG for PWR core design and utilizes Simulated Annealing[3] 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 nominal 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 fuel movements. The graphical user interface of ROSA is shown in figure 1.

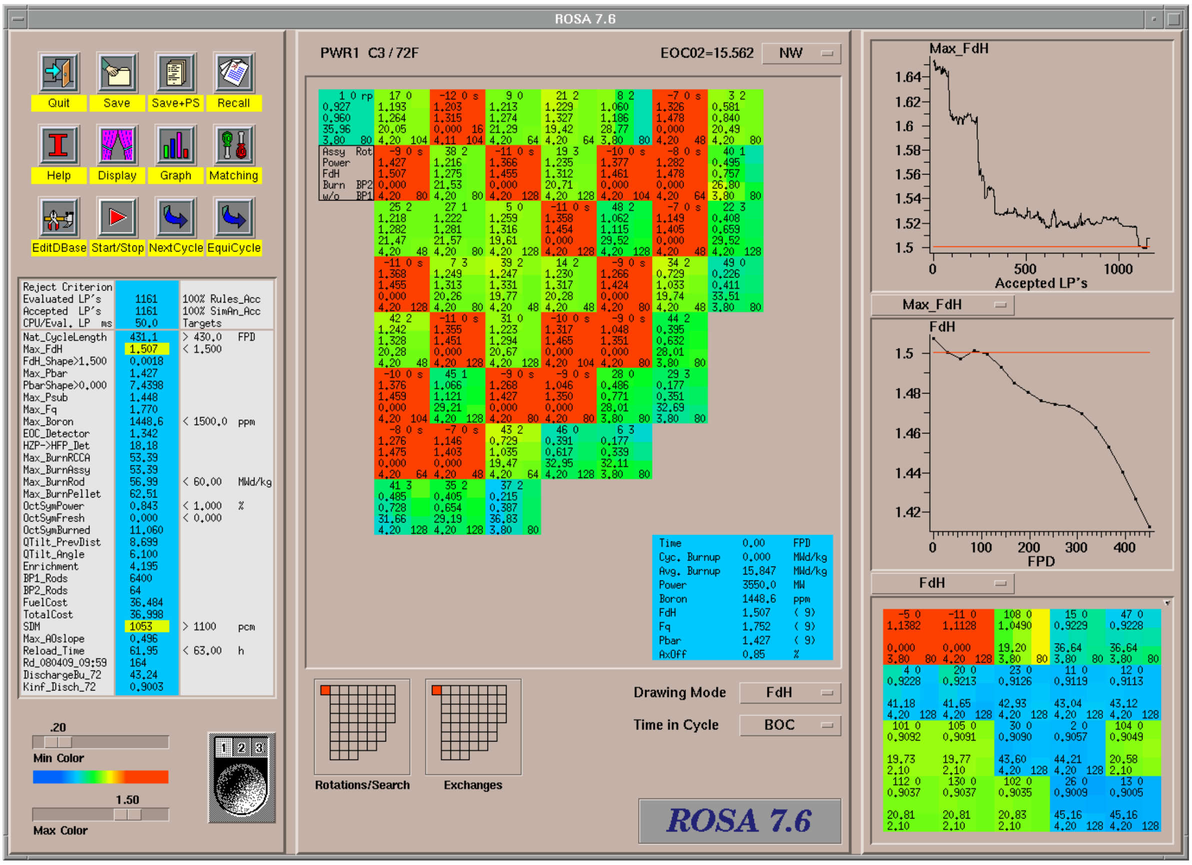

Fig. 1 ROSA graphical user interface.

The code starts by evaluating an initially provided loading pattern. In automatic mode loading pattern candidates are 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-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. Pin power reconstruction is available. About 10 to 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 $F_{\Delta H}$, and ±2 days for natural cycle length. Typical full cycle evaluation takes 10 to 100 ms CPU time per loading pattern on a 1.9 GHz PC with Cygwin, depending on core-size, axial mesh, number of burnup steps, selected parameters, and the previously evaluated loading pattern. More than 50 parameters can be optimized simultaneously, amongst others: peaking factors, natural cycle length, burnup limits, economics/fuel cost, shutdown margin, MTC, octant symmetry, quadrant tilt, CIPS- and PCI-criteria.

Acceptance of a candidate loading pattern depends on the results for 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 pattern 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 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.

3. RECENT DEVELOPMENTS

Recent developments with regard to rules and optimization parameters will be discussed in the subsequent paragraphs.

3.1 Rules

ROSA offers users a lot of flexibility with regard to applying constraints to loading patterns. As rules are evaluated before the relatively most time-consuming neutronics calculations, they offer the possibility to save CPU-time by preventing the evaluation of loading patterns that will not meet the design criteria according to the user's a-priori knowledge. A few examples are to restrict highly burned fuel to (parts of) the core periphery in order to meet burnup limits at EOC, or to limit the number of feed fuel types due to fuel fabrication contract requirements.

Recently the need has come up to control the risk of grid to rod fretting, a grid/rod vibration issue that often causes fuel failures on or near the baffle. One of the options to reduce the risk is to limit fuel assembly faces to not more than one cycle on the baffle. This option is made available in ROSA as a rule. If the rule is activated the randomly generated loading patterns with assembly faces that were on the baffle in their previous cycle of use are skipped from further evaluations.

3.2 Optimization Parameters

With the current code version more than 50 parameters can be optimized simultaneously. A selection of these parameters is shown in figure 2, where the left part of the GUI with parameter names, values and targets is enlarged. Several parameters have been developed recently:

- Max_Psub represents the maximum power in a radial subnode during the cycle. In ROSA an assembly is divided in 3x3 or 4x4 radial subnodes. Minimizing this intra assembly power is beneficial for the CIPS-risk[4]. An alternative parameter that is currently tested weighs the Psub with the boron concentration and is aimed at reducing the Psub during high boron concentrations, thereby reducing the boron deposition in the crud layer on the fuel cladding. Near EOC (low boron) higher Psub values can be tolerated, giving more flexibility in core design.

- Max_MTC@HZP is the maximum Moderator Temperature Coefficient at Hot Zero Power (HZP) during the cycle. For this parameter extra evaluation of HZP states for each burnup step in the cycle takes place until the maximum boron in the cycle has been reached.

- Max_BuGradient is the maximum EOC intra assembly burnup difference based upon 2x2 radial subnodes per assembly. It can be used to control assembly bow. At BOC a rule can be used to prevent placement of assemblies with high burnup gradients at certain core locations.

- Min_Power_Ratio is the minimum ratio of cycle average assembly power for all twice and higher burned assemblies between current and previous cycle of use. The parameter can be used to reduce the negative cycle average power jump. Typically an optimization target of >0.325 is used for this parameter, which often results in the placement of twice burned fuel on high power baffle locations and thus once burned fuel on low power baffle locations which is uneconomic. The idea behind this parameter is that enhanced rod vibration, causing Grid To Rod Fretting, can occur due to rod diameter reduction after a large negative power jump.

– Max_FdH_AST (Alternate Source Term) is a parameter that aims at keeping the maximum $F_{\Delta H}$ of all radial subnodes with a rod burnup above 54 MWd/kg under a certain level. This level corresponds to a linear power of 20.67 kW/m (6.3 kW/ft).

– Hf_Power is the cycle averaged power in the Hf-absorber rod nodes. Some plants use the Hf-absorber rods on baffle locations to minimize vessel fluence.

Reject Criterion			
Evaluated LP's	7	100% Rules_Acc	
Accepted LP's	7	100% SimAn_Acc	
CPU/Eval. LP ms	670.0	Targets	
Nat_CycleLength	659.2	> 660.0	FPD
Max_FdH	1.488	< 1.485	
FdH_Shape>1.485	0.0015		
Max_Pbar	1.350		
Max_Psub	1.395		
PsBoShape>1.320	0.1660	< 0.0000	
Max_Fq	1.863	< 1.900	
Max_Boron	1652.7		
Max_MTC@HZP	0.0	< 0.0	pcm/K
Max_BurnRCCA	54.93		
Max_BurnAssy	54.93	< 55.00	MWd/kg
Max_BurnRod	59.86	< 60.00	MWd/kg
Max_BuGradient	8.84		
OctSymPower	0.172	< 0.500	%
OctSymFresh	0.000	< 0.000	
OctSymBurned	3.010		
QTilt_Angle	4.000	< 0.000	
Enrichment	4.817		
Gad_Weight	215.96	< 200.00	kg
BP1_Rods	1440		
FuelCost	86.965		
SDM	3569	> 3000	pcm
DischargeBu_80	48.22		
Kinf_Disch_80	0.9365		
Max_FdH_AST	1.078		
PCI_2D	0.454		
PCI_3D	0.744	< 0.300	
PCI_H	0	< 0	
PCID_M	8		
PCID_H	16	< 0	

Fig. 2 ROSA optimization parameter screen.

– Gad_Weight is the total weight of the Gad in the fresh fuel. Minimizing the total amount of Gad reduces residual absorption and is an economic benefit.

– PCI (Pellet Clad Interaction) can be caused by a positive jump in pellet power, when reloaded fuel changes from a low power to a high power core location. A long coast to low power and/or rapid power increase during startup will increase the risk of PCI failures. Recently 5 PCI-related parameters have been developed. A so-called "PCI_3D" parameter is the maximum positive power jump per 3D subnode (typically 3x3x18 subnodes per assembly) between BOC of the current and EOC of the previous cycle. The impact of EOC power coast and/or BOC power uprate is taken into account. Other parameters for PCI risk mitigation have been defined that count the number of subnodes at BOC HFP above a certain burnup that exceed a certain power level or a certain jump in power. With the help of these parameters core design with a reduced PCI risk is possible.

4. PRACTICAL CASES

4.1 Discharge Burnup Range Reduction

The Dutch Borssele PWR, which is licensed to operate until 2033, has recently increased its feed fuel enrichment from 3.98 to 4.40 w/o in 2005. As a consequence the reload batch size could be reduced and the burnup of discharged fuel is now increasing. The applied AREVA HTP-fuel has an operational assembly burnup limit of 65 MWd/kgU and a rod burnup limit of 68 MWd/kgU. However the fuel transport container, for transporting spent fuel to a reprocessing facility, has an assembly burnup limit of only 55 MWd/kgU. An equilibrium cycle study has been performed to evaluate whether this limit can be met on the long term or not.

The 1366 MW_{th} plant with 121 assemblies (15x15) operates on annual cycles and has outages of 10-15 days. An energy production of 352 efpd per cycle is assumed (~354 calendar days), equivalent to a cycle burnup of 12.401 MWd/kgU. A feed batch size of 28 assemblies was selected as this yields a theoretical average discharge burnup of 53.59 MWd/kgU (121*12.401/28), which is slightly below the limit of 55 MWd/kgU. Other options like 24 or 32 feeds would result in average discharge burnups of 62.5 or 46.9 MWd/kgU. These numbers are either much too high or quite low. The challenge with the 28 feed core design is to keep the maximum assembly burnup very close to the average. The most important optimization targets are: $F_{\Delta H} < 1.77$, maximize natural cycle length, assembly burnup < 54.5 MWd/kgU (1% extra margin), HFP Max_Boron < 1330 ppm (used to maintain criticality margin during refuelling), feed fuel enrichment ≤ 4.40 w/o and no poison to be used.

The resulting BOC and EOC maps of the optimized equilibrium loading pattern are shown in figures 3 and 4. From the BOC map it can be seen that a feed enrichment reduction from 4.40 to 4.35 w/o was needed to keep the maximum boron just under 1330 ppm. Note that a burned assembly from the fuel pool is used in the core center. There is a stockpile of these assemblies so that this strategy can be maintained until the end of the

ROSA Summary Report for Reactor KCB1 C69 / 28F NW

Nat_CycleLength	320.3	Max_FdH	1.755	FdH_Shape>1.750	0.0009	Max_Pbar	1.498		
Max_Psub	1.611	Max_Fq	2.365	Max_Boron	1329.7	Max_MTC@HZP	-0.8		
Max_BurnAssy	53.81	Max_BurnRod	58.25	Max_BurnPellet	64.41	OctSymPower	1.405		
OctSymFresh	0.000	OctSymBurned	3.280	QTilt_Angle	1.100	Enrichment	4.350		
BP1_Rods	0	SDM	2955	Reload_Time	56.58	DischargeBu_29	53.35		
Kinf_Disch_29	0.8783								

Begin of Cycle

3031 0 0.386 0.484 46.51 *3.98 0*	*9 2* 8 1 0.675 0.974 44.21 *4.35 0* *6 0*	*16 38* 28 1 1.358 1.693 15.02 *4.35 0* *0 26*	*15 0* 6 0 1.409 1.648 16.96 *4.35 0* *15 0*	*11 5* 15 2 1.127 1.287 32.25 *4.35 0* *8 0*	-6 0 1.441 1.754 0.000 *4.35 0*	*0 4* 11 3 0.381 0.697 47.54 *4.35 0* *1 5*
RCCA [cm] Assy Rot Pow (Match‰) FdH (Match‰) Burnup w/o BP1(/2) x Bu% (BP2)	*9 0* 9 2 0.932 1.294 31.84 *4.35 0* *15 6*	*24 42* 22 1 1.423 1.734 14.44 *4.35 0* *0 22*	*0 5* 25 2 1.383 1.656 17.74 *4.35 0* *11 14*	*0 0* 4 3 1.090 1.214 34.07 *4.35 0* *8 8*	-6 0 1.248 1.648 0.000 *4.35 0*	*2 9* 20 3 0.297 0.657 45.93 *4.35 0* *0 8*
	24 0 26 3 1.416 1.730 14.48 *4.35 0* *42 22*	*0 26* 12 2 1.413 1.710 15.04 *4.35 0* *17 38*	*0 9* 14 3 1.135 1.311 31.81 *4.35 0* *6 15*	-6 0 1.495 1.755 0.000 *4.35 0*	*0 2* 21 0 0.507 0.879 47.12 *4.35 0* *0 1*	
	0 11 17 2 1.379 1.650 17.71 *4.35 0* *5 14*	*0 6* 3 1 1.135 1.321 31.83 *4.35 0* *14 18*	*0 4* 19 0 1.002 1.087 34.48 *4.35 0* *0 4*	-6 0 1.173 1.584 0.000 *4.35 0*	*0 4* 13 1 0.281 0.646 49.95 *4.35 0* *2 5*	
	0 4 10 3 1.081 1.194 34.55 *4.35 0* *0 4*	-6 0 1.498 1.755 0.000 *4.35 0*	-6 0 1.176 1.589 0.000 *4.35 0*	*0 1* 24 1 0.358 0.729 47.92 *4.35 0* *2 3*		
	-6 0 1.246 1.642 0.000 *4.35 0*	*0 5* 5 2 0.516 0.907 46.18 *4.35 0* *3 7*	*0 0* 31 2 0.285 0.657 49.88 *4.35 0* *10 10*			
	5 8 16 3 0.293 0.642 45.91 *4.35 0* *0 2*					

Time [FPD]	**0.00**
Cyc. Burnup	**0.000**
Avg. Burnup	**25.736**
Power [MW]	**1365.6**
Boron [ppm]	**1329.7**
FdH	**1.755 (17)**
Fq	**2.365 (6)**
Pbar	**1.498 (25)**
AxOff [%]	**0.64**

EOC68=12.401 MWd/kg Mass=38762 kgHM
2009-02-26_14:05:05 ROSA 7.7.1/12 © 2009 NRG Page 1

Fig. 3 Borssele 12 month equilibrium cycle at BOC.

ROSA Summary Report for Reactor KCB1 C69 / 28F NW

Nat_CycleLength	320.3	Max_FdH	1.755	FdH_Shape>1.750	0.0009	Max_Pbar	1.498
Max_Psub	1.611	Max_Fq	2.365	Max_Boron	1329.7	Max_MTC@HZP	-0.8
Max_BurnAssy	53.81	Max_BurnRod	58.25	Max_BurnPellet	64.41	OctSymPower	1.405
OctSymFresh	0.000	OctSymBurned	3.280	QTilt_Angle	1.100	Enrichment	4.350
BP1_Rods	0	SDM	2955	Reload_Time	56.58	DischargeBu_29	53.35
Kinf_Disch_29	0.8783						

End of Cycle

∅3031 0 0.623 0.655 53.03 58.25	4 1 8 1 0.827 0.951 53.75 57.37 2 0	6 18 28 1 1.328 1.397 31.83 36.76 0 14	8 0 6 0 1.338 1.344 34.07 37.39 8 0	7 3 15 2 1.119 1.101 46.18 49.70 5 0	15 0 -6 0 1.339 1.380 16.96 19.58 15 0	2 0 11 3 0.445 0.664 52.62 55.27 3 1
RCCA [cm] Assy Rot Pow (Match‰) FdH (Match‰) Burnup Rod Burnup ∅ x Bu%	2 0 9 2 1.026 1.140 44.21 49.09 9 6	6 15 22 1 1.364 1.403 31.84 36.55 0 9	0 0 25 2 1.317 1.349 34.55 36.96 4 4	1 0 4 3 1.085 1.058 47.54 51.23 5 4	38 17 -6 0 1.206 1.327 15.04 18.99 26 0	4 5 20 3 0.354 0.635 49.95 53.25 0 2
	6 0 26 3 1.359 1.401 31.81 36.50 15 9	0 8 12 2 1.348 1.394 32.25 35.58 5 11	0 5 14 3 1.131 1.124 45.91 50.16 2 8	14 5 -6 0 1.390 1.380 17.71 20.04 11 0	8 4 21 0 0.571 0.793 53.78 58.02 5 0	
	0 4 17 2 1.315 1.347 34.48 36.92 0 4	0 2 3 1 1.131 1.132 45.93 50.39 8 9	0 2 19 0 1.034 0.974 47.12 50.05 0 1	42 22 -6 0 1.172 1.305 14.44 18.55 24 0	3 2 13 1 0.342 0.632 53.81 56.67 1 0	
	1 3 10 3 1.079 1.038 47.92 50.78 0 2	14 11 -6 0 1.392 1.381 17.74 20.03 5 0	42 24 -6 0 1.175 1.308 14.48 18.59 22 0	5 2 24 1 0.430 0.702 52.80 56.78 3 0		
	38 26 -6 0 1.205 1.324 15.02 18.94 16 0	3 5 5 2 0.579 0.814 52.94 57.15 0 0	3 0 31 2 0.346 0.642 53.79 57.90 7 5			
	10 10 16 3 0.350 0.621 49.88 55.79 0 0					

Time [FPD]	**352.00**
Cyc. Burnup	**12.401**
Avg. Burnup	**38.137**
Rel. Power	**0.879**
Boron [ppm]	**5.0**
FdH	**1.403 (9)**
Fq	**1.707 (9)**
Pbar	**1.224 (25)**
AxOff [%]	**2.50**

2009-02-26_14:05:05 ROSA 7.7.1/12 © 2009 NRG Page 12

Fig. 4 Borssele 12 month equilibrium cycle at EOC.

operational life of the plant (>20 additional cycles). From the EOC map it can be concluded that the discharged fuel (29 assemblies) varies in assembly burnup between 52.62 and 53.81 MWd/kgU, with an average of 53.35 MWd/kgU. Note that fuel from peripheral core locations [2,7] and [7,2] is not discharged but used for a fifth cycle at [4,6] and [6,4].

The study shows that it is possible to keep the maximum assembly burnup below 54 MWd/kgU with an average assembly burnup of 53.35 MWd/kgU. However, this leaves very little flexibility and requires very good inventory management. In case a single assembly is no longer available the long-term strategy is jeopardized.

4.2 Twenty Four Month Cycle with Gadolinium

For the Belgian engineering company Tractebel a study was performed to investigate the possibilities of a 24 month equilibrium cycle for the 157 assembly Doel-4 plant. This PWR operates at 2988 MW_{th} and uses 17x17 fuel. The fuel is axially uniform and has an active height of 426.7 cm (14 ft).

For this study an energy production of 690 efpd per cycle is assumed (~691 calendar days), equivalent to a cycle burnup of ~24.6 MWd/kgU. Fuel of up to 4.95 w/o with up to 24 Gad rods of 2, 4, 6, 8, and 10% could be used. The most important optimization targets are: $F_{\Delta H} < 1.52$, maximize natural cycle length, assembly burnup < 55 MWd/kgU, rod burnup < 60 MWd/kgU, MTC@HZP < 0 pcm/K. The obtained solution meets all optimization criteria and has 80 feeds and 77 once burned assemblies (all 4.95 w/o). The 9 different feed fuel types have 4-10% Gad in 8-24 rods.

The resulting BOC and EOC maps of the optimized equilibrium loading pattern are shown in figure 5 and 6. Note that the central assembly can be taken from the only group of 4 once burned assemblies that is discharged from core location [1,6]. It can be concluded that a 24 month cycle is achievable with 4.95 w/o fuel from an energy and peaking point of view, but that the tiny margins in the burnup limits will make the transition problematic.

4.3 CIPS Risk Reduction

At Southern Nuclear (USA) the ROSA code was, apart from the normal core design campaigns, used to investigate options to reduce the CIPS-risk for the 193-assembly Vogtle plant. Initially the designers aimed to reduce this risk by developing cores with lower boron concentrations (< 1250 ppm) and very low peaking factors (typically $F_{\Delta H} < 1.40$ and maximum assembly power Pbar < 1.30). Recently it was demonstrated that by minimizing the maximum subnode power (Psub) a reduction of over 50% in CIPS-risk could be obtained, compared to a loading pattern that was only optimized for maximum assembly power. Both loading patterns had comparable (low) maximum assembly power results but quite different Psub values, due to different inner assembly power gradients. Details of the design work have been published at this conference[4].

ROSA Summary Report for Reactor DOE4 C27 / 80F NW

Nat_CycleLength	659.2	Max_FdH	1.489	FdH_Shape>1.485	0.0011	Max_Pbar	1.350
Max_Psub	1.396	Max_Fq	1.863	Max_Boron	1652.8	Max_MTC@HZP	0.0
Max_BurnRCCA	54.93	Max_BurnAssy	54.93	Max_BurnRod	59.86	OctSymPower	0.173
OctSymFresh	0.000	OctSymBurned	3.010	QTilt_Angle	4.000	Enrichment	4.817
Gad_Weight	215.96	BP1_Rods	1440	FuelCost	86.965	SDM	3568
DischargeBu_80	48.22	Kinf_Disch_80	0.9365				

Begin of Cycle

2206 0 0.851 0.897 32.31 4.81 20	3 4 25 1 0.926 1.017 31.29 4.80 20 0 5	-735 0 1.207 1.433 0.000 4.81 20@10	-725 0 1.298 1.484 0.000 4.80 20@6	18 0 7 0 1.145 1.246 29.13 4.86 12 18 0	-738 0 1.251 1.439 0.000 4.78 24@10	-728 0 1.193 1.487 0.000 4.86 12@8	3 0 4 0 0.456 0.732 32.15 4.80 20 3 0
RCCA [cm] Assy Rot Pow (Match‰) FdH (Match‰) Burnup w/o BP1(/2) x Bu% (BP2)	0 20 31 2 1.005 1.081 27.49 4.86 12 20 33	-737 0 1.157 1.352 0.000 4.77 24@8	0 25 26 2 1.133 1.289 26.89 4.89 8 17 38	14 0 14 3 1.166 1.314 26.53 4.86 12 37 27	-730 0 1.271 1.488 0.000 4.80 20@8	-723 0 1.068 1.429 0.000 4.86 12@6	3 4 13 1 0.360 0.662 32.17 4.80 20 0 3
	-737 0 1.157 1.352 0.000 4.77 24@8	-737 0 1.133 1.302 0.000 4.77 24@8	6 15 34 1 1.045 1.115 30.23 4.80 20 0 13	-730 0 1.281 1.488 0.000 4.80 20@8	-730 0 1.185 1.462 0.000 4.80 20@8	4 5 19 3 0.612 0.914 31.73 4.80 20 0 2	
	0 17 35 2 1.133 1.289 26.89 4.89 8 25 38	6 0 20 3 1.045 1.115 30.24 4.80 20 15 13	5 3 17 0 1.065 1.172 30.42 4.77 24 3 0	-730 0 1.267 1.480 0.000 4.80 20@8	-717 0 1.139 1.476 0.000 4.89 8@4	0 3 10 0 0.392 0.730 31.34 4.77 24 1 1	
	14 37 37 1 1.166 1.314 26.54 4.86 12 0 27	-730 0 1.281 1.488 0.000 4.80 20@8	-730 0 1.267 1.481 0.000 4.80 20@8	-718 0 1.160 1.468 0.000 4.86 12@4	0 2 29 0 0.519 0.914 31.73 4.80 20 4 5		
	-730 0 1.271 1.488 0.000 4.80 20@8	-730 0 1.185 1.462 0.000 4.80 20@8	-717 0 1.140 1.476 0.000 4.89 8@4	0 5 30 2 0.521 0.921 31.30 4.80 20 3 4			
	-723 0 1.068 1.429 0.000 4.86 12@6	3 0 16 1 0.613 0.916 31.35 4.77 24 1 1	0 0 3 1 0.392 0.730 31.52 4.81 20 5 5				
	3 0 33 3 0.360 0.662 32.16 4.80 20 4 3						

Time [FPD]	**0.00**
Cyc. Burnup	**0.000**
Avg. Burnup	**14.756**
Power [MW]	**2988.0**
Boron [ppm]	**1652.8**
FdH	**1.488 (13)**
Fq	**1.863 (7)**
Pbar	**1.298 (4)**
AxOff [%]	**-0.89**

EOC26=24.569 MWd/kg — Mass=83916 kgHM
2009-02-26_12:00:33 — ROSA 7.7.1/18 © 2009 NRG — Page 1

Fig. 5 Doel-4 24 month equilibrium cycle at BOC.

ROSA Summary Report for Reactor DOE4 C27 / 80F NW

Nat_CycleLength	659.2	Max_FdH	1.489	FdH_Shape>1.485	0.0011	Max_Pbar	1.350
Max_Psub	1.396	Max_Fq	1.863	Max_Boron	1652.8	Max_MTC@HZP	0.0
Max_BurnRCCA	54.93	Max_BurnAssy	54.93	Max_BurnRod	59.86	OctSymPower	0.173
OctSymFresh	0.000	OctSymBurned	3.010	QTilt_Angle	4.000	Enrichment	4.817
Gad_Weight	215.96	BP1_Rods	1440	FuelCost	86.965	SDM	3568
DischargeBu_80	48.22	Kinf_Disch_80	0.9365				

End of Cycle

2206 0 **0.839** **0.824** **52.14** **56.19**	*1 5* **25 1** **0.926** **0.963** **53.43** **59.15** *0 6*	*0 5* **-735 0** **1.299** **1.324** **31.52** **35.19** *0 5*	*3 0* **-725 0** **1.260** **1.298** **32.15** **35.37** *3 0*	*6 0* **7 0** **1.011** **1.031** **54.77** ∅ **59.86** *6 0*	*0 1* **-738 0** **1.310** **1.336** **32.20** **35.23** *0 1*	*18 0* **-728 0** **1.194** **1.288** **29.13** **34.39** *18 0*	*17 0* **4 0** **0.533** **0.755** **43.85** **52.11** *17 0*
RCCA [cm] Assy Rot Pow (Match‰) FdH (Match‰) Burnup Rod Burnup ∅ x Bu%	*0 11* **31 2** **1.012** **1.007** **51.85** **59.66** *11 19*	*0 3* **-737 0** **1.295** **1.315** **31.34** **34.71** *1 1*	*0 7* **26 2** **1.031** **1.089** **52.80** **58.82** *5 11*	*3 0* **14 3** **1.030** **1.071** **52.70** **59.17** *12 10*	*3 3* **-730 0** **1.292** **1.320** **32.17** **35.18** *3 0*	*37 14* **-723 0** **1.100** **1.248** **26.53** **33.94** *27 0*	*19 5* **13 1** **0.434** **0.702** **41.57** **50.78** *11 0*
	0 1 **-737 0** **1.295** **1.315** **31.35** **34.71** *3 1*	*5 3* **-737 0** **1.262** **1.313** **30.42** **33.91** *3 0*	*3 7* **34 1** **0.973** **0.980** **54.48** **59.86** *0 6*	*0 4* **-730 0** **1.260** **1.293** **31.73** **35.27** *2 5*	*15 6* **-730 0** **1.228** **1.294** **30.24** **35.13** *13 0*	*21 9* **19 3** **0.666** **0.885** **47.15** **56.89** *13 0*	
	0 5 **35 2** **1.031** **1.089** **52.80** **58.82** *7 11*	*3 0* **20 3** **0.973** **0.980** **54.49** **59.86** *7 6*	**17 0** **0.970** **0.980** **54.93** **58.70**	*4 5* **-730 0** **1.238** **1.277** **31.29** **34.90** *3 0*	*38 17* **-717 0** **1.068** **1.217** **26.89** **34.11** *25 0*	*21 8* **10 0** **0.443** **0.734** **41.33** **50.25** *13 0*	
	3 12 **37 1** **1.030** **1.071** **52.70** **59.17** *0 10*	*0 2* **-730 0** **1.260** **1.293** **31.73** **35.27** *4 5*	*4 3* **-730 0** **1.238** **1.277** **31.30** **34.91** *5 0*	*33 20* **-718 0** **1.080** **1.196** **27.49** **33.75** *20 0*	*19 9* **29 0** **0.535** **0.822** **44.37** **53.43** *11 0*		
	4 3 **-730 0** **1.291** **1.320** **32.16** **35.17** *3 0*	*15 13* **-730 0** **1.227** **1.294** **30.23** **35.12** *6 0*	*38 25* **-717 0** **1.068** **1.218** **26.89** **34.11** *17 0*	*21 13* **30 2** **0.537** **0.828** **43.99** **52.73** *11 0*			
	37 27 **-723 0** **1.100** **1.248** **26.54** **33.94** *14 0*	*21 13* **16 1** **0.665** **0.886** **46.78** **56.79** *7 0*	*17 9* **3 1** **0.443** **0.734** **41.50** **50.05** *6 0*				
	19 11 **33 3** **0.434** **0.702** **41.57** **50.78** *5 0*						

Time [FPD]	**690.00**
Cyc. Burnup	**24.569**
Avg. Burnup	**39.324**
Rel. Power	**0.952**
Boron [ppm]	**10.0**
FdH	**1.336 (6)**
Fq	**1.582 (6)**
Pbar	**1.247 (6)**
AxOff [%]	**4.48**

2009-02-26_12:00:33 ROSA 7.7.1/18 © 2009 NRG Page 12

Fig. 6 Doel-4 24 month equilibrium cycle at EOC.

4.4 Improved Next Cycle Design

At NEK (Slovenia) the use of ROSA for the core design work for cycle 24 of the 121-assembly Krško plant resulted in an improved loading pattern with respect to the fuel vendor's design[5]. The NEK design had a lower average feed enrichment (cost reduction) and improved safety parameters.

5. CONCLUSIONS

The ROSA code system has shown to be a powerful practical tool for optimizing PWR fuel reloads, being presently applied to numerous reactors worldwide. The primary objective in most cases being minimizing fuel reload cost, the code in addition allows the simultaneous optimization of over 50 parameters, including a variety of safety related parameters. Considerable savings in the fuel cost for a core reload can be achieved by ROSA, especially when faced with the significantly increased number of constraints that has been introduced over the last few years.

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