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ROSA, A FLEXIBLE LOADING PATTERN OPTIMIZATION TOOL FOR PWRs

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ABSTRACT

Core design is a challenging optimization problem due to the vast number of loading pattern possibilities, in combination with a variety of complex constraints and economical targets. 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 in a day. Several new developments with regard to rules and optimization parameters have been realized recently e.g. a true shutdown margin parameter has been implemented. With the ROSA code system economic core designs with challenging constraints have been realized. It is concluded that the ROSA code is a powerful tool for core design and has been applied successfully in a variety of cases.

1. INTRODUCTION

Core design is a challenging optimization problem due to the vast number of loading pattern possibilities, in combination with a variety of complex constraints and economical targets. During the last decade PWR load factors have improved significantly, enrichment and assembly burnup has been further increased and many plants have been upgraded in power level. Several new issues have appeared in PWR core behavior e.g.: control rod insertion problems in highly burned assemblies, core axial offset anomaly, axial offset deviation, grid to rod fretting in certain core regions, quadrant tilt problems, fuel failures in high power core regions with adjacent feed assemblies etc..

During the same timeframe the ROSA code system for PWR core design has been further developed and is now capable to account for most of the issues mentioned above. Even the elaborate evaluation of shutdown margin has been successfully implemented for use during the automated core design phase.

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 (including cycle depletion) can be evaluated on a workstation in a day. The code can be switched between manual and automatic mode. In addition to single cycle also equilibrium cycle optimization is possible.

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.

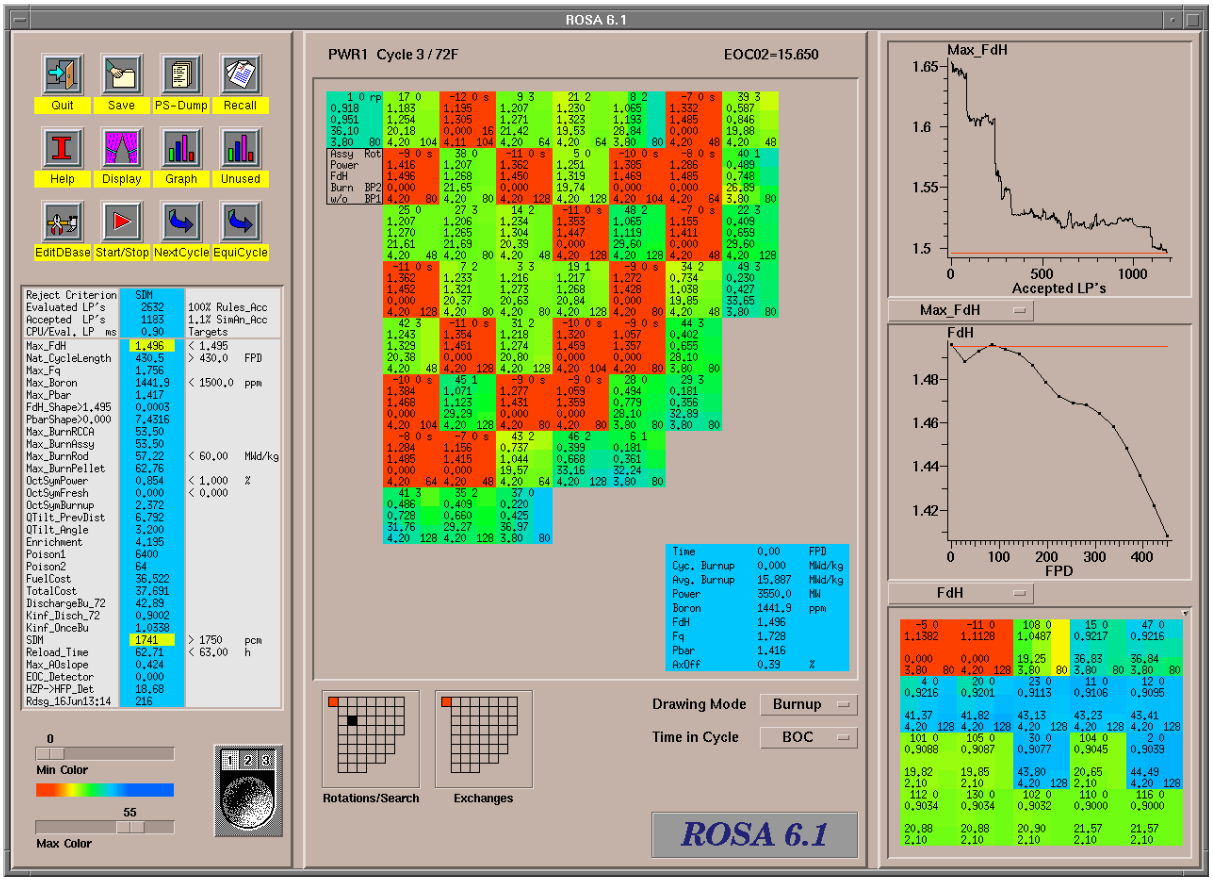

Fig. 1 ROSA graphical user interface.

A flow chart of the ROSA code is shown in figure 2. The code starts by evaluating the initial 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).

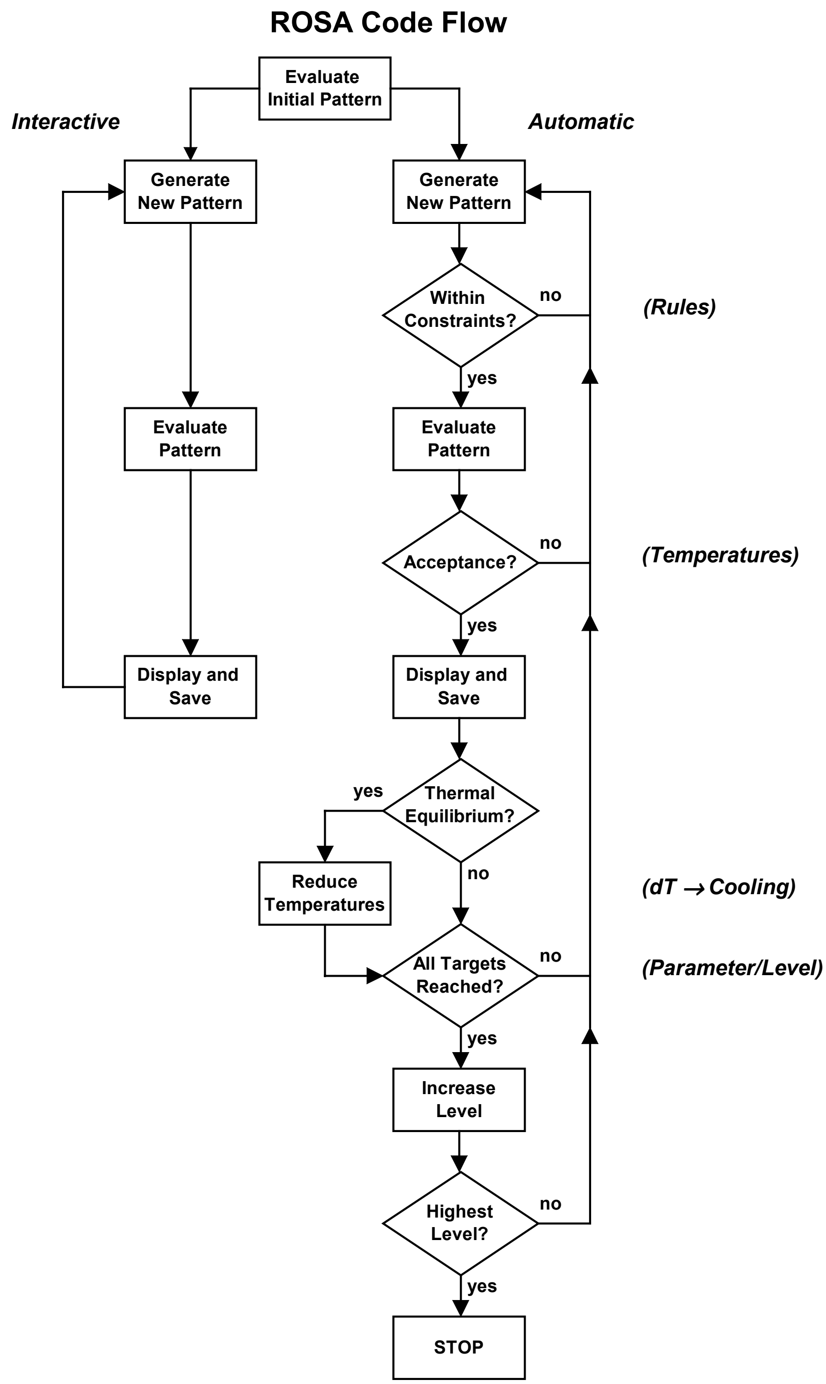

Fig. 2 ROSA Flow Chart.

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 (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 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 ±3 days for natural cycle length. Typical full cycle evaluation takes 25 to 250 ms CPU time per loading pattern (on a 550 MHz HP C3600 workstation), depending on core-size, axial mesh, number of burnup steps, and the previously evaluated loading pattern (convergence). More than 30 parameters can be optimized simultaneously, amongst others: peaking factors, natural cycle length, burnup limits, economics (fuel cost), shutdown margin, and octant symmetry.

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 (typically after ~500 accepted loading patterns at so-called “thermal equilibrium”) 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. Examples are to restrict highly burned fuel to (parts of) the core periphery in order to meet burnup limits at EOC, or to force a certain number of feed assemblies under control rods in order to meet shutdown margin (see also the SDM parameter in section 3.2).

Recently the need has come up to control the feed pattern in a way that the number of feed assemblies adjacent to a feed assembly can be restricted, because of the occurrence of fuel failures in high power core regions with adjacent feed assemblies in a US power plant. A new rule option is implemented in ROSA to allow users to restrict the number of feed-feed interfaces per assembly to values between zero and three for given core locations. Use of a value of zero will force a checkerboard loading of feeds in the specified core region, whereas a value of two will prevent so-called T-joints of feeds.

The risk of grid to rod fretting around the central assembly can be reduced by not allowing those assemblies to come back in the same core region in a subsequent cycle. A rule to control this is not a new code development, but a new application of existing possibilities.

Extensive use of 156-IFBA (Integral Fuel Burnable Absorber) assemblies could lead to potential DNB propagation concerns. Although this is of minimal concern, a conservative rule option is implemented in ROSA to prevent adjacent 156-IFBA assemblies and in addition (optionally) to restrict burned 156-IFBA assemblies to certain core locations (e.g. to the low power core periphery).

3.2 Optimization parameters

With the current code version more than 30 parameters can be optimized simultaneously. Most of these parameters are shown in figure 3, where the left part of the GUI with parameter names, values and targets is enlarged. Several parameters have been developed recently:

Reject Criterion	SDM		
Evaluated LP's	2632	100% Rules_Acc	
Accepted LP's	1183	1.1% SimAn_Acc	
CPU/Eval. LP ms	0.90	Targets	
Max_FdH	1.496	< 1.495	
Nat_CycleLength	430.5	> 430.0	FPD
Max_Fq	1.756		
Max_Boron	1441.9	< 1500.0	ppm
Max_Pbar	1.417		
FdH_Shape>1.495	0.0003		
PbarShape>0.000	7.4316		
Max_BurnRCCA	53.50		
Max_BurnAssy	53.50		
Max_BurnRod	57.22	< 60.00	MWd/kg
Max_BurnPellet	62.76		
OctSymPower	0.854	< 1.000	%
OctSymFresh	0.000	< 0.000	
OctSymBurnup	2.372		
QTilt_PrevDist	6.792		
QTilt_Angle	3.200		
Enrichment	4.195		
Poison1	6400		
Poison2	64		
FuelCost	36.522		
TotalCost	37.691		
DischargeBu_72	42.89		
Kinf_Disch_72	0.9002		
Kinf_OnceBu	1.0338		
SDM	1741	> 1750	pcm
Reload_Time	62.71	< 63.00	h
Max_AOslope	0.424		
EOC_Detector	0.000		
HZP->HFP_Det	18.68		
Rdsg_16Jun13:14	216		

Fig. 3 ROSA optimization parameter screen.

- Shape parameters for FdH and Pbar reflect the time integrated value of pin- and assembly power above a specified target. Max_Pbar and PbarShape can be used to minimize the maximum assembly power and its shape during the cycle. Both can be applied to reduce the risk of axial offset anomaly. Figure 4 shows examples of a Max_Pbar (left) and of a PbarShape (right) optimized core design. Note that both designs have about the same low Max_Pbar value of 1.30, but that the shape-optimized cycle has more margin during certain parts of the cycle, resulting in a (further) reduced AOA-risk.

- Max_BurnRCCA is the maximum assembly burnup under a control rod at EOC. With this parameter the risk of incomplete rod insertion can be reduced.

- QTilt_PrevDist can be used to reduce the risk of quadrant tilt by preventing clusters of burned assemblies that were located close to each other in their previous cycle of use. An alternative parameter is QTilt_Angle. Instead of comparing previous cycle assembly distances, change in angle with respect to previous cycle core location is evaluated for each burned assembly in the quarter core. A flat distribution of angle differences is the optimization target.

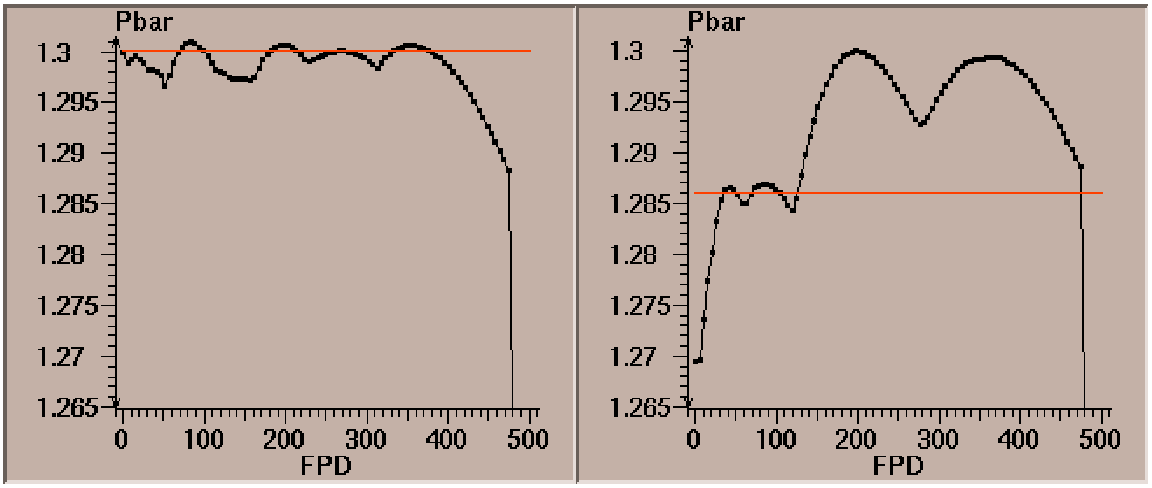

Fig. 4 Pbar (left) and PbarShape (right) optimized cycle.

– SDM is the shutdown margin [pcm], which is evaluated with a full core model at EOC (needed for the “stuck-rod” cases). Impact of uncertainties like rodworth, extra cooldown and reactor overpower can be modeled explicitly. Preconditioning (cycle depletion with partially inserted D-bank) is not yet modeled. The CPU-time consumption of this parameter is relatively small in automatic optimization mode, because most of the cases have already been rejected before the SDM parameter needs to be calculated at EOC (depending on other parameters and annealing temperatures involved). In interactive mode this parameter can add 50–200 ms of CPU-time per case, which is relatively small compared to assembly drag and drop time. Note that the availability of the SDM parameter prevents users from having to define rules based on a-priori knowledge to force a certain number of feed assemblies under control rods.

– Reload_Time is an estimate of the time needed to shuffle the previous cycle core to the new core. In-core or ex-core shuffling mode can be selected. The parameter can be used to design a core with a reduced number of insert shuffles and minimized number of assembly moves, thereby saving outage time. Details of this application have been published in [4].

– Max_AOslope can be used to reduce rapid changes in the core axial offset, a phenomenon, sometimes occurring during gadolinium-burnout, that requires frequent calibration of detectors at the plant. With this parameter the AO-changes can be minimized. A possible reduction of ~10% in AO-slope has been demonstrated for the same core inventory of a Gd cycle of one of TVA’s

Sequoyah units. More reduction is possible when the feed inventory can be changed.

- EOC_Detector is the EOC assembly power at a user-defined location (typically a D-bank location). It can be minimized to improve rod ejection margin (in both reactivity and F_q). An explicit rod ejection calculation (like SDM) will be implemented in the near future to reduce the need for iteration with the license code.

- HZP->HFP_Det can be used to reduce the change in ex-core detector response between hot zero power and hot full power state at BOC startup. ROSA performs an additional HZP state calculation at BOC when this parameter is requested. Changes of almost 25% in detector response during startup have been observed in calculations of actual plant cycles. This value could be reduced to below 12%, without (negative) impact on other optimization parameters. Good linearity of ex-core detectors is important to prevent frequent calibration during plant startup.

- Rdsg_… is a parameter that counts the required number of assembly moves between an initial core design and the current loading pattern. Optionally the number of extra insert moves can be added. This parameter can be used for emergency core redesign with minimal extra assembly (and insert) moves.

4. RESULTS AND CONCLUSIONS

The latest Dutch Borssele plant cycles have, in addition to the normal safety and economics parameters, also been optimized for reduced outage length[4]. It was possible to save approximately 5-7 hours of core reloading time by using a new design strategy, aimed at reducing insert shuffles and minimizing assembly moves. Besides for the Dutch Borssele plant, the ROSA code is also being used for several PWRs in the USA.

For TVA's Watts Bar unit 1 reactor it was possible to design a cycle 4 core with only 76 feed assemblies, followed by a high energy cycle 5 core with only 77 feed assemblies and approximately 535 days of natural cycle length. It was possible to design an economical core using only 72 bundles for cycle 6. Details of the cycle 6 design work have been published in [5]. The Watts Bar core has 193 assemblies and uses Vantage 5H / RFA-2 fuel.

For Southern Nuclear's Vogtle unit 2 cycle 11 an aggressive core design with a very low maximum normalized assembly power (approximately 1.30) could be realized using only 80 feed assemblies. This low maximum assembly power was required to reduce the risk of axial offset anomaly. Details of the cycle 11 design have been published in [6]. The Vogtle core has 193 assemblies and uses Vantage 5 fuel.

It is concluded that the ROSA code is a powerful tool for core design that has been applied successfully in a variety of cases.

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