Loading Pattern Optimization for Standard and End-Of-Life Cycles of Ringhals PWR's with ROSA.

H.P. Vierstraete¹, F.C.M. Verhagen¹, P.H. Wakker¹, H.P.M. Gibcus¹,
J. Loberg², E. Dalborg², C. Malm²

1) Company: NRG
   Address: Utrechtseweg 310, Arnhem, The Netherlands
   Telephone: +31 26 356 8563
   E-mail: f.verhagen@nrg.eu

2) Company: Vattenfall
   Address: Evenemangsgatan 13, Solna, Sweden

Summary – The core-loading pattern is decisive for fuel cycle economics and safety parameters. ROSA, NRG’s manual and automatic loading pattern optimization code system for PWR’s, has proven to be a valuable tool for reactor operators to improve their fuel economics for over two decades. ROSA uses simulated annealing as optimization technique, in combination with an extremely fast 3-D neutronics code for loading pattern calculations. This paper outlines two recent applications of the ROSA code system for different Ringhals PWR units.

The purpose of the work was twofold: first to demonstrate the value of the ROSA tool by a blind 5 cycle core design benchmark against utility core design methods for Ringhals-4. A predefined discharge burnup increase with respect to 5 reference cycle designs had to be demonstrated. A complicating factor was the use of shielding assemblies, causing reduced core design flexibility.

The second part of the work was an End-Of-Life study for Ringhals-2 aiming at maximum energy production during the last two cycles. Reference designs for comparison were available.

ROSA models for quarter and full core were setup for both Ringhals units and successfully validated against core design code results for natural cycle length (boron curve), peaking, EOC assembly and rod burnups, MTC, and SDM. In order to compensate for (small) peaking differences between ROSA and license codes an easy to use peak-matching method was implemented in ROSA. This helped a lot to generate optimized solutions that also worked in the license code after one or a few iterations.

For Ringhals-4 the average discharge burnup of 212 assemblies (5 cycles) could be increased by 0.6 MWd/kg, whereas the target was 0.24 MWd/kg. For Ringhals-2 an extra energy production of 10 EFPD could be demonstrated during the same number of calendar days and with the same fuel inventory. Both studies were confirmed by license code calculations.

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 neutronics code. With this code hundreds of millions to even billions of loading patterns can be evaluated 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.

One of the recent efforts has been the development of a full core version of the ROSA code. Until recently ROSA’s quarter core design capability appeared to be sufficient for all customers,
however during the last few years severe bow and twist issues with certain PWR fuel assemblies in both the US and Europe has resulted in the loss of sometimes more than 10 fuel assemblies per cycle. As these lost bundles were not distributed quarter core symmetric the need for full core redesign capability became urgent, as quarter core symmetric replacement of damaged fuel assemblies would cost a substantial fraction of the core inventory. The new standalone full core version has the ability to evaluate and optimize loading patterns in full core geometry and is compatible with the quarter core version (nearly the same set of parameters can be evaluated and optimized).

With the latest version 70 parameters can be optimized simultaneously. Recently several new parameters have been developed in cooperation with users to e.g. enable DNBR optimization for German nuclear power plants. Other examples are the capability to optimize on vessel fluence, cold zero power boron concentration or a customer specific quadrant tilt parameter.

2. ROSA CODE SYSTEM OVERVIEW

The ROSA code system\textsuperscript{1,2,3,4} has been developed at NRG for PWR core design and utilizes Simulated Annealing\textsuperscript{5} as optimization technique in combination with a very fast and accurate 3-D core neutronics code. With this code hundreds of millions to even billions of loading patterns (including cycle depletion, MTC, and SDM) can be evaluated on a workstation or PC in a day. ROSA’s strong points are fuel cost reduction (approximately 1% savings\textsuperscript{6} but in special cases more\textsuperscript{7}), enhanced operational margins, outage time reduction, and engineering time reduction.

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 (NW) previous cycle burnup, also the impact of short (SW) or long (LW) previous cycle burnup (the burnup window) can be evaluated. For each of these burnup states the impact of the Rod Insertion Limit (RIL) can also be evaluated. In addition evaluation and optimization of the combined SW-, LW-, and NW-state is possible (SLNW). This enables the user to find loading patterns with good peaking results in the NW-state, that will also have good peaking results in both the SW- and LW-state.

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, rotations, and/or fresh fuel composition changes. A GUI example of the ROSA quarter core version is shown in figure 1.

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, no fresh fuel with removable poison under control rods) and/or a-priori knowledge (e.g. no fresh fuel on the core periphery after cycle 1).

When a loading pattern satisfies the user defined rules, neutronics calculations are performed in 3D quarter or full 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 by pin power reconstruction is implemented. About 25 burnup steps per cycle are typically 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 5 to 500 ms CPU time per loading pattern on a modern PC with Cygwin or a Linux machine (with a single processor). The speed depends on the size of the reactor core (31-257 assemblies with 12-18 axial nodes), number of burnup steps, selected parameters, and the 3D-power differences with the previously evaluated loading pattern. More than 70 parameters can be optimized simultaneously, amongst others: peaking factors ($F_{\Delta H}$, Pbar, Psub, Fq, DNBR),
natural cycle length, burnup limits, economics/fuel cost, SDM, MTC, octant/quadrant symmetry, quadrant tilt, axial offset, vessel fluence, detector response, 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 activated parameters do improve the candidate loading pattern is always accepted. Worsening of certain parameter results may still be acceptable, depending on annealing temperatures. If the pattern is accepted, the results are displayed and the new pattern is the starting point for subsequent pattern generation. 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 will be increased, and optimization continues with additional parameters. When the highest level has been reached the optimization is completely finished and the code will stop.

In automatic mode an effective calculation time in the order of 0.01-1 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 to billions of 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. RINGHALS-4 DEMONSTRATION CASE

In order to demonstrate the value of ROSA for Vattenfall (VNF) a blind comparison was setup between Vattenfall’s core design team using their methods and NRG using ROSA. As a first step, ROSA models for quarter and full core were setup for Ringhals-4 and successfully validated against license code results of past cycles for natural cycle length (boron curve), peaking, EOC assembly and rod burnups, MTC and SDM. In order to compensate for (small) peaking differences between ROSA and license codes an easy to use peak-matching method was implemented in ROSA. This helped a lot to generate optimized solutions that also worked in the license code after one or a few iterations.

Ringhals-4 is a Westinghouse designed 3-loop PWR with 157 fuel assemblies and a current thermal power of 3292 MW. To prolong the vessel lifetime Shielding Fuel Assemblies (SFA) were introduced in 2009 in twelve peripheral positions of the core. Obviously the SFAs reduce the core design flexibility since 12 out of 157 assemblies are fixed, but moreover they increase the load of the other assemblies resulting in complexity to meet thermal peaking parameters.

The demonstration consisted of designing five consecutive projected cycles of Ringhals-4 which should comply with all standard safety and economic constraints. After all cycle designs were confirmed with Vattenfall’s license code to comply with the constraints, the designs were compared on the average assembly burnup of all discharged assemblies during the five cycles. A goal of an increase of 0.24 MWd/kgU in average assembly burnup was set by Vattenfall for ROSA to be called successful.

The fuel assemblies to be used in the demonstration case had a fixed enrichment, but the number and concentration of the Gadolinium burnable poison pins could be varied. Only one Gadolinium concentration per cycle was allowed.

Table 1 gives a summary of the outcome of the demonstration case. For each cycle the End-Of-Full-Power in Equivalent Full Power Days (EFPDs), the number of feed assemblies, the number of discharged assemblies and the average burnup of the discharged assemblies is presented. The ROSA core designs consistently showed a higher average discharge burnup for each cycle and also a slightly higher sum of EOFP. The average discharge burnup of 212 assemblies (5 cycles) could be increased by 0.6 MWd/kg, whereas the target was 0.24 MWd/kg. An increase of the average burnup of 0.6 MWd/kgU relates to about 500,000 € of fuel savings per cycle.
Table 1. Summary of VNF and ROSA results

<table>
<thead>
<tr>
<th>Cycle</th>
<th>VNF</th>
<th>ROSA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EOFP (EFPDs)</td>
<td>VNF</td>
</tr>
<tr>
<td>N</td>
<td>346.6</td>
<td>48</td>
</tr>
<tr>
<td>N+1</td>
<td>265.5</td>
<td>40</td>
</tr>
<tr>
<td>N+2</td>
<td>305.8</td>
<td>48</td>
</tr>
<tr>
<td>N+3</td>
<td>238.8</td>
<td>32</td>
</tr>
<tr>
<td>N+4</td>
<td>289.5</td>
<td>44</td>
</tr>
<tr>
<td>Total</td>
<td>1446.2</td>
<td>212</td>
</tr>
</tbody>
</table>

4. RINGHALS-2 END-OF-LIFE CASE

The second part of the work was an End-Of-Life study for Ringhals-2 aiming at maximum energy production during the last two cycles. Reference designs for comparison were available.

Again, first ROSA models for quarter and full core were setup and successfully validated against license code results of past cycles for natural cycle length (boron curve), peaking, EOC assembly and rod burnups, MTC, and SDM.

Next ROSA was used to design the core for the last two cycles of Ringhals-2. The fuel inventory was fixed for these last two cycles (N and N+1). A total number of 60 feed assemblies was available, 28 with lower enrichment and no Gadolinium rods and 32 with higher enrichment and different numbers of Gadolinium rods. The EOFP and total energy production of cycle N were boundary conditions determined by economic evaluations. The EOFP and total energy production of cycle N should be maximized within the given number of available calendar days.

The ROSA designs came out with 10 EFPDs more than the reference designs. One of the main contributions to this result, is the fact that ROSA was able to use feed fuel assemblies without Gadolinium rods in the last cycle. The last cycle was too short to burn the Gadolinium, so using any feed assemblies with Gadolinium rods would cause an undesired reactivity penalty at end of the last cycle. However, using only non-Gadolinium feed assemblies in the last cycle was not trivial with respect to keeping the thermal peaking parameters under the limits. This really required the use of a smart optimization tool such as ROSA. The extra 10 EFPDs are roughly equivalent to 6 M€.

5. CONCLUSIONS

The ROSA code system has shown to be a powerful practical tool for optimizing PWR fuel reloads, being presently used for about 30 reactors worldwide. The primary objective in most cases being minimizing fuel reload cost, the code in addition allows the simultaneous optimization of over 70 parameters, including a variety of safety related parameters. Due to its powerful optimizer considerable savings in fuel cost and/or enhanced operational margins can be achieved by ROSA.
For the two presented cases for the Ringhals reactors the following results were achieved. For Ringhals-4 the average discharge burnup of 212 assemblies (5 consecutive cycles) could be increased by 0.6 MWd/kg with respect to a reference design. For Ringhals-2 an extra energy production of 10 EFPD could be demonstrated during the same number of calendar days and with the same fuel inventory.

REFERENCES


