This paper presents the latest developments of the ROSA (Reloading Optimization by Simulated Annealing) code system with an emphasis on the first full-core version and the minimum DNBR (Departure from Nucleate Boiling Ratio) as a new optimization parameter. Designing the core loading pattern of nuclear power plants is becoming a more and more complex task. This task becomes even more complicated if asymmetries in the core loading pattern arise, for instance due to damaged fuel assemblies. For over almost two decades ROSA, NRG’s (Nuclear Research and consultancy Group) loading pattern optimization code system for PWRs, has proven to be a valuable tool to reactor operators in accomplishing this task. To improve the use of ROSA for designing asymmetric loading patterns, NRG has developed a full-core version of ROSA besides the original quarter-core version which requires rotational symmetry in the computational domain. The extension of ROSA with DNBR as an optimization parameter is part of ROSA's continuous development.

Introduction

The reload core design of a nuclear power plant is characterized by the placement of fresh fuel assemblies, the search of fresh fuel enrichment and poison, and the shuffling of burned fuel assemblies. Usually the fresh fuel assemblies are equally divided over the four quadrants of the core and located on rotational symmetric positions, thereby forming groups of four. If every group of four (burned) fuel assemblies stays on quarter-core symmetric locations until they are offloaded, the core stays quarter-core rotational symmetric. Asymmetries can arise if fuel assemblies are placed asymmetrically e.g. in case one or more assemblies of a group of four have to be offloaded from the core.

Not seldom these asymmetrical patterns are the result of distorted and/or damaged fuel assemblies discovered during outage inspections requiring an emergency core redesign. Especially during an emergency redesign any saving of (computing) time is important. Due to ROSA’s high speed it is very well suited for this kind of work. However the increasing number of asymmetrical core changes seen recently by some of our customers could not be comfortably handled by the original quarter-core ROSA version. To accommodate the optimization of asymmetrical loading patterns for normal and emergency core design, NRG has developed a full core version of ROSA. This new full-core version offers reactor operators a reliable optimization tool in complex asymmetrical loading pattern searches and has already proven to be a very valuable tool during recent outages.

Another recent development of ROSA is the extension of the code with DNBR as an optimization parameter. DNBR is an important operational thermal hydraulic safety
parameter that has to be considered in the design of a loading pattern. Although in some countries the minimum DNBR is used as the most important peaking criterion, most operators use a derived quantity like $F_{\Delta H}$ as their most important peaking criterion in loading pattern searches. In order to being able to offer ROSA to operators with a license dictating a sufficient safety margin to the minimum required DNBR for each loading pattern, the minimum DNBR is added as an optimization parameter to ROSA.

**ROSA Code System Overview**

The ROSA code system [1] 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.

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 central part contains the core display, a data block (blue) for the values of several parameters at the selected time in cycle, a mode and time selector, and two small windows showing assemblies involved in the last accepted change of the loading pattern and assembly locks (red). The left-hand side contains control buttons, optimization parameter values and targets, color scale sliders, and a mouse help button. The right-hand side contains a plotter showing the optimization process, a plotter showing parameter behavior during the cycle and the Spent Fuel Pool (SFP).

![Figure 1: ROSA Graphical User Interface](image-url)
The code starts by evaluating an initially provided loading pattern. In automatic mode new loading patterns candidates are generated automatically. A generated loading pattern is checked against flexible user-defined rules (e.g. no feed fuel on the core periphery or no removable poison on control rod locations). When a loading pattern satisfies the user defined rules, neutronics calculations are performed. Acceptance of a candidate loading pattern depends on the results of the activated optimization parameters. If the pattern is accepted, the results are displayed, if not a new pattern is generated. If all the targets have been reached the optimization is finished.

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.

**ROSA Full-Core Version**

The full core version (f-version) of ROSA was developed to accommodate the optimization of asymmetrical loading patterns and has basically the same functionality as the quarter-core rotationally symmetry version (q-version) including cycle depletion. The only exception is the equilibrium cycle option. This is not available in the f-version as it is not expected that any asymmetrical pattern will serve as a starting point in a study for an equilibrium cycle search.

Figure 2 shows the GUI of the ROSA f-version. The core display shows the full core. The user can toggle between this display or one of the four quarters of the core. When a quarter-core display is selected the right-hand side of figure 1 including two plotters and the SFP will be shown too. Manually dragging fuel assemblies from and to the SFP can be done in any of the quarter core displays. To facilitate the (un)loading of a core the user can switch between asymmetrical and symmetrical mode. In symmetrical mode a whole group of four assemblies can be swapped in one action. The SFP shows all individual fuel assemblies unlike the q-version, where each group of four assemblies is represented by only one assembly in the SFP. The left-hand side of the GUI containing the control buttons and optimization parameters was left unchanged.

Reactor operators try to avoid asymmetrical core loading patterns. If still being forced the operator will try to return to a symmetrical pattern again as soon as possible. In order to facilitate this the f-version has the following possibilities:

- Enabling symmetrical mode when working in manual mode. In this mode dragging one assembly from one position to another will result in equivalent actions of all assemblies belonging to the same group in the other three quarters of the core.
- Selecting automatic mode for the generation of new loading pattern candidates. In this mode part of the changes to the loading pattern will be octant symmetrical, quadrant symmetrical, or random. Changes are defined as exchanging fuel assemblies, rotating burned fuel assemblies, and/or changing the composition of fresh fuel assemblies by changing the enrichment and/or poison loading.
- Using the two new optimization parameters with respect to quadrant symmetry. The first one calculates the worst quadrant symmetry of the power distribution for all time points in the cycle while the second one calculates the quadrant symmetry of the core placements of burned fuel assemblies at Begin of Cycle.
Most operators use the maximum enthalpy rise hot-channel factor ($F_{\Delta H}$) as their most important peaking criterion as a measure of the core thermal margin in loading pattern searches. Where $F_{\Delta H}$ is commonly being defined as the relation between the maximum fuel rod power and the average fuel rod power in the core. In some countries, like Germany, not $F_{\Delta H}$ but the Minimum DNBR (MDNBR) is the most important peaking criterion. Figure 3 shows a typical cloud of DNBR versus $F_{\Delta H}$ data points from which can be seen that a difference as large as 0.15 in $F_{\Delta H}$ can yield the same DNBR values. This difference is caused by the fact that not only the enthalpy rise is decisive for DNBR, but also differences in subchannel geometry, mass flow, local quality, pressure and axial power shape.

ROSA contains a neutronics code for calculating the 3D quarter- or full-core power distribution. In order to be able to calculate DNBR two important modifications to the code system were made. First an improved pin-power reconstruction method was developed. This new method uses either the original 8x8 grid per assembly or a real pin by pin grid. To be able to calculate DNBR pin by pin reconstruction is needed. Secondly a DNBR-routine was added to the code system.
The DNBR-routine calculates the MDNBR based on the W3-correlation including corrections for the axial power shape (shape factor) and the cold wall factor in case a subchannel includes a guide tube [2]. For the calculation of the different parameters a non-iterative calculation method is developed. Most time consuming is the calculation of the enthalpy rise in all subchannels. The solution method starts at the bottom of the core and moves upward using the core inlet enthalpy as a starting condition. DNBR geometry information (rod diameters, pin and assembly pitch), a DNBR flow (tuning) factor and flow mixing (tuning) factors are required for this calculation. Additionally flow correction per assembly can be activated to correct mass flow in case assemblies with different flow resistances exist in one core loading.

In order to optimize a loading pattern for MDNBR ROSA contains two DNBR optimization parameters. The first one is the MDNBR based on the W3-correlation. The second DNBR parameter counts the weighted sum of the DNBR-factors for each fuel assembly below the DNBR target during the cycle. To view DNBR values DNBR information is added to the available drawing modes of the ROSA GUI. This means that one can see DNBR values for the assemblies that are loaded in the core as well as the axial DNBR distributions. Further a DNBR plotter has been added with functionality to view individual assembly DNBR (green line in Figure 4) in addition to the core wise minimum (black line) during the cycle. Figure 4 shows this plotter. The blue line represents the DNBR target (> 2.4).

DNBR values calculated by ROSA were compared to the licensed results for a German 16x16 plant. Figure 5 shows this comparison for the (most important) lower range of DNBR values. The comparison is done at 6 efpd and for four different loading patterns. In order to exclude a power distribution difference contribution in the comparison the DNBR-routine of ROSA was run with the 3D power distribution taken from the reference calculation. Finally the DNBR flow and mixing factors were tuned in order to ensure an optimum agreement for the lower DNBR values. The figure shows that ROSA is capable of predicting DNBR within ± 0.06 for the lowest values which is believed to be accurate enough for core loading pattern optimization purposes.
Conclusions

Two important developments of ROSA were presented in this compact: the full-core version and MDNBR as an optimization parameter. The full-core version is and has already proven to be a valuable and engineering time saving tool for core loading pattern optimization in case asymmetries in the loading pattern cannot be prevented. The extension of ROSA’s set of parameters with MDNBR offers the use of ROSA to operators using MDNBR as their most important thermal hydraulic safety criterion.

References