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# ECONOMIC OPTIMIZATION OF PWR CORES 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 for over a decade to be a valuable tool to reactor operators for improving their fuel management economics. 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 and discusses results of PWR specific applications of ROSA.
Core designs with a large variety of challenging constraints have been realized with ROSA. As a typical example, for the 193 assembly, Vantage 5H/RFA-2 fueled TVA's Watts Bar unit 1, a cycle 4 core with 76 feed assemblies was designed. This was followed by a high-energy cycle 5 with only 77 feed assemblies and approximately 535 days of natural cycle length. Subsequently, an economical core using 72 bundles was designed for cycle 6. This resulted in considerable savings in the cost of feed assemblies for reloads. The typical accuracy of ROSA compared to results of license codes is within ±0.02 for normalized assembly powers, ±0.03 for maximum enthalpy rise hot channel factor ($F_{\Delta H}$), and ±3 days for natural cycle length.

## I Introduction

PWR core design involves a multitude of possible loading patterns (LPs) and a variety of complex constraints and economical targets to consider. The number and nature of these so-called parameters may vary in nature. Some parameters are straightforward optimization parameters, either involving costs or safety margins. Other parameters must be satisfied in order to meet safety criteria set in the operating license and are hard constraints in nature, such as the peaking factors or the requirement to meet detector response criteria. Finally, parameters may be preferred, but not strictly required for LP approval, such as axial offset swing.
Reactor operators seek to find optimum ways to satisfy all above criteria. Traditionally, this is done manually by combining expert judgement with 3D neutronic calculations. Whereas providing fair results, this approach leaves room for much improvement in terms of fuel costs. In addition, requiring experienced resources and sufficient available time, the traditional approach is not always possible. For example in case of failure of a fuel assembly intended to be reloaded in the next cycle, the available time for core redesign may be severely reduced and less cost-effective loading patterns may result.
The ROSA code[1),2)] has been developed at NRG for PWR core design optimization. It applies simulated annealing as optimization technique, in combination with an extremely fast and accurate 3-D core simulator code. Over 35 parameters can be optimized simultaneously. An optimization run with the ROSA code takes in between five minutes and one day, depending on details of the optimization case, thus allowing comparison of various optimization strategies.
Several new issues have recently appeared in PWR core behavior, such as control rod insertion problems in high burnup assemblies, core axial offset anomalies and grid to rod fretting. The ROSA code has been extended to account for these new issues. In addition, the evaluation of shutdown margin has been implemented and can be applied during automated core design.

## II Overview of the ROSA code system

### II.1 Methodology

ROSA, acronym of Reloading Optimization by Simulated Annealing, generates loading pattern candidates by randomly shuffling and rotating assemblies and varying the composition of feed

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assemblies under a user-defined set of constraints. It uses simulated annealing to obtain optimum loading patterns. The code evaluates millions of loading patterns (including cycle depletion) on a workstation or PC in a day. The code can be switched between automatic and manual mode, thus allowing the user to interact with the optimization process. A powerful graphical user interface (GUI) enables the user to change optimization targets during the run or perform manual fuel movements (see Figure 1.) Besides single cycle, also equilibrium cycle optimization is possible.

### II.2 Optimization sequence

The code starts by evaluating the initial loading pattern, the reference pattern. In automatic mode, loading pattern candidates are generated by randomly exchanging fuel assemblies, rotating burned fuel assemblies, and changing the enrichment or burnable poison (BP) loading of fresh fuel assemblies. The generated loading pattern is first checked against user-defined constraints (denoted as rules), such as position lock of the central assembly or no feed fuel on the core periphery. When a loading pattern passes this test, neutronics calculations are performed in order to evaluate the candidate loading pattern for the entire cycle. This is done in a quarter core geometry, assuming rotational symmetry, and using typically 12 to 18 axial nodes. A 1½ group 3-D coarse mesh kernel method is applied, coupled to a 2-D fine mesh method, and using 3×3 or 4x4 nodes per assembly.

The results of the neutronics calculation are evaluated against the active optimization parameters. More than 35 parameters can be optimized simultaneously, such as fuel cost, peaking factors, natural cycle length, burnup limits, shutdown margin and octant symmetry. Evaluation consists of comparing the loading pattern to the previously accepted pattern. If all parameters improve, the pattern is accepted. Deterioration of some parameters may still result in acceptance of a loading pattern, depending on the so-called annealing temperatures of those parameters[3)4)]. Results of an accepted pattern are displayed. After typically 500 accepted loading patterns during an optimization run, thermal equilibrium is reached and annealing temperatures are automatically lowered in order to reach convergence. The optimization is completed if all targets have been met.

### II.3 Special features

ROSA contains a special feature to speed up the optimization process: multi-level optimization. The user can define specific parameters and targets for each level. When all targets of the current level are reached, optimization proceeds with the next level with the parameters defined for that level. This continues until the targets of the highest level have been reached.

Optimization can be run fully automatically or in interactive mode[5)]. In the latter, the user can interrupt a run, manually exchange two fuel assemblies, rotate a burned assembly or change the composition (enrichment, poison loading) of a fresh fuel assembly. The new loading pattern is evaluated with respect to neutronics, and always accepted and displayed.

### II.4 Performance

The typical accuracy compared to results of license codes is within ±0.02 for normalized assembly powers, ±0.03 for maximum enthalpy rise hot channel factor ($F_{\Delta H}$), and ±3 days for natural cycle length. A typical full cycle evaluation takes in between 25 and 250 ms CPU time per loading pattern on a 550 MHz HP C3600 workstation, the precise CPU time depending on the core size, axial mesh, number of burnup steps and the previously evaluated loading pattern. About 100 million loading patterns can be evaluated in automatic mode in one day.

### II.5 Optimization parameters

The current version of ROSA contains over 35 user-activated, optimization parameters. ROSA allows users to either maximize of minimize any of the optimization parameters. Table 1 shows the ROSA optimization parameters.

### II.6 Fuel and Absorber model

The fuel is modeled on assembly basis in ROSA, allowing for a large flexibility in defining fuel composition and geometry. At present, up to 999 assembly types can be defined and each assembly type can be divided in up to five axial zones, or subtypes (see Figure 2.) For each assembly type, burnup limits can be defined for the assembly, per rod and per pellet. These limits are used to define the burnup related optimization parameters.

ROSA allows the simultaneous use of a variety of burnable poison (BP) rods. At present integral and removable poison rods can be accommodated in one core, including IFBA (Integrated Fuel Burnable Absorber), WABA (Wet Annular Burnable Absorber), Pyrex, LBP (Lumped Burnable Poison), and Gadolinium.

Sometimes fuel assemblies with an asymmetric poison loading are used in a first cycle. This can be accommodated by defining 3×3 or 4×4 subtypes for each axial section individually.

### II.7 Economy model

By activating the FuelCost parameter, the ROSA code will calculate the reloading cost, based on

basic data for cost items to be provided by the user. Most of these items refer to fuel cycle cost, comprising the kg price of natural uranium including conversion, the SWU price of enrichment, the percentage of U-235 in the tails, and the assembly fabrication cost per type or per kgU.
Burnable poison rods can present an important cost, and related cost items are the price of the two types of burnable poison rods allowed in ROSA, and - if applicable - the money equivalent of free burnable poison rods, to be subtracted from the fuel cost.
The total cost is calculated from the fuel cost and the production loss during the coastdown period. The production loss during the coastdown period is converted into money by multiplying with the income or replacement power cost of a full power day.

## III Recent developments of ROSA

Although clearly at the forefront of core reload optimization, the ROSA code is continuously extended with new features in order to implement user specific needs. Four recent developments will be described below.

### III.1 Reload Time

The “Reload_Time” parameter in ROSA gives the user access to the potential for reducing the shuffling time, both for in-core and ex-core shuffles. It has been shown in practice that PWR reload times can be reduced by typically seven hours or more. This results in accompanying net increase in production and net savings of personnel cost. The “Reload_Time” parameter in ROSA is an estimate of the time (in hours) needed to shuffle the previous core to the new core, based on all required unit core movements, such as incore assembly move, a core to pool assembly move, a control cluster move, and a thimble plug move. The estimated reload time for each loading pattern is evaluated as the sum of the unit core movements, multiplied by their movement time. In order to properly estimate the reload time, the user specifies typical times for all unit core movements. Also the possibility of specifying the optional mast sipping action for fuel that does not need to be moved in case of leakers in the core is implemented. In addition, various thimble plug and control rod types can be specified, in order to allow taking into account the impact of black and gray control rods or several control rod management strategies on reload time. It must be noted that the actual net production gain also depends on the natural cycle length and the applied coast down period.[6)]

### III.2 Shutdown margin

The shutdown margin (SDM) is a safety relevant parameter, defining the amount of reactivity by which the reactor is subcritical at End of Cycle (EOC) in case of a stuck-rod, i.e. the single rod cluster assembly of highest reactivity worth that is assumed to be fully withdrawn. ROSA calculates the SDM in pcm with a full core model at EOC in a simple, fast way. The implementation has been benchmarked to more detailed core design results, showing the ROSA estimate of SDM to be accurate. Uncertainties, such as rodworth, extra cooldown, and reactor overpower can be modeled explicitly. The CPU penalty of this extension is relatively small. The parameter is relevant for plants with little SDM, in particular in case SDM may be degraded due to crud induced power shift (CIPS)[)].

### III.3 Shape parameters

Shape parameters provide useful safety relevant information to the core designer. Decreasing average and peak assembly powers (Pbar and FdH, respectively) is the usual method for decreasing CIPS, formerly denoted as axial offset anomalies (AOA). CIPS refers to deviations in the axial offset, usually defined as the difference between the integrated powers in the top and bottom halves of the core, normalized to their sum. The phenomenon is associated with boron crud formation due to subcooled boiling in high power core regions. The ROSA power shape parameters for FdH and Pbar reflect the time integrated value of pin and assembly power above a specified target value. The maximum relative assembly power during the cycle (ROSA parameter Max_Pbar) and the weighted sum of the peak Pbar-factors in the core during the cycle (PbarShape) on the other hand can be used to minimize the maximum assembly power and its shape during the entire cycle or during a certain boron window only. Both can be applied to reduce the possibility of CIPS. Figure 3 shows examples of a Max_Pbar (left) and of a PbarShape (right) optimized core design. It is striking to see that both core designs have a Max_Pbar value as low as 1.30, but that the shape-optimized core design has more margin during a considerable part of the cycle, resulting in a further reduced CIPS risk.

### III.4 Rules

In practice, many plant-specific constraints may limit the flexibility of core design. For this reason, ROSA has been equipped with features, denoted as “rules” that allow the user to specify almost any limitation and constraint on core geometry and loading pattern. Rules are evaluated immediately following loading pattern generation, implying that loading patterns not satisfying the rules are

rejected at an early stage. An example of the application of rules is the control of the feed pattern in such a way that the number of feed assemblies adjacent to a feed assembly can be restricted. The development of this feature was triggered by the occurrence of fuel failures in high power core regions with face adjacent fuel assemblies in a power plant. The new rule allows the user to limit the number of feed-feed interfaces per assembly and per specified core location between zero and three. Note that use of a value of zero results in a checkerboard loading of feeds, whereas a value of two will prevent T-joints of feeds.
Other examples of recently implemented rules are the restriction of high-burnup assemblies to user-defined parts of the core periphery, in order to meet burnup limits at EOC, or to force a specified number of feed assemblies below control rods, in order to meet shutdown margin. Finally, a conservative rule was implemented in ROSA to prevent adjacent 156-IFBA assemblies and to restrict burned 156-IFBA assemblies to certain user-defined core locations, for example to the low power core periphery. This development was triggered by recent findings that extensive use of 156-IFBA assemblies could lead to potential DNB propagation concerns.

## IV Results

### IV.1 Number of feed assemblies

ROSA was applied to obtain optimum core designs for SNC's Vogtle unit 2, the prime optimization parameter being low maximum normalized assembly power.[7)] For this purpose, core designs with low Pbar and FdH were searched, by minimizing the number of feed assemblies. A three enrichment zone core design was applied, with enrichments of 4.0, 4.4 and 4.95 w/o. The design resulted in a normalized assembly power as low as 1.30. Only 80 feed assemblies were needed, resulting in a financial savings in the cost of feed assemblies for the core reload of approximately 1 million USD relative to the reference core designs found with existing methods. Scoping studies showed that similar savings are feasible for future core designs[7)]. Through its feature of generating detailed costing data per cycles, such as enrichments, poison rods, and batch burnups, ROSA allows easy production of long-term budget estimates. The Vogtle unit 2 core has 193 assemblies and uses Vantage 5 fuel.
For cycle 4 of TVA's Watts Bar unit 1 reactor, use of ROSA resulted in a new core with only 76 feed assemblies[8)]. Cycle 4 was followed by a high energy cycle 5 with only 77 feed assemblies, and approximately 535 days of natural cycle length. The subsequent cycle 6 could be designed with 72 feed assemblies. The Watts Bar core has 193 assemblies and uses Vantage 5H/RFA-2 fuel.

### IV.2 Reload time

ROSA has been applied for optimizing core reloads of the Dutch Borssele reactor for many years and, starting with cycle 28 in 2001, also for reloading time optimization. Other parameters that are considered in core design optimizations are $F_{\Delta H}$, natural cycle length, maximum rod and pellet burnup. The unit core movements applied for calculating shuffling time are listed in Table 2. The Borssele core has 121 fuel assemblies, 28 control rods and 24 instrumented assemblies. The distribution of instrumented assemblies over the core quadrants is not symmetrical. Cycle 30 involved two types of fresh feed assemblies. In addition, a number of partially burned fuel assemblies from the spent fuel storage pool were reloaded into the core. The remaining fuel assemblies were retained from the previous core. Approximately 25% of the fuel is replaced every cycle. For cycle 28, a reload time of 34 hours was achieved, whereas for cycle 30 a reload time of 25 hours was achieved. To our knowledge, the latter is a world record. Whereas without optimization the total number of insert shuffles was typically 95, this number was reduced to 50-60 with reload time optimization. Figure 4 shows scatter plots of reload time versus the maximum enthalpy rise hot channel factor Max-FdH, and reload time versus natural cycle length. Reload optimization may in principle result in slight loss of natural cycle length. However, as follows from Figure 4, reload time correlates only weakly with natural cycle length. For the case shown, the net extra production achieved by means of reload time optimization was 3.3 hours at full power for cycle 28, compared to loading patterns optimized for maximum achievable natural cycle length. For cycle 30, the net extra production amounted to 5.7 hours at full power.

## V Summary and conclusions

The ROSA code system has shown to be a powerful practical tool for optimizing PWR fuel reloads, being presently applied to over ten reactors worldwide. The primary objective in most cases being minimizing fuel reload costs, the code in addition allows the simultaneous optimization of over 35 parameters, including safety-relevant parameters. Considerable savings in the cost of feed assemblies for a core reload can be achieved by ROSA, values of 1 million USD per cycle have been attained. The values of core safety parameters calculated with ROSA tend to be conservative with respect to values obtained with detailed codes or measurements.

A special feature of the ROSA code system is its speed, with a typical core optimization run defined by a set of user-defined rules and optimization parameters taking typically less than a day on a modern workstation.

The code does full justice to the real world, in which plant-specific features make every core-optimization a unique one. ROSA has proven to be a fast reliable way to perform scoping studies of various fuel products and design concepts, which is hard to achieve in another way. Through its feature of generating detailed costing data of cycles, ROSA allows the production of longer-term budget estimates. Finally, through its speed, ROSA is extremely suitable for generating emergency core redesigns during an outage.

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Table 1. Overview of ROSA optimization parameters.

| Optimization parameter | Description |
|---|---|
| SDM | Shutdown margin |
| Max_FdH | Maximum enthalpy rise hot-channel factor $F_{\Delta H}$ |
| Nat-CycleLength | Natural cycle length in full power days |
| Max_Fq | Maximum heat flux hot-channel factor |
| Max-Boron | Maximum boron concentration during cycle |
| Max_Pbar | Maximum relative assembly power |
| FdH_Shape | $F_{\Delta H}$ distribution above Max_FdH target in the core and during cycle |
| Max_MTC@HZP | Maximum moderator temperature coefficient (MTC) at hot zero power (HZP) during cycle |
| Min_Detector | Minimum power during cycle at first detector |
| EOC_Detector | End of Cycle (EOC) power at second detector for rod ejection control |
| HZP->HFP_Det | Begin of Cycle (BOC) BOC HZP to Hot Full Power (HFP) response change of first detector |
| Max_BurnRCCA | Maximum assembly burnup under a control rod at EOC |
| Max_BurnAssy | Maximum assembly burnup at EOC minus limit |
| Max_BurndRod | Maximum fuel rod burnup at EOC minus limit |
| Max_BurnPellet | Maximum fuel pellet burnup at EOC minus limit |
| Max_BuGradient | Maximum intra assembly burnup difference (2×2) at EOC |
| OctSymPower | Proportional to octant symmetry in the power distribution during cycle |
| OctSymFresh | Proportional to octant symmetry of fresh fuel (core position, w/o, BPs) |
| OctSymBurnup | Proportional to octant symmetry on the burnup at BOC |
| QTilt_PrevDist | Measure of previous distances between old fuel to prevent clustering |
| QTilt_Angle | Alternative quadrant tilt parameter based on assembly angle change |
| Enrichment | Average enrichment of fresh fuel |
| BP1_Rods | Total number of type 1 (often integrated) poison rods in fresh fuel |
| BP2_Rods | Total number of type 2 (often removable) poison rods in fresh fuel |
| BP2_Clusters | Total number of type 2 poison clusters in fresh fuel |
| FuelCost | Fuel cost according to the economy model |
| TotalCost | Total cost according to the economy model |
| Max_AOslope | Maximum slope of the Axial Offset-curve during cycle |
| Reload_Time | Time needed to reshuffle from previous to current core |
| Redesign | Number of Loading Pattern changes with respect to initial loading pattern |
| Discharge Burnup | Average burnup of the discharged fuel |
| Kinf_Discharge | Multiplication factor of the discharged fuel |
| Kinf_OnceBU | Multiplication factor of the once burned fuel |
| Min_Power_Ratio | Minimum ratio of assembly average power in current and previous cycle |
| Min_Pin-to-Box | Minimum $F_{\Delta H}$ /Pbar for assemblies with $F_{\Delta H}$(T)>0.9*FdHmax(T) |
| Max_Pin_Census | Maximum pin power value with 30% of pins higher during cycle |

Table 2. Borssele reactor unit movement times for shuffling operations.

| Unit movement | Time [min] |
|---|---|
| Incore assembly move (base time) | 8.0 |
| Incore assembly driving per assembly width | 0.054 |
| Incore assembly positioning per co-ordinate | 0.11 |
| Assembly move from core to pool or vice versa | 10.3 |
| Control rod move | 11.0 |
| Thimble plug move | 11.0 |
| Assembly mast sipping (optional) | 8.0 |

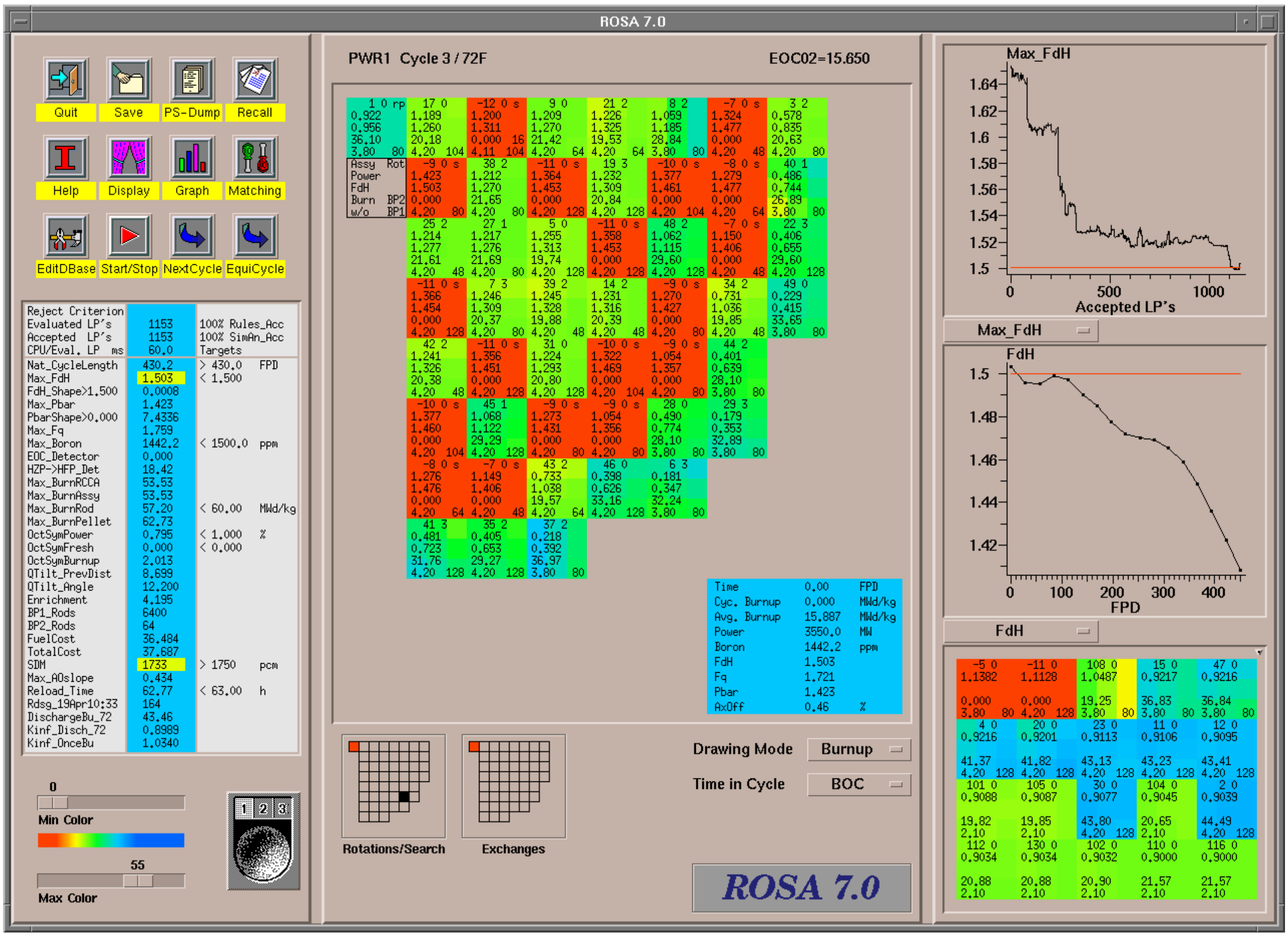

Figure 1. ROSA graphical user interface.

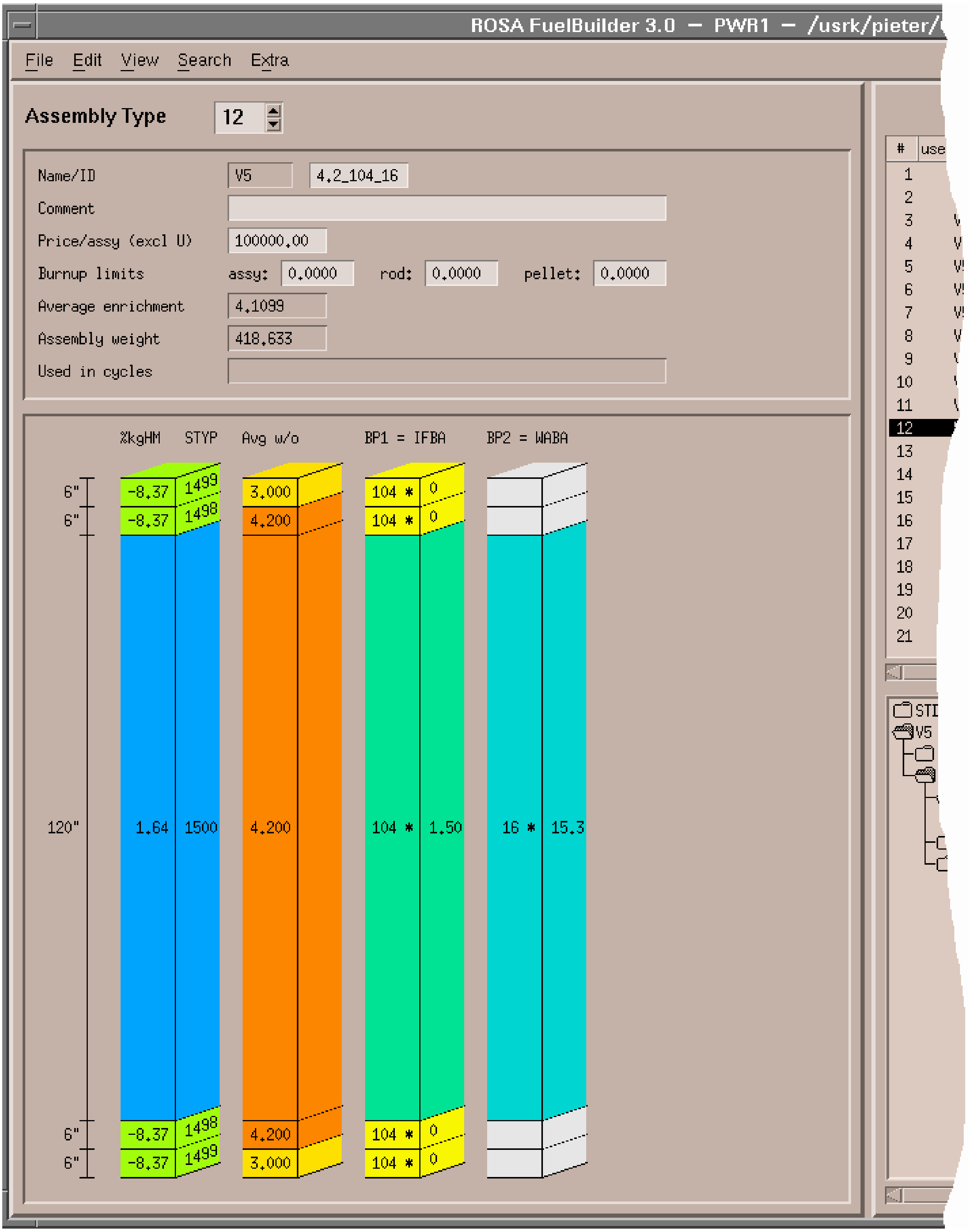


Figure 2. Current assembly info and view

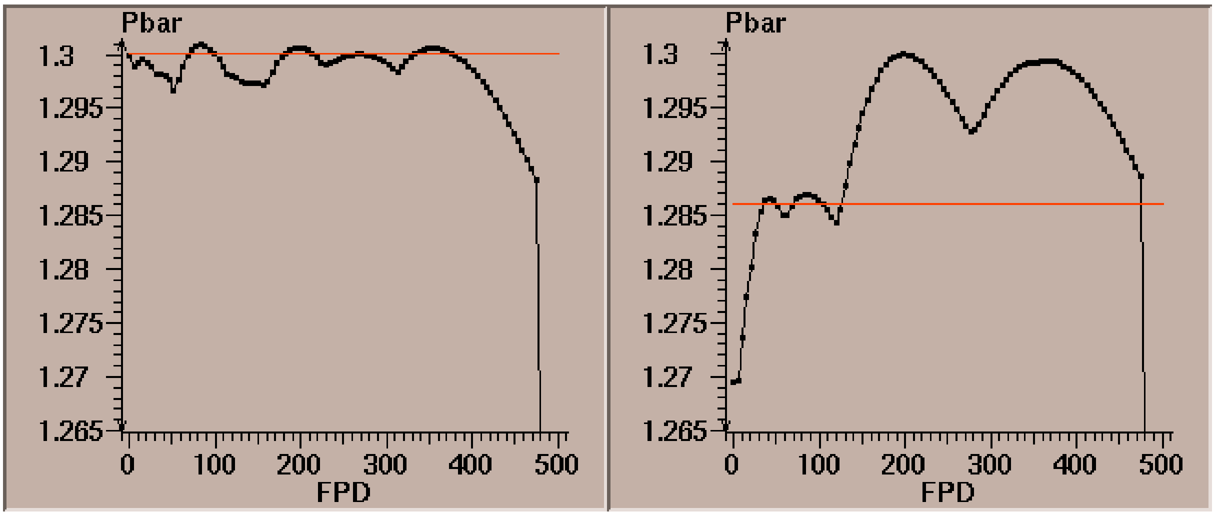


Figure 3. Pbar (left) and PbarShape (right) optimized cycle.

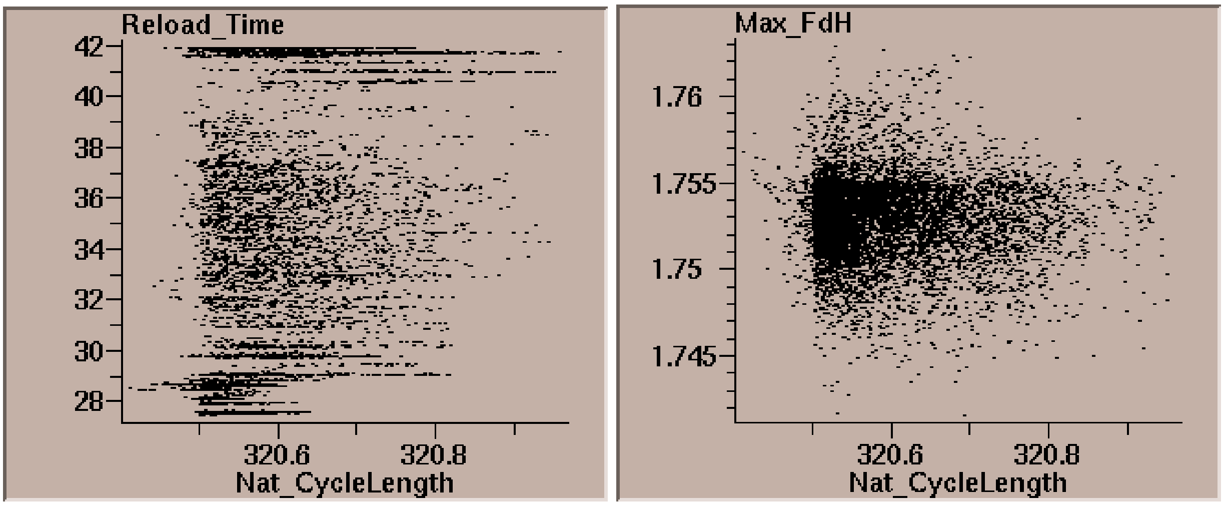


Figure 4. Reload time versus natural cycle length (left) and maximum enthalpy rise hot channel factor (right) scatter plot for $10^4$ LPs.

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