Advances in Nuclear Fuel Management III (ANFM 2003)
Hilton Head Island, South Carolina, USA October 5-8, 2003, on CD-ROM American Nuclear Society, LaGrange Park, IL (2003)

SNC'S USE OF ROSA TO FIND MORE ECONOMICAL LOADING PATTERNS FOR VOGTLE

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Keywords: SNC NRG ROSA Vogtle Optimization

ABSTRACT

Southern Nuclear's (SNC's) two Vogtle units are uprated, high power density T-hot plants. There are several reason why SNC needs to lower Vogtle's peaking factors far below the design limits. SNC would like to also lower nuclear fuel costs by reducing the number of feed assemblies. ROSA, NRG's loading pattern optimization code, is now being used by SNC to find loading patterns that have low peaking factors and have fewer feed assemblies.

1. INTRODUCTION

Vogtle is a two-unit four-loop Westinghouse plant that has been uprated to 3565 MWt. It is one of the Southern Nuclear Operating Company's (SNC's) three two-unit plant sites. Vogtle uses 17X17 Westinghouse Vantage-5 (skinny rod) fuel and operates with a Tavg of 586.4°F, which makes it a "hot" plant. Within Vogtle Unit 1 Cycle 9 SNC Core Analysis began increasing the number of feed assemblies and adding WABA's (to the IFBA's already being used) in order to address three issues. WABA's are the discrete Wet Annular Burnable Absorbers that reside in the guide tubes. IFBA's (Integral Fuel Burnable Absorbers) are boron coatings directly on the pellets. WABA's result in a small economic penalty (about ½ MWD/MTU per WABA rod). IFBA's result in virtually no economic penalty since it totally burns out and do not displace water like WABA's.

First, feed batch size was increased to reduce power and burnup in the once-burned fuel to gain additional RIP (rod internal pressure) margin in the once-burned fuel. SNC had already modified the fuel design in order to gain RIP margin by adding annular pellets, but there still was not a full core of fuel with annular pellets.

Secondly, due to the occurrence of AOA (Axial Offset Anomaly) in several prior cycles, SNC increased the number of feed assemblies in order to decrease average and peak assembly powers (P-bar and FΔh, respectively). AOA is a phenomenon that usually only occurs when "hot," high power density plants operate with relatively high boron concentrations. With higher P-bar's and FΔh's hot plants undergo a large amount of localized boiling in the upper grid spans. When a plant also has higher boron concentrations (i.e., greater than about 1200 ppm), boron in the coolant attaches itself to the crud in the high boiling regions. This results in more negative than predicted axial power distributions. Moderate amounts of AOA result in having to reevaluate the applicability of the core safety analysis models that were generated to calculate axial peaking factor margins (F_q). Worse AOA's can result in significant reduction in Shutdown Margin (SDM) to the point where derates have been necessary (though not at Vogtle). The interactions between the core physics and the chemistry are complex and not well understood. To address the coolant chemistry aspects of AOA, WABA's were added to the design to lower boron concentrations.

Lastly, WABA's were also added for the first time in several cycles in order to reduce Unfavorable Exposure Time's (UET's). UET is a criterion sensitive to HFP MTC and is used to evaluate a plant's vulnerability to an ATWS (Anticipated Transients without Scram). Just like for AOA, lower boron concentrations with WABA's result in lower MTC's, which result in lower UET's.

In Unit 1 Cycle 10 SNC again used a large number of feed assemblies and WABA's in order to deal with the issues discussed above. As one would expect, discharge burnups went down, and fuel costs began trending up. As a result of Westinghouse licensing an enhanced fuel rod design methodology and Vogtle having an entire core of fuel with more RIP margin, SNC looked seriously at decreasing the number of feed assemblies in Cycle 11. Also, Vogtle had not had AOA for several cycles, and Westinghouse had performed analysis to relax Vogtle's UET constraints. Thus, SNC designed Cycle 11 with fewer feed assemblies and WABA's. P-bar's and $F\Delta h$'s were up only slightly.

SNC had informally used NRG's ROSA loading pattern optimization code to assist in performing some scoping studies, budget calculations and preliminary loading patterns for several years. (NRG is the abbreviation for the Nuclear Research and consultancy Group in the Netherlands. NRG would be considered the Dutch knowledge center for nuclear technology.)

Since NRG's ROSA optimization code had not been integrated into SNC's core design process, it was not used to search on feed patterns or enrichments for Cycle 11. ROSA was constrained to optimize the burned fuel locations after the feed assemblies and locations had already been chosen. In hindsight, SNC did not allow ROSA to be used to its full potential in terms of generating new feed patterns in Cycle 11. During Vogtle 2, Cycle 9, AOA was observed for the first time in several years. SNC chose not to increase the number of feeds in Vogtle 1, Cycle 11 since the design had already been finalized. Thankfully, only mild AOA has been observed in Cycle 11. However, the number of feed assemblies and WABA's were increased in Vogtle 2, Cycle 10 due to the recurrence of AOA.

2. ROSA

ROSA[1] is a PWR fuel-management code. The name ROSA is an acronym for *Reloading Optimization by Simulated Annealing*. It generates loading pattern candidates by randomly shuffling and rotating assemblies under a flexible, extensive set of user defined constraints. ROSA also randomly changes the enrichments and poison loading of the feed assemblies. It uses Simulated Annealing to obtain optimum loading patterns, and ROSA is run with an incredibly flexible mouse driven X Window / Motif Graphical User Interface (GUI). It uses a lightning-fast version of the neutronics code LWRSIM.

After starting with an initial loading pattern, ROSA randomly selects a new pattern as discussed above. The pattern is checked against user-defined rules. If the rules are met with the new pattern, it is evaluated; if not, a new pattern is generated. Acceptance or rejection of patterns is performed by the simulated annealing algorithm. If "equilibrium" has been reached with an accepted pattern, the simulated annealing temperature is reduced. When all of the targets are reached the optimization is finished.

2.1 Optimization Parameters

In addition to P-bar and FΔh, there are a number of other parameters upon which SNC optimizes in ROSA. It should be noted that ROSA allows the user to either minimize or maximize any of the optimization parameters. Optimization parameters that are of particular interest to SNC are natural cycle length and boron concentration. Obviously, the core designer would like to maximize the cycle length for a respective fuel inventory. By minimizing boron concentrations, SNC minimizes the propensity for having AOA as discussed above.

In order to help ROSA minimize boron concentration, SNC usually seeks to maximize the number of WABA's used (to a certain level – say 300-400). Otherwise, while minimizing P-bar and FΔh, ROSA tends to minimize the number of WABA's used. This helps ROSA to balance the SNC's desires to lower peaking factors and boron concentrations.

SNC normally seeks to maintain eighth-core symmetry. Eighth-core symmetry is easier for the core designer to deal with and avoids some detector response issues. SNC normally maximizes eighth-core symmetry unless the economic impact is significant.

Excore detector response is an issue at Vogtle due to the distance between the core and the detectors. SNC has ROSA meet a certain power requirement on the outside diagonal in order to maintain acceptable detector response.

NRG has recently added an optimization parameter to maximize shutdown margin (SDM) for Vogtle. Vogtle, like other Westinghouse 4-loop plants with their control rod configuration, has very little SDM. SDM is of even greater concern due to the possibility of SDM degradation due to AOA. ROSA performs a simple end-of-cycle SDM margin calculation which has been benchmarked to more detailed core design results.

When ROSA seems to have settled on an "optimal" pattern but has not met the constraints, the user normally saves the pattern and reviews the annealing "temperatures." If the temperatures are very small, it is possible a local minimum has been reached. The user then raises key temperatures, normally relating to peaking factors, and lets the optimization process continue.

2.2 Constraints

In addition to the optimization parameters and associated targets, there are also a number of rigid constraints that have been placed into a "rules" file. For instance, one rule that is always included is that WABA's cannot be placed under control rod. Other rules that SNC uses includes excluding feed assemblies from peripheral locations in order to decrease the leakage and increase the energy for a given fuel inventory. There is no reason for ROSA to even look at a pattern with feeds on the periphery.

A rule that is normally used seeks to minimize the number of 156-IFBA assemblies due to DNB propagation concerns. Another rule that we frequently use is one that will not permit "quads." A quad is four fresh assemblies in a 2x2.

Another rule that used to be used with Vogtle would force ROSA to place fresh feed assemblies under most of the control rods in order to maximize SDM. Due to the new SDM optimization parameter, this constraint is no longer necessary. It is better to convert a rigid constraint into an optimization parameter if possible. Rigid rules tend to over constrain the optimization such that good patterns may not even be evaluated. Even if the pattern itself is not great, if the rule has been translated into an optimization parameter the evaluated pattern (that would have otherwise been thrown out with a rule) may lead to other creative loading pattern solutions.

2.3 Vogtle 1 Cycle 12 Design

Due to the observance of AOA in Vogtle 2, Cycle 9, SNC decided to be very aggressive in reducing P-bar's and FΔh's in Vogtle 1, Cycle 12. NRG personnel were invited to the SNC site to use ROSA to assist in generating loading patterns with low peaking factors with as few feed assemblies as possible. Loading patterns with 84, 85, 88, 89, 92 and 93 feed assemblies were generated. Upon review, all of the patterns met the requirements and constraints. Surprisingly, a loading pattern was found for Cycle 12 with even fewer feed assemblies than in Cycle 11 **AND** lower P-bar's and comparable FΔh's. The decrease in P-bar is especially significant relative to addressing AOA concerns. The design used a higher enrichment split (0.6) than SNC had ever used before. The enrichment split allowed the loading of almost all of the high enriched fuel in the outer "ring of fire" while the lower enriched fuel in the middle had low peaking factors. Due to the number of relatively high reactivity 4.8 w/o assemblies at the EOC 12, scoping studies with ROSA indicate that Cycle 13, which is a longer cycle (about 502 EFPD), will require only 84 feed assemblies also. Each cycle will save about $1 million relative to 88 or 89 feed patterns. SNC was very happy with these results and was committed to rely on ROSA much more in the future.

A table summarizing Vogtle 1 Cycles 8-12 has been attached as Table 1. The Vogtle 1 Cycle 12 loading pattern in ROSA has been attached as Figure 1 in the Appendix.

TABLE 1: SUMMARY OF VOGTLE 1 CYCLE 8-12

CYCLE	ENERGY (EFPD)	FEED ASSEMBLIES	IFBA'S	WABA'S	FΔh	P-bar	BORON (max PPM)
8	499	52 @ 4.0 w/o 37 @ 4.2 w/o	8704	0	1.499	1.376	1387
9	529	45 @ 4.2 w/o 52 @ 4.6 w/o	6144	896	1.445	1.348	1240
10	507	61 @ 4.0 w/o 32 @ 4.4 w/o	6400	704	1.424	1.334	1221
11	496	49 @ 4.2 w/o 40 @ 4.6 w/o	7040	544	1.445	1.340	1320
12	483	40 @ 4.2 w/o 44 @ 4.8 w/o	7552	432	1.449	1.322	1177

2.4 Vogtle 2 Cycle 11 Design

Due to the apparent success using ROSA within Vogtle 1, Cycle 12 loading pattern search, SNC decided to be even more aggressive in reducing P-bar's and FΔh's in Vogtle 2, Cycle 11 while reducing fuel assembly feed requirements. NRG personnel were again invited to the SNC site to use ROSA to assist in generating loading patterns with low peaking factors with as few feed assemblies as possible. Loading patterns with 76, 80, 81, 84, 85, 88 and 89 feed assemblies were generated. Upon review, all of the patterns except the 76 feed pattern met the requirements and constraints. A loading pattern was found for Vogtle 2 Cycle 11 with even fewer feed assemblies than in Vogtle 1 Cycle 12 **AND** even lower P-bar's and FΔh's. The design used a three enrichment split of 4.0, 4.4 and 4.95 w/o. The three enrichments and the large enrichment split allowed the loading of all of the high enriched fuel in the outer "ring of fire" while the lower enriched fuel in the middle had low peaking factors. Just as in Vogtle 1 Cycle 12, due to the number of relatively high reactivity 4.95 w/o assemblies at the EOC 11, scoping studies with ROSA indicate that Cycle 12, which is a slightly longer cycle (about 483 EFPD), will require only 84 feed assemblies. Each cycle of these cycles will save about $1 million relative to 88 or 89 feed patterns.

A table summarizing Vogtle 2 Cycles 7-11 has been attached as Table 2. The Vogtle 2 Cycle 11 loading pattern in ROSA has been attached as Figure 2 in the Appendix.

TABLE 2: SUMMARY OF VOGTLE 2 CYCLE 7-11

CYCLE	ENERGY (EFPD)	FEED ASSEMBLIES	IFBA'S	WABA'S	FΔh	P-bar	BORON (max PPM)
7	494	49 @ 4.2 w/o 40 @ 4.5 w/o	9536	0	1.462	1.364	1412
8	493	61 @ 4.2 w/o 32 @ 4.5 w/o	7264	832	1.421	1.359	1186
9	495	33 @ 4.0 w/o 60 @ 4.4 w/o	6400	832	1.430	1.363	1221
10	481	57 @ 4.0 w/o 36 @ 4.4 w/o	7296	704	1.425	1.317	1102
11	474	24 @ 4.0 w/o 20 @ 4.4 w/o 36 @ 4.95 w/o	7808	288	1.437	1.305	1171

2.5 Other Applications of ROSA

After ROSA was benchmarked so successfully to higher level physics methods within the Vogtle 1 Cycle 12 and Vogtle 2 Cycle 11 core design efforts, other applications of the technology were sought. Obviously, ROSA is a fast, reliable way to perform scoping studies of different fuel products and design concepts. Beyond that, SNC felt like the multi-cycle capabilities in ROSA could be used to generate core design budget type calculations. Core design normally provides number of feeds, enrichments, IFBA's and WABA's, and batch burnups to our commercial group for several cycles into the future each year so that they can generate detailed nuclear fuel budget projections.

NRG worked with SNC to implement a capability into a ROSA auxiliary code to generate such data and place it into EXCEL format. The core designer just has to generate the ROSA models for the cycles. The budget spreadsheet just falls out, saving the core designers a great amount of effort. SNC is quite pleased with the results so far.

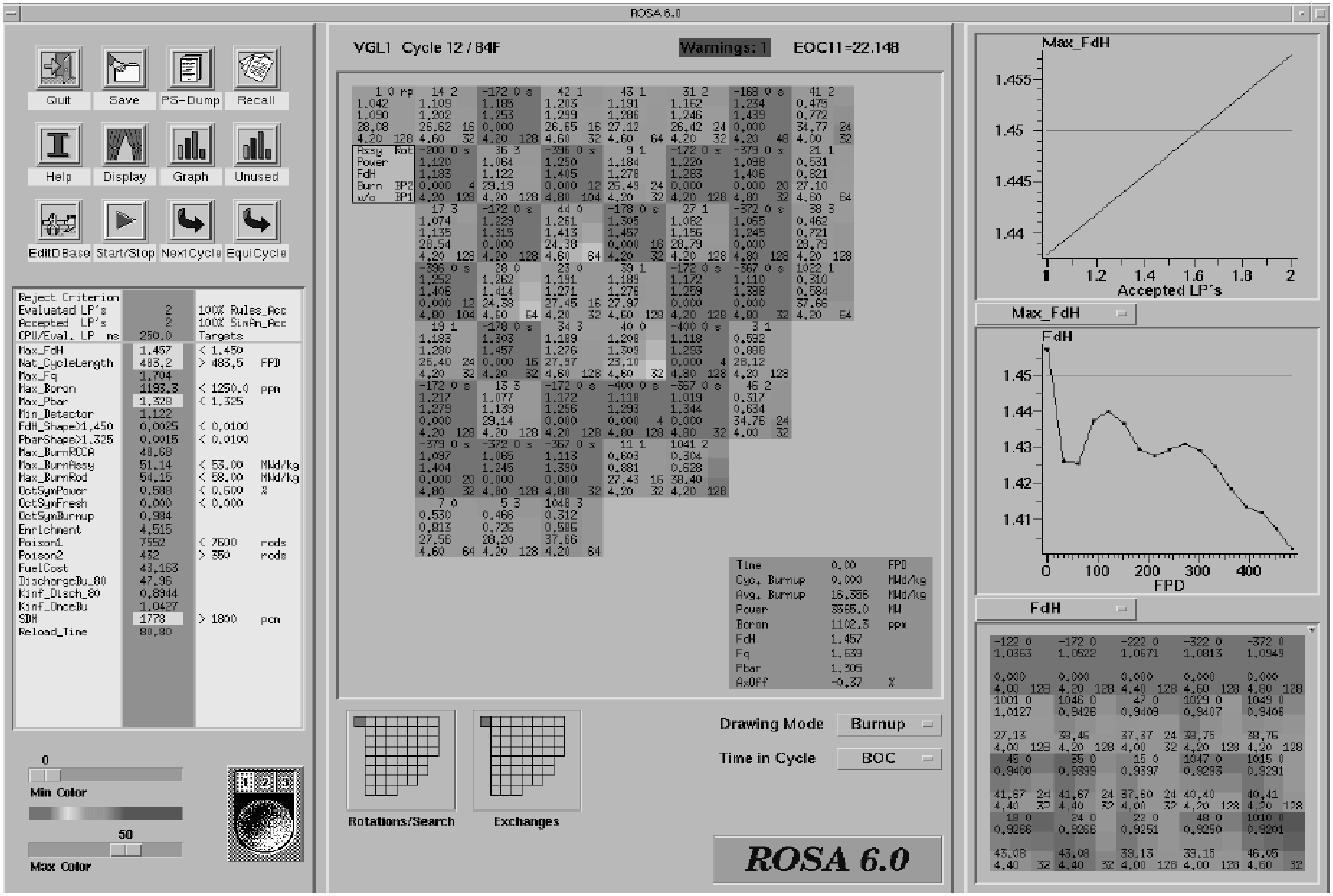
3. CONCLUSIONS

By using ROSA, SNC was able to "think outside the box" and designed a couple of cycles that were different than what would have been designed otherwise. The 0.6 w/o split in Vogtle 1 Cycle 12 allowed SNC to maintain incredibly low P-bar's while minimizing feed requirements. The 0.95 w/o split between three sub-batches in Vogtle 2 Cycle 11 allowed SNC to get even lower P-bar's while minimizing feed requirements. This allowed SNC to save millions of more dollars. By using ROSA more intensely SNC is finding that there may be other acceptable ways to "creatively" load feed assemblies in the middle of the core in a number of strange configurations. The "X's" and crosses ROSA is finding need to be further evaluated with more detailed safety analysis methods. However, ROSA has opened up new ways for SNC to meet a variety of requirements while minimizing costs.

REFERENCES

1. P. H. WAKKER and F. C. M. Verhagen, "ROSA User's Guide," NRG, April 2002.

FIGURE 1


ROSA 6.0
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Save
PS-Dump
Recall
Help
Display
Graph
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EditDBase
Start/Stop
NextCycle
EquiCycle
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EOC11=22.148
Max_FdH
Accepted LP's
FdH
FPD
Drawing Mode
Burnup
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BOC
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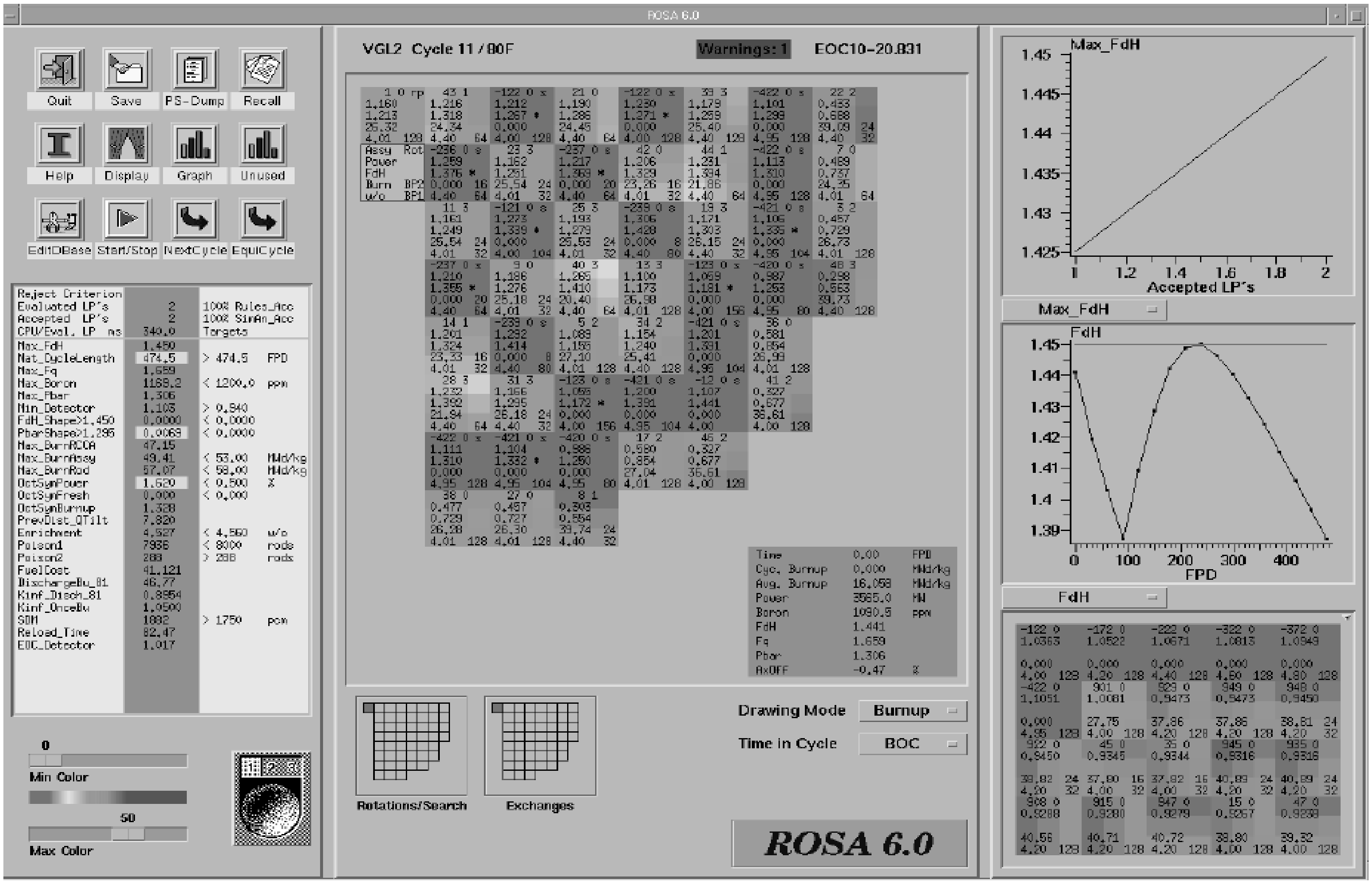
Exchanges
Min Color
Max Color
ROSA 6.0

FIGURE 2


ROSA 6.0
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NextCycle
EquiCycle
VGL2 Cycle 11 / 80F
Warnings: 1
EOC10-20.831
Max_FdH
Accepted LP's
FdH
FPD
Drawing Mode
Burnup
Time in Cycle
BOC
Rotations/Search
Exchanges
Min Color
Max Color
ROSA 6.0