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REDUCING REFUELING OUTAGE DURATION BY OPTIMIZING CORE DESIGN AND SHUFFLING SEQUENCE

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ABSTRACT

Reducing refueling outage duration is possible by optimizing the core design and the shuffling sequence. For both options software tools have been developed that have been applied for the three most recent cycles of the Dutch Borssele plant. The applicability of the shuffling sequence optimization to BWRs has been demonstrated by a comparison to a recent shuffle plan of the US Hatch plant. It is shown that both core design and shuffling sequence optimization can be exploited to reduce the time needed for reloading a core with an in-core shuffling campaign. Ex-core shuffling campaigns for PWRs can still have substantial benefit from a core design with a minimized number of insert shuffles.

1. INTRODUCTION

During the last decade refueling outages of PWR nuclear power plants have been reduced from 4-6 weeks average to 1-2 weeks for top-performers nowadays. For BWR plants outages were 7-9 weeks on average, going down to 2-3 weeks for the current record holders. For these top-performers one of the time consuming efforts on the critical path is core reloading. In many PWR plants the complete core is still offloaded during an outage. In this way core reloading takes about 2.5 to 5 days, mainly depending on core size. Several plants recently apply the so-called in-core shuffling strategy, thereby saving approximately 1-2 days of outage time[1]. To further minimize the reloading time there are two options. First, one could optimize the core design by keeping assemblies on their positions and minimize insert shuffles. Second, one could optimize the sequence of refueling machine steps needed to shuffle the old core to the new core. For both types of optimization NRG has developed software tools that are successfully applied for the three most recent cycles of the Dutch Borssele PWR plant. The shuffling sequence optimization has also been applied to one of the latest shuffles of the US Hatch BWR as a comparison to the current method.

2. CORE-DESIGN WITH ROSA

The ROSA[2,3,4] code system has been developed at NRG for PWR core design and utilizes Simulated Annealing[5] as optimization technique in combination with a very fast and accurate 3-D core simulator code. A BWR version of ROSA is under development.

Besides for Borssele, ROSA is also being used for several PWRs in the USA. With ROSA millions of loading pattern (including cycle depletion) can be evaluated on a workstation in one day. The code can be switched between manual and automatic mode. In addition to single cycle also equilibrium cycle optimization is possible. More than 30 parameters can be optimized simultaneously.

A powerful graphical user interface (GUI) allows the user to interact with the optimization process by e.g. changing targets during the run or perform manual fuel movements. The graphical user interface of ROSA is shown in figure 1.

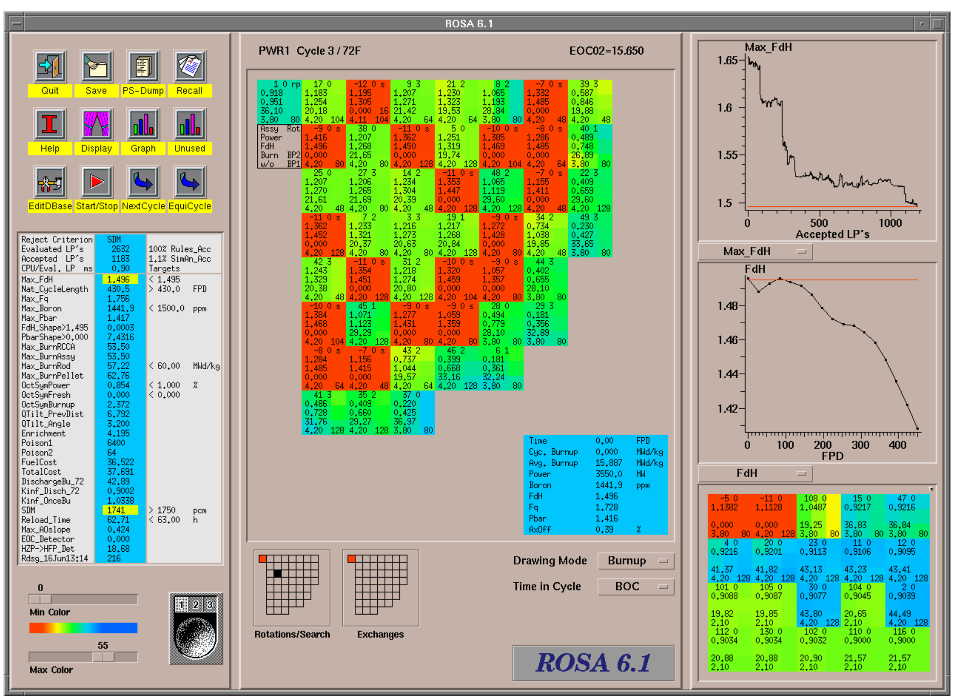


Fig. 1 ROSA graphical user interface.

One of the recently developed parameters is “Reload_Time”. This is an estimate of the time (hours) needed to shuffle the previous cycle core to the new (candidate) core, accounting for all required assembly and insert moves. The user can specify the average time needed for an in-core assembly move, a core to pool assembly move, a control rod cluster move, a thimble plug move, a pull action of a removable poison cluster, and optionally a mast sipping action for fuel that does not need to be moved (in case of leakers in the core). Different thimble plug types and control rod types can be specified on a full core basis. This can be used to take into account the impact on reloading time of black and gray control rods and/or a control rod management strategy. Also asymmetries in plug type positions between quadrants (asymmetric instrumentation) can be taken into account. The estimated reloading time for each evaluated loading pattern is the sum of the number of different actions multiplied by their required time. The user has the choice to select between in-core and ex-core shuffling mode. The extra calculation time for this parameter is negligible compared to the average evaluation time per loading pattern.

Optimization of a loading pattern to minimize reloading time may reduce the outage by several hours, but may also cost some of the achievable natural cycle length of the pattern. This is shown in figure 2. The reloading time optimized cycle starts up earlier at BOC (Δt_1: the curve is shifted right so here shown as EOC production gain). If the core designer allows a reduction in natural cycle length, the optimized cycle starts earlier with its coast down (Δt_2). When this is the case (Δt_2 is positive), then it depends on the length of the coast down period whether a net production increase will be achieved. In addition to the potential of extra production a reduction in outage time of several hours may also be an interesting saving in personnel cost.

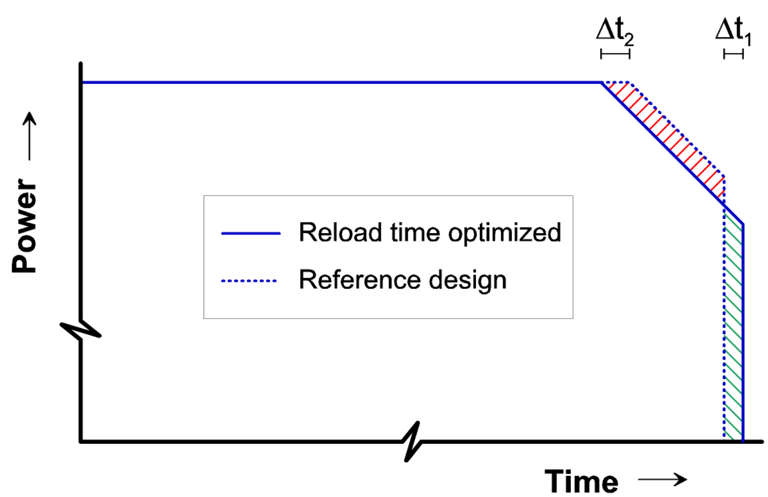


Fig. 2 Reactor power versus time in cycle for two scenarios (not to scale).

3. SHUFFLING SEQUENCE OPTIMIZATION

Basically optimizing in-core shuffling is solving a travelling salesman problem. The refueling machine must visit a number of core and spent fuel pool locations within the shortest possible amount of time. Contrary to the traditional travelling salesman problem however, the refueling machine must visit several places twice or even three times (to address assembly and inserts shuffles) and in a specific order (e.g. a fresh fuel assembly cannot be placed before the old one has been moved). Furthermore, closed loops of assemblies or inserts can be embedded in the problem, when for example one group of assemblies is exchanged with another. In case of such a closed loop an additional step is needed to create an open position, after which the assemblies or inserts in the closed loop can be shuffled.

Next to the shuffling sequence, also the positions of the to be loaded and unloaded fuel in the spent fuel pool can be optimized. For example, a spent assembly giving its control rod cluster to a fresh assembly should be placed next to the receiving assembly.

NRG has developed a software tool SOSA (Shuffling Optimization by Simulated Annealing) that performs the above optimizations while respecting a number of constraints. For example the maximum number of control rods that may leave the core at the same time (PWR subcriticality), the support for each assembly from its neighbors at each step during the shuffling process, the support of BWR control rods, and the number of empty core locations around an (ex-core) detector.

First, an initial solution is generated, which takes about 1 s CPU time. Next, the optimization process generates small changes in the shuffling plan and subsequently evaluates the shuffling time. Generating and evaluating a shuffling solution in the optimization process takes about 60-100 μs CPU time (550 MHz HP C3600 workstation), therefore about 0.9-1.4 billion shuffling plans can be evaluated in a day.

SOSA can handle different groups of PWR inserts (e.g. control rod clusters and thimble plugs with or without instrumentation holes) and BWR double blade guides. Sipping of the assemblies remaining on their position can be optionally turned on or off. Distinction is made between times for separate actions, such as driving the refueling machine, positioning the refueling machine, lifting and lowering of assemblies and inserts either in the core or in the spent fuel pool, rotating inserts, and switching from assembly to insert handling and vice versa. For all steps in the shuffling plan the times of the appropriate actions are summed. The result is the total time needed to go from one loading pattern to another, which is the parameter to be optimized.

4. BORSSELE

The Dutch Borssele plant is a 480 MWe Siemens PWR that started to operate in 1973. The plant is currently (mid 2003) in its 29th cycle of operation (12-month cycles). The core consists of 121 fuel assemblies (15x15-20), 28 control rods, and 24 instrumented assemblies (aeroball system entering at the top of the core). The core geometry with control rod and instrumented locations is shown in figure 3.

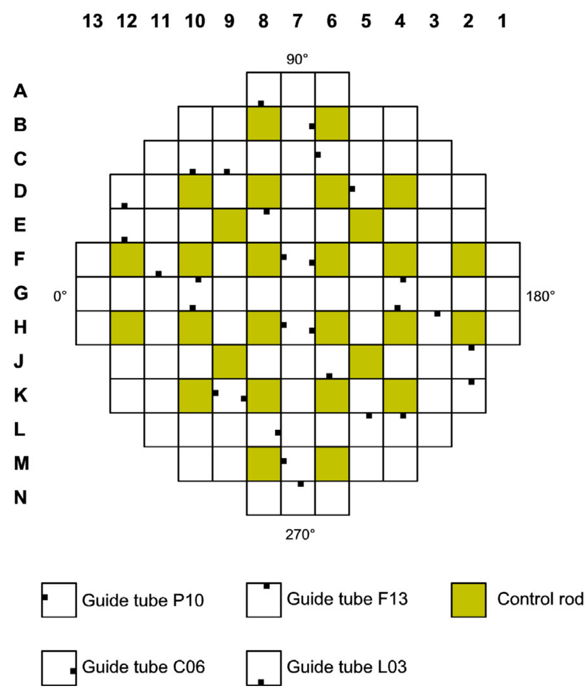


Fig. 3 Borssele core geometry.

Due to the asymmetric position of the instrumentation finger inside an assembly (no central guide tube), three different types of thimble plugs are used: with no, one, and two holes. The plugs with two holes accommodate a thermocouple in addition to an aeroball system finger. Note that the instrumented locations are not distributed symmetrically over the core quadrants.

Core design is full low leakage without poison. Approximately 25% of the fuel is replaced each cycle. The maximum allowed fresh fuel enrichment is 4.0 w/o.

The first in-core shuffling campaign was applied during the loading of the cycle 28 core in 2001 and the outage time was 14.6 days, including defective fuel repair. A record load-factor of 95.0% was achieved in 2001, including outage and coast down. The loading of the cycle 29 core in 2002 was an ex-core campaign due to inspection needs and lasted 18.4 days. A load-factor of 93.5% was achieved in 2002. The next refueling outage (autumn 2003) is planned to have a total length of 10.8 days with an in-core shuffling campaign.

4.1 Borssele Core Design with Reloading Time Optimization

The cycle 28 core design in 2001 was the first time that reloading time optimization was included in the core design process. Other parameters that were optimized / constrained in this design were $F_{\Delta H}$, natural cycle length, maximum burnup (assembly, rod, and pellet), and octant symmetry of the feed fuel.

The individual times needed for the core optimization code ROSA to calculate core reloading time are listed in table 1. It should be noted that calculated in-core assembly moving time is partially based upon actual distance moved and actual positioning time. In the core design phase the second part of the ride (full) is known and taken into account, as old and new assembly positions are known for each evaluated loading pattern candidate. For the rest of the step (empty driving and lifting) an average time is assumed (base time). Loading patterns will therefore show a slight preference for in-core assembly moves over short distances and in one direction. For all other actions average times are used.

Table 1 ROSA times needed for separate shuffling actions.

Action	Time [min]
In-core assembly move (base time)	8.0
In-core assembly driving per assembly width	0.054
In-core 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 (if needed)	8.0

During the core design phase typically hundreds of millions of loading patterns are evaluated. Optimization targets of $F_{\Delta H}$<1.755 and $T_{natural}$>320.5 days were used in an example case to investigate the possible variation in reloading time for in-core shuffling. Results for the actual core inventory are plotted in two scatter plots in figure 4, where each dot represents a loading pattern. Sipping was not included in this optimization.

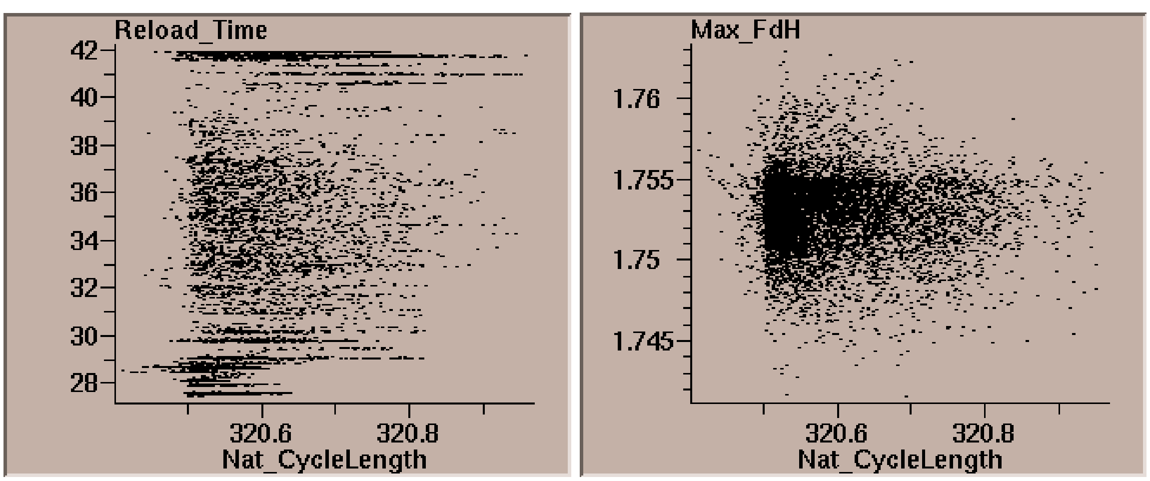


Fig. 4 Borssele cycle 28 optimization example for 10,000 loading patterns.

The left plot shows that variation in reloading time between 27.4 and 41.9 hours is possible, whereas the correlation with natural cycle length (days) appears to be weak. The right plot shows the correlation between $F_{\Delta H}$ and $T_{natural}$ for the same set of loading patterns. A best reloading time case with 27.43 h was found that also satisfied the above mentioned optimization criteria for the other two parameters. The finally selected loading pattern had an estimated reloading time of 28.5 h. A reference case with maximum achievable natural cycle length of +0.8 days could be found with a reloading time of +7.0 h. The +0.8 days difference in natural cycle length is equivalent to 0.8*24*(1-0.86)=2.7 h of energy production, as EOC reactor power was approximately 86%. A net extra production of 0.86*7-2.7=3.3 h (see also figure 2) could be achieved due to the reloading time optimization. For this cycle 28 slightly more production (4-5 h) might have been achievable by maximizing an energy production parameter, defined as the difference between reloading time gain and coast down loss.

In the finally selected cycle 28 loading pattern 32 fuel assemblies did not have to change position and 12 of the 28 assemblies with a control rod could be kept on a rodded location. In figure 5 (left part) the number of insert shuffles is plotted for cycles 6-30. A reduction in total number of insert shuffles from ~95 to ~57 is achieved for the last three optimized cycles, compared to non-optimized cycles 20-27. The theoretical maximum is 121 for this reactor. In the right part of figure 5 total and best achievable number of insert shuffles is shown. This minimum is the number of assemblies that come from the pool into the core (new + old fuel from pool). These assemblies always have to get an insert, assuming there is neither a stockpile of inserts for preparation nor usage of removable poison rod clusters. The remaining fuel may need a new insert, but that depends on the core design. In the cycle 29 design it was possible to keep the total fraction of insert changes for the remaining fuel below 23% (only 19 out of 84 inserts had to be changed). This is even further improved for the cycle 30 design with a total fraction of insert changed for the remaining fuel of 18% (16 out of 88).

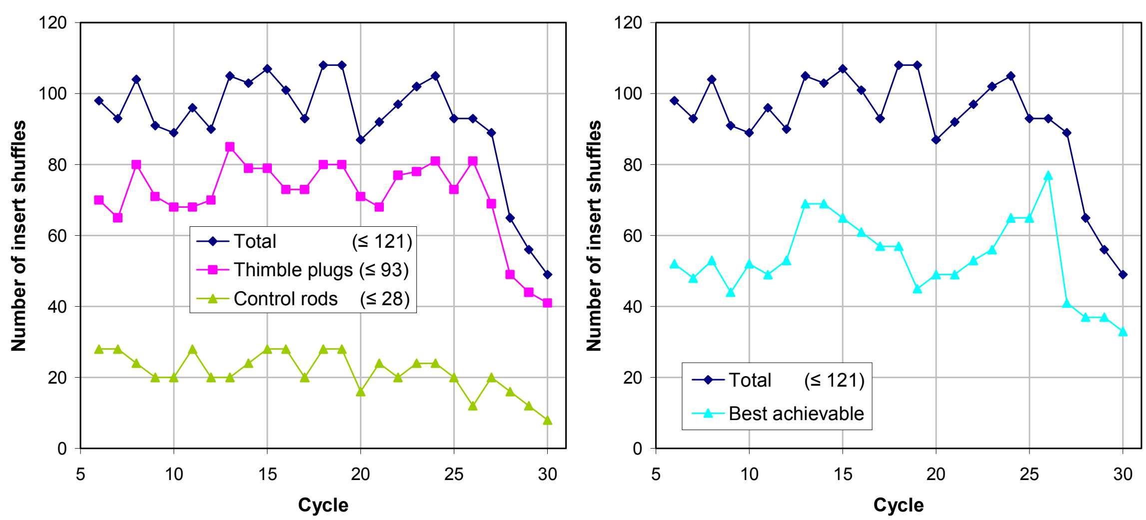


Fig. 5 Borssele insert shuffles per cycle.

4.2 Borssele Shuffling Sequence Optimization

For the cycle 28 reloading campaign SOSA has been used and compared to a hand-made shuffling plan. Initially the times for separate actions had to be roughly estimated since little data was available. During the cycle 28 reloading campaign the time needed for each step in the shuffling plan has been recorded. From that data more accurate estimates for the action times have been derived as listed in table 2.

Table 2 Times needed for separate Borssele shuffling actions.

Action	Time [min]
Moving refueling machine one assembly width	0.054
Positioning refueling machine per co-ordinate	0.11
Lift/lower assembly in the core	4.0
Lift/lower assembly in the spent fuel pool	2.9
Lift/lower insert in the core	5.3
Lift/lower insert in the spent fuel pool	3.8
Lifting time saved when taking insert directly from assembly in the core	3.5
Lifting time saved when taking insert directly from assembly in the pool	2.0
Switching from assembly to insert handling or vice versa	0.25
Rotating an assembly or insert	1.0

Traditionally the shuffling plan was made with as little switches between assembly and insert handling as possible. Also the SOSA shuffling plan for the cycle 28 reloading campaign was designed with this constraint. A second constraint imposed on the design was to keep all control rods but one in the core. Two other constraints were to keep all assemblies supported by at least one straight neighbor and to create as little empty core locations as possible around the ex-core detectors next to positions A6 and N8. However, these last two constraints are not limiting since only a few empty core locations are created at the same time.

Because during cycle 27 several leakers were detected sipping of all 32 assemblies remaining on their old position had to be performed. In SOSA sipping is simulated as lifting and immediately lowering of the assembly. The additional time needed for sipping (about 4 h) explains most of the difference between the ROSA and SOSA reloading times.

The results of the SOSA optimization are listed in table 3, column SOSA-1. Savings of about 2.7 hours in comparison with the hand-made shuffling plan were realized. Since the number of switches was limited no savings in lifting time could be realized by for example taking an insert directly after moving the assembly. Therefore the

2.7 hours saving was mainly realized by optimizing the travelling and positioning time of the refueling machine. This can be seen from figures 6 and 7. The first shows the total traveled path of the refueling machine, the second the empty trips only. One can clearly see that the total traveled path is shorter for the SOSA plan (less blue) and that the SOSA plan has a preference for trips perpendicular to the axes (less positioning time needed). Another striking feature is the significantly smaller number of empty trips to the spent fuel pool for the SOSA plan. For most trips to or from the pool SOSA puts the return trip to good use, while the engineer is often forced to return empty in the hand made plan.

After the cycle 28 reloading campaign is was concluded that two imposed constraints were not necessary. The constraint on switches could be lifted because switching proved not to take as much time and trouble as was initially thought. The constraint on control rods was unnecessary since the subcriticality calculations are performed under the assumption of all control rods out. To see what could have been saved, the shuffling plan was redesigned without the above constraints. The results of this redesign are listed in table 3, column SOSA-2. As could be expected additional savings are made for the lifting time, while losing some time in switching between assembly and insert handling. The extra savings are about 2.5 hours.

Table 3 Borssele cycle 28 shuffling sequence optimization results. Shuffling times [h], total and split into separate actions, number of shuffle and sipping steps, maximum number of control rods out of the core, and maximum number of empty core locations.

	Hand-made	SOSA-1	SOSA-2
Empty rides	2.19	0.91	0.67
Full rides	4.86	3.88	4.15
Positioning	1.25	0.94	0.92
Lifting/lowering	27.64	27.41	24.78
Switching	0.01	0.02	0.24
Rotations	0.00	0.07	0.00
Total time	35.95	33.23	30.76
Total number of steps	205	205	205
Number of sipping steps	32	32	32
Max. # control rods out of core (≥ 1)	1	1	4
Max. # empty core locations (≥ 1)	3	6	7

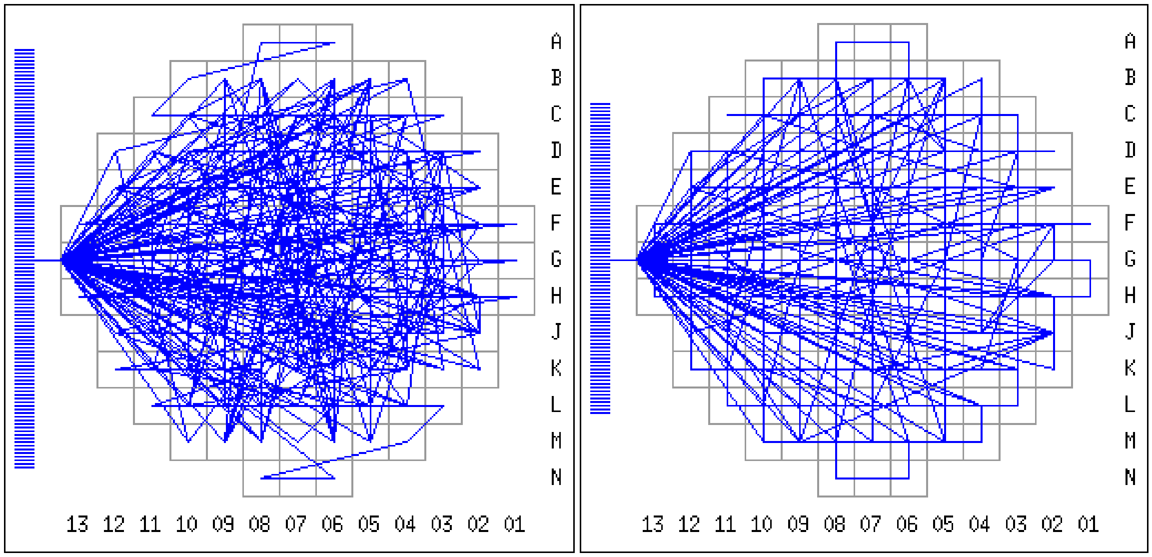


Fig. 6 Total traveled path by the refueling machine in the core region. Left the hand-made shuffling plan, right the SOSA-1 shuffling plan. The column of lines on the left side of the figures indicates the number of trips (back or forth) to the spent fuel pool.

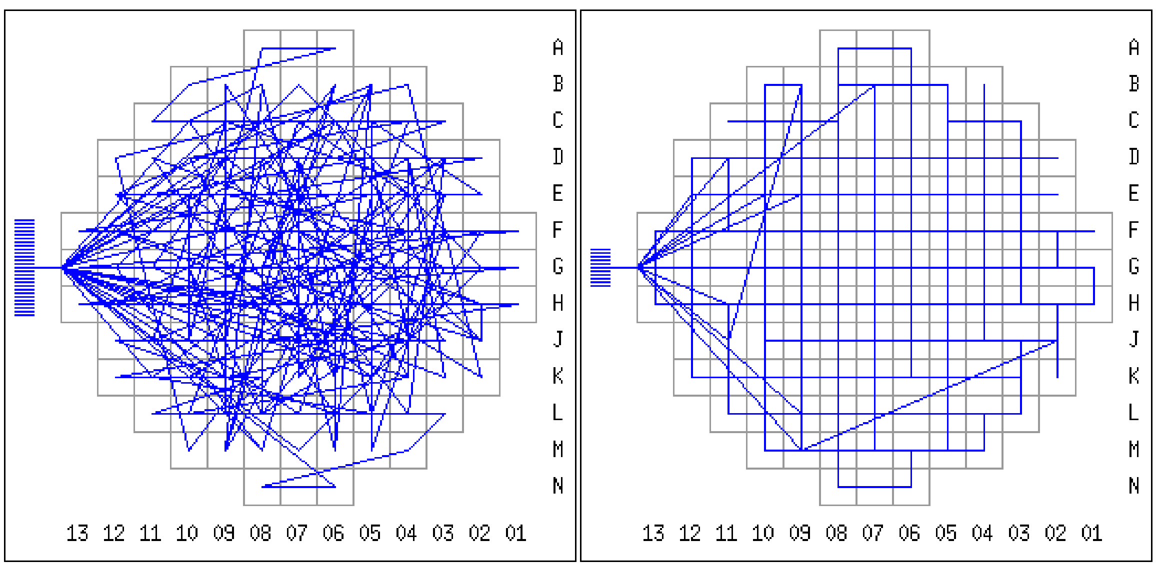


Fig. 7 Traveled path by the refueling machine in the core region, empty trips only. Left the hand-made shuffling plan, right the SOSA-1 shuffling plan. The column of lines on the left side of the figures indicates the number of trips (back or forth) to the spent fuel pool.

5. HATCH

Together with Southern Nuclear an assessment has been made whether SOSA can be useful for BWRs as well. To this purpose a plan for the fuel shuffle of Hatch-2 EOC 17 has been generated with SOSA and checked by the utility for compliance with the shutdown margin criterion.

Plant Hatch is a twin unit 924 MWe General Electric BWR. Unit 1 started to operate in 1975, unit 2 in 1979. The core consists of 560 fuel assemblies, 137 control rods, and contains 4 Source Range Monitors (SRM).

5.1 Hatch-2 Cycle 17 Shuffle

Going from the EOC 17 loading pattern to the BOC 18 loading pattern 232 fresh assemblies are loaded, 4 fuel assemblies remain on their position and there are 4 so-called closed loops as two groups of fuel assemblies switch position, which requires 4 additional moves to open the closed loops. The theoretical minimum number of shuffle moves, if no inspection or maintenance is needed, is therefore:

Moving each core assembly (to new core position or pool):	560
Loading fresh assemblies:	232
Additional moves for closed loops:	4
Moves avoided by assemblies remaining on their position:	-4 +
Total	792

This is confirmed by SOSA, which was able to generate shuffle plans without inspection needs with 792 moves.

The original fuel shuffle consists of two parts, first the Initial Core Offload in which fuel assemblies that need inspection are offloaded and control rod cells are emptied by offloading the fuel assemblies and loading a double blade guide to enable control rod drive maintenance. In the second part, the Core Shuffle, the actual transition to the BOC 18 core takes place.

During the Initial Core Offload 6 fuel assemblies are offloaded and 20 control rod cells are emptied, which gives a total of 86 fuel assemblies offloaded and 20 double blade guides loaded. Of these 86 fuel assemblies 54 need to be reloaded again. Six additional moves are used in the Initial Core Offload to handle extra double blade guide and inspected bundle moves. This gives a total of 112 moves (86+20+6) for the Initial Core Offload.

From 3 of the 4 closed loops an assembly is offloaded during the Initial Core Offload, therefore only 1 additional move for the closed loops is needed in the Core Shuffle. This gives a minimum number of shuffle moves for the Core Shuffle:

Moving each core assembly (to new core position or the pool):	474 (=560-86)
Loading fresh assemblies:	232
Reloading offloaded assemblies:	54
Offloading double blade guides:	20
Additional moves for closed loops:	1
Moves avoided by assemblies remaining on their position:	-4 +
Total	777

Since the Initial Core Offload is merely straightforward offloading of assemblies not much can be optimized, therefore for simplicity this part has been kept the same and only a SOSA plan for the Core Shuffle part has been generated.

5.2 Hatch Shuffling Sequence Optimization

The individual action times, needed as input for SOSA, have been estimated from known average move times for a core-core, pool-core, or pool-pool move and the total time of the original plan. The result is listed in table 4.

Table 4 Times needed for separate Hatch shuffling actions.

Action	Time [min]
Moving refueling machine one assembly width	0.036
Positioning refueling machine per co-ordinate	0.1
Lift/lower assembly in the core	1.5
Lift/lower assembly in the spent fuel pool	1.35

This gives a total time calculated by SOSA for the entire original plan of 102.5 hours, which is close to the value of 102.4 hours based on the average move time. The total time of the Core Shuffle part of the original shuffle plan calculated by SOSA is 84.0 hours.

To comply with the shutdown margin criterion ($k_{eff} < 0.99$) a rule has been applied that avoids having three once-burnt assemblies in a single control rod cell. An exception is made for the control rod cells adjacent to the baffle and the outer control rod cells on the diagonals, since these control rod cells do not comply with this rule in the original plan anyway. Afterwards shutdown margin calculations of each step in the SOSA plan have been performed with PANACEA. This showed that the SOSA plan meets the requirements.

Two additional constraints have been imposed. First, to avoid unsupported control rods the number of empty positions within each control rod cell has been limited. At least one of the diagonals of a control rod cell needs to be filled at all times. Second, at least two exposed bundles need to stay in the four positions around an SRM to ensure sufficient response.

The original plan takes 787 moves for the Core Shuffle, ten more than the minimum required. Two of those are moves with a double blade guide in the core, two are moves where a bundle is moved to a temporary core position, and six are moves where a bundle is moved to a temporary pool position.

The SOSA plan takes 778 moves, one more than the minimum required, but nine less than the original plan. The extra move is needed to keep at least two exposed assemblies around one of the SRMs.

Table 5 shows the time needed for the original and SOSA Core Shuffle plans. The SOSA plan takes about 5.8h (7%) less time. Most of these savings are made in the empty rides. Figures 8 and 9 show the empty rides in the core and all rides in the pool respectively for both the original and SOSA plan. Similar to the Borssele comparison one can clearly see that the total traveled path is shorter for the SOSA plan (less blue) and that the SOSA plan has a preference for trips perpendicular to the axes (less positioning time needed).

In contrast to the Borssele comparison the number of empty trips to the pool is not significantly reduced. This can be explained by the fact that in this case the 86 offloaded assemblies during the Initial Core Offload determine the number of empty trips to the pool. Each of these assemblies generates an empty trip to the pool during the Core Shuffle, partly compensated by the 20 to be offloaded double blade guides, resulting in a minimum number of empty trips to the pool of 66.

Table 5 Time in hours needed for the Core Shuffle.

	Original CS plan	SOSA CS plan	Time saved
Empty rides	8.30	5.10	3.20 (39%)
Full rides	32.67	31.17	1.50 (4.6%)
Positioning	4.98	4.30	0.68 (14%)
Lifting/lowering	38.05	37.64	0.41 (1.1%)
Total time [h]	84.00	78.21	5.79 (6.9%)

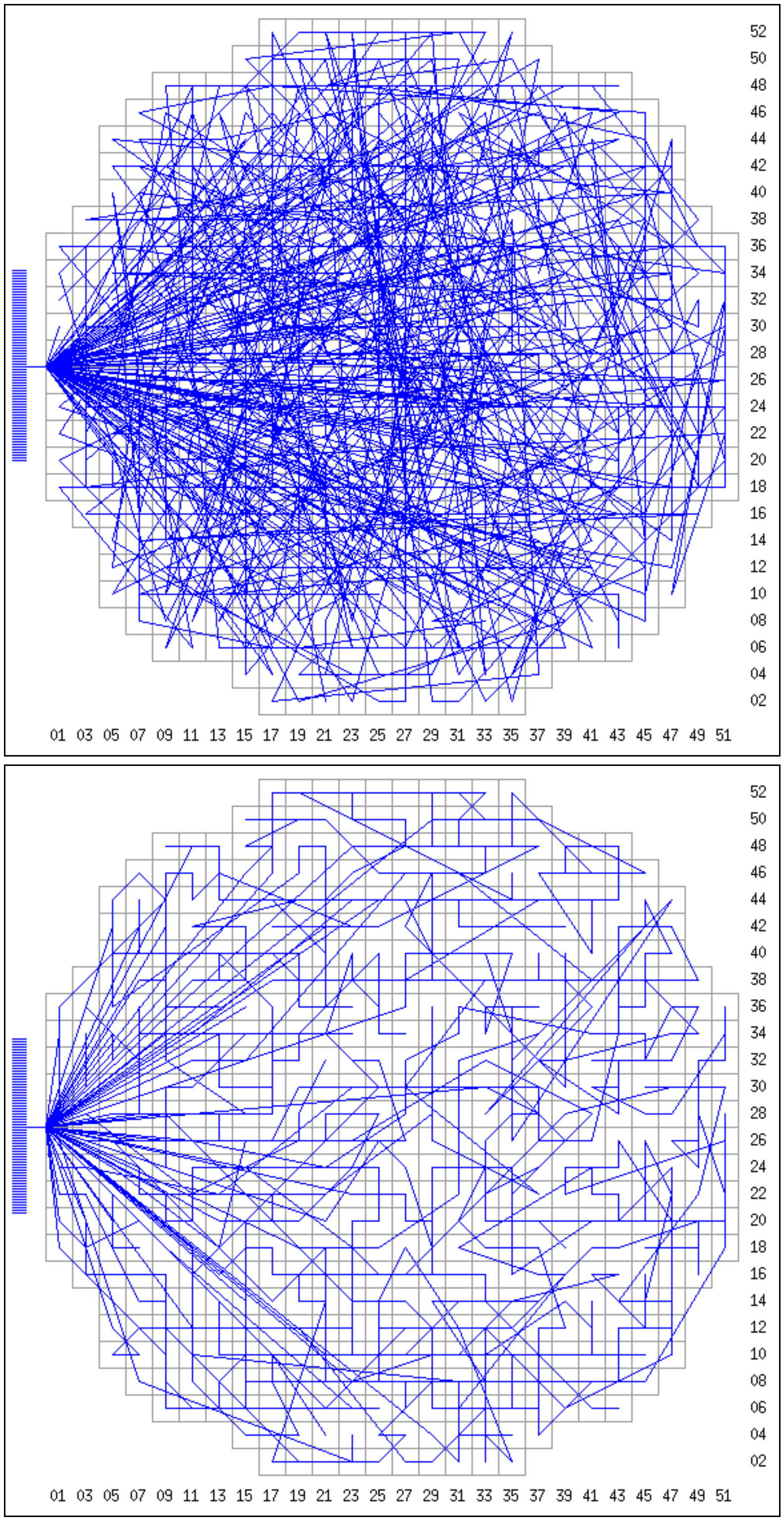
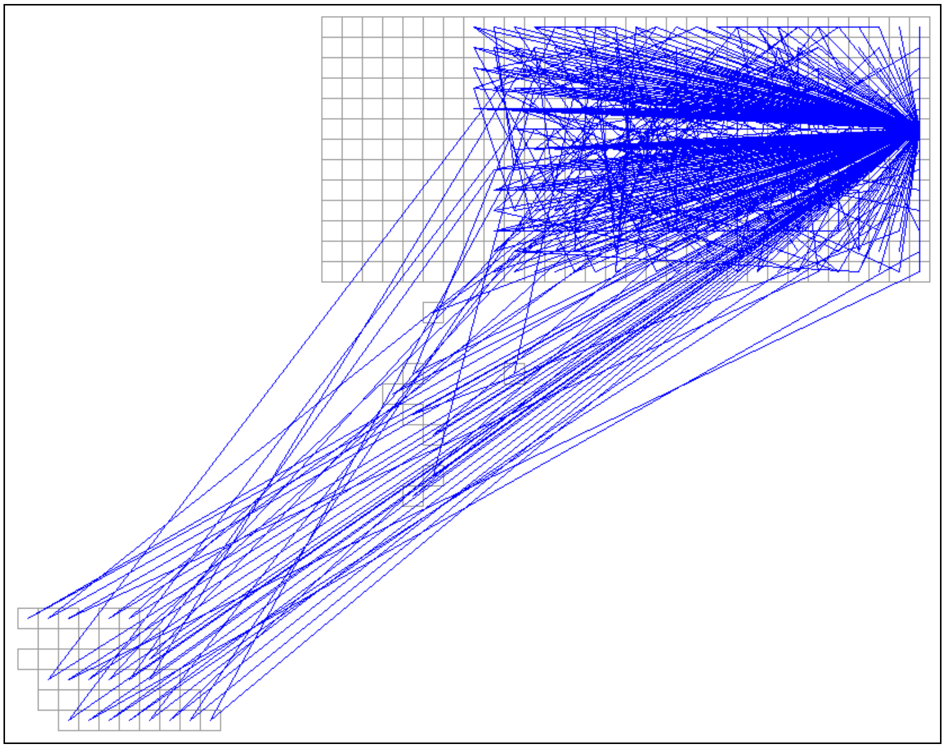


Fig. 8 Traveled path by the refueling machine in the core region, empty trips only. On top the original Core Shuffle plan, at the bottom the SOSA plan. The column of lines on the left side of the figures indicates the number of trips (back or forth) to the spent fuel pool.



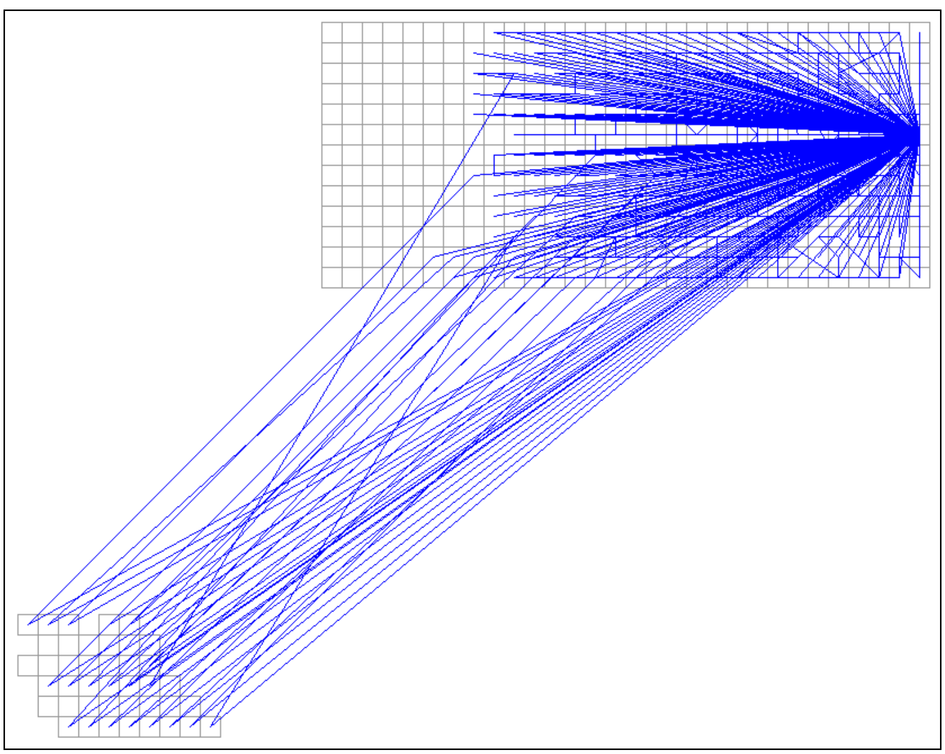


Fig. 9 Total traveled path by the refueling machine in the pool region. On top the original Core Shuffle plan, at the bottom the SOSA Core Shuffle plan. Only the available pool positions used in the optimization are shown. In the bottom-left region the double blade guides are placed, which has been kept the same in both plans.

6. CONCLUSIONS

Both the core design and shuffling sequence optimization methods have been successfully applied for the cycle 28 design and (first) reloading campaign with in-core shuffling of the Dutch Borssele plant in 2001. In the core design 26% of the assemblies were kept on the same core location and the number of insert shuffles (control rods + thimble plugs) was reduced by approximately 30% compared to previous cycles. With respect to a maximum energy core design with the same inventory the outage time could be reduced by approximately 7 h. This was equivalent to at least 3.3 h of extra production. In the subsequent shuffling sequence optimization about 8% of the time (2.7 h) was saved with respect to the reference hand-made shuffling plan. Later redesign with lifted constraints showed a possible extra reduction of 2.5 h.

For the Borssele cycle 29 design (with an ex-core shuffling campaign due to inspection needs) it was possible to reduce the number of insert shuffles by about 40% with respect to old cycles. In cycle 30 a further improvement to 50% has been realized.

Applicability of the shuffling sequence optimization tool SOSA to BWRs has been demonstrated by reducing the outage time of an existing Hatch shuffle plan by 7% (5.8h) while complying with the shutdown margin criterion.

It can be concluded that both core design and shuffling sequence optimization can be exploited to reduce the time needed for reloading a core with an in-core shuffling campaign. Ex-core shuffling campaigns for PWRs can still have substantial benefit from a core design with a minimized number of insert shuffles.

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