OPTIMIZATION OF BWR FUEL RELOADS USING TABU SEARCH

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ABSTRACT

We have developed a system to optimize BWR fuel reloads using the 3D neutron core simulator CM-PRESTO code; in this code the combinatorial technique tabu search along with the heuristic rules of Control Cell Core (CCC) and Low Leakage (LL) have been incorporated. The objective of this work is to maximize the cycle length while satisfying the operational thermal limits and cold shutdown constraints. To test our optimization system an actual BWR operating cycle was used, corresponding this cycle to an 18-months cycle with a length of 9,281 MWD/TU which used 112 fresh fuel assemblies of 3.53 w/o of U-235, the corresponding loading pattern was generated using engineer expertise. We used a modified tabu search technique to seek for a loading pattern of maximum energy without violating the operational and safety limits. Numerical experiments show a maximum cycle length of 9,788 MWD/TU which does not violate the operational thermal limits and has a cold shutdown margin of 1.06% $\Delta k/k$, which is greater than the 1% $\Delta k/k$ minimal limit value. If we want to increase the cold shutdown margin up to 1.5% $\Delta k/k$ the energy is penalized obtaining only a maximum of 9,381.6 MWD/TU. However, we have in both cases an increase of energy produced in comparison with the energy produced by the actual operating cycle achieving the goal of this task.

1. INTRODUCTION

From an economical point of view for a BWR it is necessary to get as much fuel energy as we can to avoid under burnt fuel and waste energy. Thus, the fuel loading pattern plays a very important role to achieve that goal.

In commercial plants the technique used to fuel reload design is engineer expertise, which is a technique based on human knowledge that does not optimize the use of the fuel assemblies. Recently, several techniques [1-3] have been used to optimize the loading pattern having in all the cases the objective of maximizing the cycle length while satisfying the operational thermal limits and cold shutdown constraints. Among these techniques is the tabu search (TS).

Previously, Jagawa et al [3] designed an automatic system that uses a modified tabu search method, which starts from a reference loading pattern and a simple linear perturbation method. We explored also a modified TS technique. In our algorithm it is not necessary to give an initial loading pattern, it generates a random loading pattern and through a tabu time array the process is more efficient leading to explore more scenarios in fewer time than the original TS. Furthermore, some heuristic rules will be applied along this technique. These are the Control Cell Core (CCC) and Low Leakage (LL) techniques, to follow the strategies used in many BWR plants. The first one does not allow the use of fresh fuel in Control Rod (CR) positions and the former does not allow also the use of fresh fuel assemblies in the periphery to avoid damage to the core vessel.

In this work our optimization system is based in the codes HELIOS-1.5 [4] and CM-PRESTO-B [5] from the Fuel Management System by Studvik-Scandpower to perform the neutron core calculations. HELIOS code provides the fuel lattice parameters to be used by the 3-D core simulator CM-PRESTO-B.

2. LOADING PATTERN DESIGN

The Laguna Verde Boiling Water Reactors have 444 fuel assemblies. To get an optimized loading pattern it can be assumed as a combinatorial problem. Furthermore, considering one quarter symmetry the problem is reduced to allocate 111 fuel assemblies.

The problem to be solved is to get the “best” assembly distribution, making shuffling (permutations) of the fuel assemblies in the core. The objective is to get as much energy as we can from the cycle without violating the operational and safety limits and have enough shutdown margin to not jeopardize the integrity of the core.

Getting more energy means to optimize the fuel reload, which can be done trough combinatorial analysis. Assuming one octant symmetry there are 60 different positions to allocate the fuel assemblies which represent 8.32×10^{81} permutations or possible movements.
If we introduce the low leakage and control cell core rules, which are common practices followed in fuel management, the optimization problem is reduced to 7.361×10^{54} different permutations. This still being a big number of permutations.

In particular the problem to be solved, given the assumptions proposed, will use the following rules:

1. Upper quarter core will be analyzed
2. There is one octant symmetry
3. Only once and twice cycles burnt fuel assemblies can be used in the periphery (LL), which will be identified with the letter P in Figure 1.
4. Diagonal fuel assemblies only can have position exchange among them as long as they do not violate any other rule, they are identified with the letter D in Figure 1.
5. There are no new fuel assemblies in control cell positions (CCC), these are marked with the letter C in Figure 1.

P	P	P	P	P	P	P				
Ä	Ä	Ä	Ä	Ä	Ä	Ä	P			
C	Ä	Ä	C	C	Ä	Ä	C	P/D/C		
C	Ä	Ä	C	C	Ä	Ä	D/C			
Ä	Ä	Ä	Ä	Ä	Ä	D				
Ä	Ä	Ä	Ä	Ä	D					
C	Ä	Ä	C	D/C						
C	Ä	Ä	D/C							
Ä	Ä	D								
Ä	D									
D/C										

Figure 1. Fuel reload design rules.

3. TABU SEARCH

Tabu search is an iterative process. It starts from an initial feasible solution and tries to reach a global optimum of an objective function *F*, by moving from one solution to another. Now, we must define a set *M* of simple modifications that can be applied to a given solution *x* to move to another solution *x'*. The notation *x'=m(x), mÎM* indicates that *m* transforms *x* into *x'*. This leads us to definition of neighborhood *N(x).* At each step of the iterative process, we generate a subset *V** with *j* elements, and we move from *x* to the best solution *x** in *V**, whether or not *F(x*)* is better than *F(x)*, in this case, the best solution in *V** is the best loading pattern with respect to the energy obtained. If *N(x)* is not large, it is possible to take *V*=N(x)*, in our problem we revised just part of the whole neighborhood. On the other hand, to reduce the sampling size of *V** we can take the first move that improves the current solution, in this way one can speed up the search because the mean calculation time of a step is less than to revise the whole neighborhood. Up to this point, the algorithm is close to a local improvement technique, except that we may move from x to a worse solution x^*, and, thus, we may escape from any local optimum in F. To avoid cycling, a tabu list of length t (fixed or variable) is provided. Its purpose is to forbid moves between solutions that reinstate certain attributes of past solutions. Each forbidden move is removed after t iterations. However, this list may forbid interesting moves (such as a move that improves the best solution found so far). In order to cancel the tabu status of such moves, an aspiration criterion is introduced.

The most important points in the implementation of tabu search technique to our application are: the search space, the moves (exchanges allowed without violating the restrictions imposed), the cost function F (CM-PRESTO runs), the neighborhood, the length of the tabu list and the stop criterion.

In general, TS starts from the hypothesis that it is possible to build up a neighborhood along the iterative search process. In our problem, a neighborhood shall be a set of exchanges of the fuel assemblies settled in a 1/8-symmetry reactor core. In each move the energy obtained for such array, the thermal safety limits and the shutdown margin are calculated. All these values are included in the objective function that will be shown later on.

Once that the way to build up the neighborhood is defined, it is also necessary to build up the tabu list to verify forbidden moves on each iteration. Our tabu list is implemented as an array Tabu Time, which records the earliest iteration that a move is removed from the list. The number of iterations t that a move or exchange will keep its tabu is randomly selected in the range *(7 t 15)*. This random selection provides a more versatile search process. In addition, the implementation of the TS was carried out with two modifications to make more robust the search. In the first, only part of the neighborhood is reviewed accordingly to a number randomly generated. In the second one, the search ends once that the first optimal value of the objective function was found. With these modifications the search of the optimal value is diversified making the process more efficient and economic.

The tabu search technique implemented in this work maximizes the following objective function:

$$F = \text{Energy} \cdot w_1 + \Delta\text{MRNP} \cdot w_2 + \Delta\text{RPPF} \cdot w_3 + \Delta\text{XLHGR} \cdot w_4 + \Delta\text{XMPGR} \cdot w_5 + \Delta\text{XMCPR} \cdot w_6 + \Delta\text{SDM} \cdot w_7$$

where

Energy	=	Cycle Mean Core Burnup
ΔMRNP	=	$\text{MRNP}_{max} - \text{MRNP}_c$
ΔRPPF	=	$\text{RPPF}_{max} - \text{RPPF}_c$
ΔXLHGR	=	$\text{XLHGR}_{max} - \text{XLHGR}_c$
ΔXMPGR	=	$\text{XMPGR}_{max} - \text{XMPGR}_c$

$\Delta XMCPR = XMCPR_c - XMCPR_{min}$
$\Delta SDM = SDM_c - SDM_{min}$
$w_1, \ldots, w_7$ are called weighting factors
$w_1 > 0$
$w_i = 0$ if limit is OK, for i=2,…,7

Energy	Maximum possible energy value in the cycle
MRNP	Mean Ratio of Nominal Power
RPPF	Radial Power Peaking Factor
XLHGR	Linear Heat Generation Rate
XMPGR	Maximum Power Generation Rate
XMCPR	Minimal Critical Power Ratio
SDM	Shutdown Margin

All the parameters are obtained from the output of the CM-PRESTO code. The objective function was built in such a way that maximizes the energy if safety limits are not violated and penalizes it when the safety limits are violated, in other words, the safety limits are satisfied when

$MRNP_c < MRNP_{max}$
$RPPF_c < RPPF_{max}$
$XLHR_c < XLHGR_{max}$
$XMPGR_c < XMPGR_{max}$
$XMCPR_c > XMCPR_{min}$
$SDM_c > SDM_{min}$

4. SYSTEM DESIGN

The modified tabu search technique along with the heuristic rules were implemented in the CM-PRESTO-B. Then, we will perform several fuel core calculations to find an optimized loading pattern. Due to the way that the objective function is constructed, the system requires four different runs of CM-PRESTO; first one is to calculate the energy and the seven parameter associated with the operational and safety limits, the other three runs are to calculate the cold shutdown margin. The way that the system is configured is shown in Figure 2.

The system has been implemented using FORTRAN-77 in an Alpha computer which uses a UNIX system. The time required to get an optimized loading pattern assuming one octant symmetry was approximately 6 hours, where the objective function was evaluated about 80,000 times.

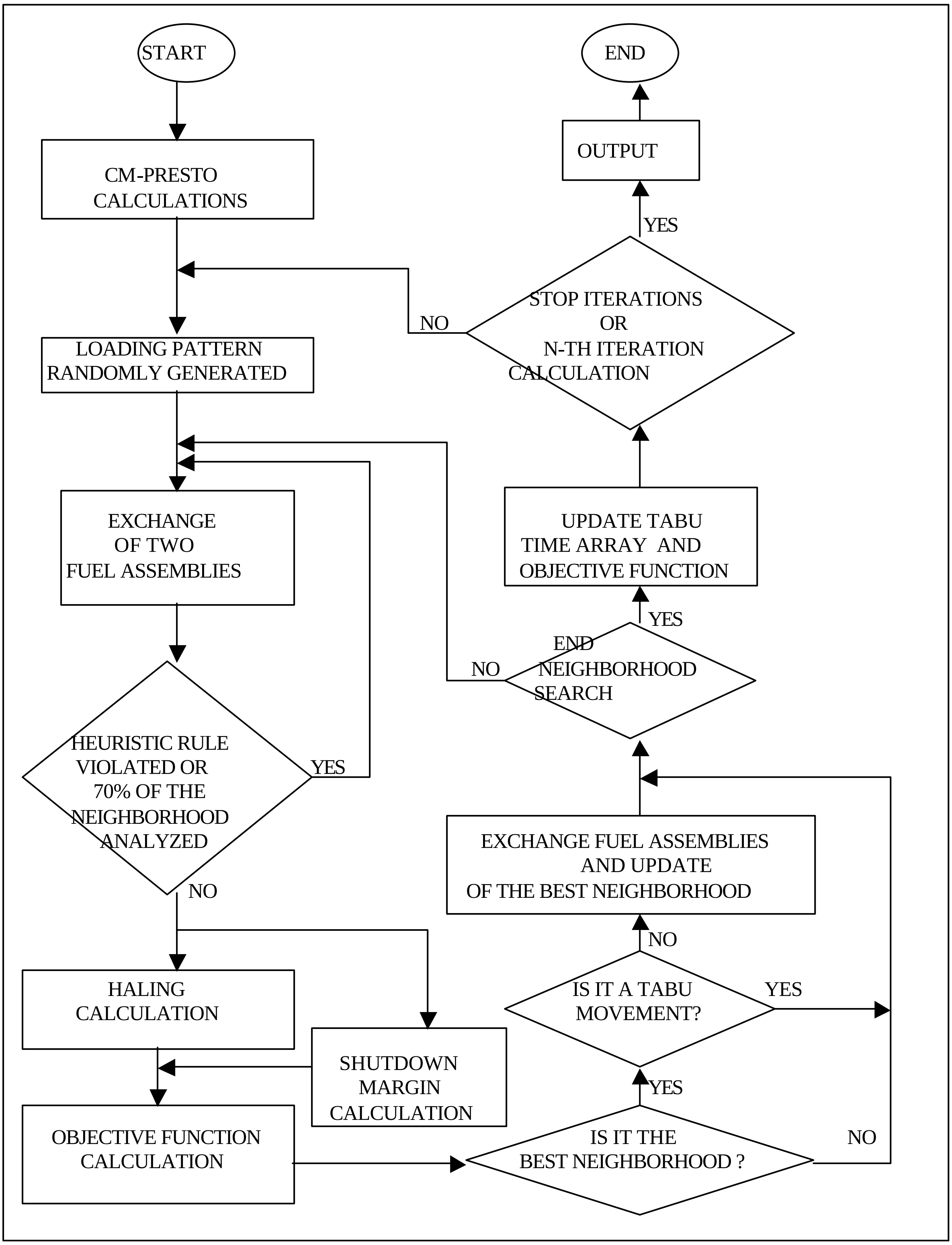

Figure 2. Tabu search system structure

5. TEST PROBLEM AND RESULTS

To test our optimization method an actual operating cycle was simulated, corresponding this cycle to an 18-month cycle with a cycle length of 9,281 MWD/TU, which used 112 fresh fuel assemblies of 3.53 w/o of U-235, this loading pattern was generated using engineer expertise and will be used as a comparison base. The objective is not to violate the operational and safety limits at the end of the cycle (Haling calculation), which are described in Table I. On the other hand the cold shutdown margin will be assessed at the beginning of the cycle and it needs to be more than 1% $\Delta k/k$ to not jeopardize the integrity of the reactor core.

Table I. Operational and safety limits

Mean Ratio of Nominal Power	MRNP	1.83	Maximum Value
Radial Power Peaking Factor	RPPF	1.51	Maximum Value
Linear Heat Generation Rate	XLHGR	370	Maximum Value
Maximum Power Generation Rate	XMPGR	0.85	Maximum Value
Minimal Critical Power Ratio	XMCPR	1.5	Minimum Value
Shutdown Margin	SDM	1.0	Minimum Value

Using our system we analyze three different cases to assess the impact of the limit values in the objective function. In those cases we relax the linear heat generation rate parameter and restrict the cold shutdown margin. The best results that we found are shown in Table II. From these results we realize that it could have a maximum energy of 9,788 MWD/TU, which is about a 5.5 % of extra energy using the same fuel assemblies given by engineer expertise, which represents about 20 days of full operation. Furthermore, Figure 3 shows the energy behavior during the numerical experiments of this assessment.

Table II. Optimized fuel reload results

Parameter	**Case 1**		**Case 2**		**Case 3**	
	Limit Value	**Obtained**	**Limit Value**	**Obtained**	**Limit Value**	**Obtained**
MRNP	1.83	1.8187	1.83	1.8233	1.83	1.8219
RPPF	1.51	1.5062	1.51	1.5086	1.51	1.5084
XLHGR	363	364.1	370	364.9	370	364.8
XMPGR	0.85	0.7763	0.85	0.782	0.85	0.7917
XMCPR	1.5	1.608	1.5	1.606	1.5	1.6
SDM	1.0	0.9997	1.5	1.5005	1.0	1.0106
Energy		9190.9		9381.6		9788

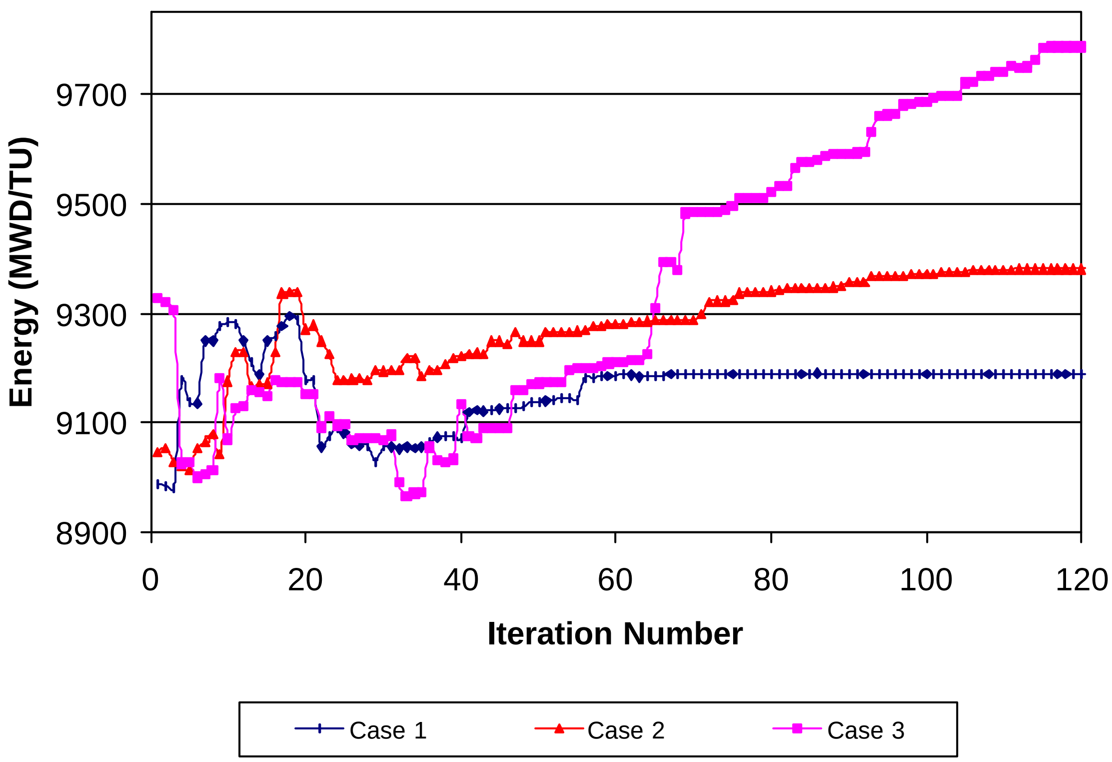

Figure 3. Energy behavior for the tabu search

Parameters more restrictive in this search were the linear heat generation rate (XLHGR) and the shutdown margin (SDM) as it was expected. However, both are inside the operational and safety limits and if we want to increase the shutdown margin the objective function is penalized by producing less energy.

CONCLUSIONS

The system generated in this research optimize fuel reloads. Results of this modified Tabu search technique shows a maximum cycle length of 9,788 MWD/TU which does not violate the operational and safety thermal limits and has a cold shutdown margin of 1.06% Δk/k, which is greater than the 1% Δk/k minimal limit value. If we want to increase the cold shutdown margin up to 1.5% Δk/k the energy is penalized obtaining only a maximum of 9,381.6 MWD/TU. However, we have in both cases an increase of energy produced in comparison with the energy produced by the actual operating cycle achieving the goal of this task.

To get a whole reload design system it is necessary to implement the control rod pattern in our system, which will be a future work.

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