

A New Coupled System for BWR Nuclear Fuel Management

**Alejandro Castillo¹, Juan Jose Ortiz-Servin¹, Jose Luis Montes-Tadeo¹, Raul Perusquia¹
and Roberto Leonel Martinez Rizo²**

¹Instituto Nacional de Investigaciones Nucleares, Ocoyoacac, Estado de México, México

²Universidad Autónoma de Campeche, Campeche, México

alejandro.castillo@inin.gob.mx, juanjose.ortiz@inin.gob.mx, jose Luis.montes@inin.gob.mx,
raul.perusquia@inin.gob.mx, roberto_oblivion@hotmail.com

Abstract

In this work, a system to solve four stages of the fuel management problem is showed. The system uses different heuristic techniques to solve each stage of that area, and this problem is solved in a coupled way. Considered problems correspond to the following designs: fuel lattice, fuel assembly, fuel reload and control rod patterns. Even though, each stage of the problem can have its own objective function, the complete problem was solved using a multi-objective function. The solution strategy is to solve each stage of design in an iterative process, taking into account previous results for the next stage, until to achieve a complete solution. The solution strategy to solve the coupled problem is the following: the first solved stage is the fuel lattice design, the second one is fuel assembly design, finally an internal loop between both fuel reload design and control rod pattern design is carried out. For this internal loop, a seed reload using Haling principle is generated. The obtained results showed the advantage to solve the whole problem in a coupled way.

Keywords: BWR, Fuel Management, Optimization, Heuristic techniques.

1. Introduction

The nuclear fuel management in a BWR include different stages, four of them are: fuel lattice design, fuel assembly design, fuel reload and control rod pattern design. There are a wide variety of papers whose purpose is to solve some of these problems. However, nowadays there is not enough work to solve the four stages in a coupled way.

In the past, attempts to solve some of these stages in a coupled way have been made by some researchers [1,2, 3]. However, those papers solve only two of the mentioned stages. In [1], authors used both a genetic algorithm and if-then heuristic rules to solve both load pattern and control rod pattern problem in a coupled way. On the other hand, in [2] the tabu search was implemented to solve the same two problems in a coupled way. Finally, in [3] a genetic algorithm, a neural network and ant colony system techniques were applied to solve the same two problems. In all cases, the problem (including two stages) was not solved due to lack of computational resources in that time.

For this reason, in this research, a system to solve the four stages for nuclear fuel management above mentioned is shown. In our system, fuel lattice design is solved using an hybrid between scatter search and path relinking, a local search is used to solve fuel assembly design, and finally, both fuel reload and control rod pattern designs are solved using tabu search technique. Built system involves an iterative process, which will be explained in next section.

2. Methodology

This section will be divided in three parts, the first one includes applied heuristic techniques to build the system, in the second part, the used objective functions for each stage of the problem will be explained, those objective functions involve the four stages of the fuel management area above mentioned, finally, the last part includes the iterative process to solve the coupled problem.

For a reference point, an equilibrium cycle was considered, as a reference solution. Mentioned cycle has two fresh fuel batches, with the same average uranium enrichment but different gadolinia content, which are called FB1 and FB2 respectively. Each fuel batch has 4.06 of average uranium enrichment. First fuel batch (FB1) has 52 fresh fuel assemblies and the second one (FB2) has 60 fresh fuel assemblies. Each fuel assembly was divided in 5 axial zones (see Figure 1). In this figure, zones A, E, and F have natural uranium and, zones B, C and D may have ^{235}U and U_2O_3 . Finally, the cycle length was 10,876 MWD/TU.

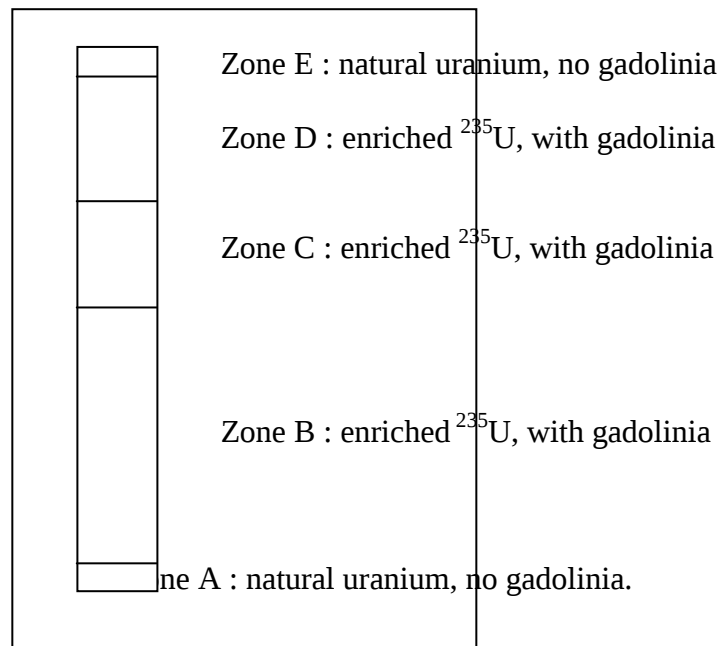


Figure 1. Axial zones for fuel assembly.

2.1 Heuristic techniques

As it was mentioned, to solve the complete problem, some heuristic techniques were applied. In the next, a brief explanation about these techniques is shown.

2.1.1 Path relinking

PR technique [4] constructs different paths considering basic solutions set in an intelligent way, these solutions can be seen as paths generated inside and outside of these elements. Sometimes, the new

solutions can be used to generate other paths, if it is considered necessary. When this information is added, then we can generate new paths obtaining the good attributes from the original solutions.

Basic solutions' set is generated using either a local search method or a global search method. Characteristic of these paths depends of both to add or to eliminate attributes from the original paths. Attributes of these solutions are evaluated using the objective function to determinate which is the best. During the iterative process it is possible that the new paths does not improve anyone solution, however, they can be considering to generate new paths. PR has three following stages to generate new paths:

- a) Step 1: To build the basic solutions set it is possible to use either local or global search method.
- b) Step 2: Once two solutions have been chosen of this set, the first one will be the initial solution, the second one will be the guide solution.
- c) Step 3: If anynew path improved the reference solution then it is updated.

2.1.2 Scatter search

To apply Scatter Search (SS) technique [5], it is necessary to build linear combinations from two solutions in an intelligent way, considering a set named *reference set*. New solution has attributes of both two previous solutions. In this manner, the new solution can be considered of better quality than the original solutions. SS works with an adequate strategy to choose from a small set of 20 elements. During the iterative process, SS updates this set adding new solutions from the linear combinations between the reference set. The steps of SS are the following:

- a) Step 1: Seed Generation. One or two seed solutions must be generated using either a local search method or a global search method.
- b) Step 2: A diverse solutions generator. From a solution seed, a set of 100 diverse elements is built. These solutions can be improved with either a local or global search method.
- c) Step 3: Reference Set. 100 previous solutions are evaluated using the objective function, after the 10 best solutions are taken. From these, 5 elements are the first part of the reference set. Once, the first part of reference have been generated, the maximum distance of this set to the reference set is obtained taking into account the maximum distance from the diverse set elements to the reference set. It is necessary to define a metric function. This set is the second part of the reference set and it has 10 elements.
- d) Step 4: A combination method. It is a procedure to obtain linear combinations using the reference set. Two elements can be used to obtain a new solution. However, it is possible to use three or more elements to generate the linear combinations.
- e) Step 5: Reference set update. To update the reference set, the new solution must be better than anysolution included in the reference set. It is necessary to maintain the reference set with the best solutions during the iterative process. The attribute "best" is obtained using the objective function.

2.1.3 Tabu search

Tabu search (TS) [6] starts from the hypothesis that it is possible to build up a neighborhood $N(x)$ along the iterative search process. It starts from an initial feasible solution and after the iterative process a global minimum is obtained. We must define a set M of simple moves, $m \in M$ indicates that it is a move between two positions. For each feasible solution x , the neighborhood $N(x)$ is the set of all feasible solutions by a single move m in M . It is very important to note that the algorithm is close to a local improvement method, however, in this technique we may move from x to a worse solution x^* , thus we may to escape from local minima. To avoid cycling, any move that return to local optimum recently visited is forbidden (tabu). A move remains forbidden during t iterations, through the set T , called *tabu list* of fixed length t .

Due to, the set $N(x)$ is considerably large and evaluate the objective function in this domain is very expensive then the objective function is only evaluated in the subset V of $N(x)$, which is randomly generated, and the move is made from x the first solution in V improving the objective function. However, if there is not solution that improves x , then one must to examine all neighbors in V . In this case, we have a best solution in each iteration which not necessarily is the best of the whole process, there will be some solutions that did not satisfy all constrains, however, when the process ends the best solution founded satisfies all the constrains considered.

Our tabu list was implemented with the tabu time array, which records the previous iteration in which a move is removed from the list. On the other hand, the number of iterations called “*tabu_tenure*” that a move or exchange will keep its tabu status is randomly selected, reference 5 suggests that this value must be lower than 25.

Finally, an *aspiration criterion* is introduced to diversify the search. In this case, when the tabu list forbid some interesting moves, we consider very important to cancel the tabu status in this cases. In this way, we avoid to refuse a move that improved the objective function.

2.2 **Objective functions**

During the iterative process, four objective functions are evaluated, one by one for each stage of the process. At the end of each equation, a brief explanation about its implementation is included. The implementation depends on the analyzed problem.

These objective functions include weighting factors, which are obtained with a statistical analysis. There are different methods to choose weighting factors, taking into account their importance in a particular optimization process. For this investigation, this analysis was made in the following way: at the beginning all weighting factors are equal to one and several runs are executed. The next step is to verify all obtained values for each single term; after, the weighting factors are changed to normalize their values with their respective terms. Later several runs are executed again, to analyze the new results and it is necessary to change weighting factors again. Finally, when all single terms were normalized, some weighting factors can be increased either when one variable is considered more important than others or when one variable can not fulfilled. The above was made for each objective function.

The objective functions are the following:

2.2.1 Fuel lattice design

As it was mentioned, the fuel lattice design was made using a hybrid between scatter search and path relinking techniques. In Equation (1) this objective function is shown.

$$\begin{aligned} \min F_1 &= LPPF \cdot w_1 + K(k_\infty) \\ \text{where} & \\ K(k_\infty) &= \begin{cases} |k_\infty| \cdot w_2 & \text{if } |k_\infty - k_{tar}| > 0.005 \\ 0 & \text{otherwise} \end{cases} \end{aligned} \quad (1)$$

where

LPPF : local power peaking factor of the fuel lattice.

k_∞ : neutron infinite multiplication factor of the fuel lattice.

k_{tar} : target neutron infinite multiplication factor.

In this case, w_1 and w_2 are weighting factors obtained with the statistical analysis previously explained. It is clear that when the k_∞ parameter is fulfilled, then only LPPF parameter is minimized. To evaluate the fuel lattice designs, obtained with the above heuristic techniques, CASMO-4 [7] code was used. In the same sense, as it was mentioned two fresh fuel batches were taken into account, for this reason k_{tar} has two possible values, these values are shown in the results section. Additionally, from Equation (1), a maximum difference of 500 pcm's was considered between k_∞ and k_{tar} values.

It is very important to note that fuel lattice design problem is to allocate different uranium pellets in an array such that LPPF can be minimized and k_∞ value is kept into a proposed interval. It is well known that low values of k_∞ can produce that the requirements of energy is not reached. On the contrary, high values of k_∞ can produce high reactivity, which can be difficult to control, for this reason, it was chosen a value equal to 500 pcm's for the k_∞ interval.

2.2.2 Fuel reload design

To evaluate the different fuel reload configurations, two objective functions were used. The first one was used to design a seed fuel reload, in this case Haling Principle [8] was applied. Second one is applied when fuel reload was optimized including its corresponding set of control rod patterns.

In the first case the objective function is the following:

$$\begin{aligned} \max F_2 &= k_{eff} \cdot w_1 + \Delta \lim_1 \cdot w_2 + \Delta \lim_2 \cdot w_3 + \Delta \lim_3 \cdot w_4 + \\ &+ \Delta \lim_4 \cdot w_5 \end{aligned} \quad (2)$$

where

k_{eff} : effective multiplication factor at the end of cycle according to Haling Principle

$\Delta \lim_1 = MFLPD_{lim} - MFLPD_{obtained}$

$$\Delta \lim_2 = \text{MAPRAT}_{\lim} - \text{MAPRAT}_{\text{obtained}}$$

$$\Delta \lim_3 = \text{MFLCPR}_{\lim} - \text{MFLCPR}_{\text{obtained}}$$

$$\Delta \lim_4 = \text{SDM}_{\text{obtained}} - \text{SDM}_{\lim}$$

w_i are weighting factors, obtained with the statistical analysis previously explained.

In the second case the objective function is the following:

$$\begin{aligned} \max F_3 = & k_{EOR} \cdot w_1 - \sum_{i=1}^{n-1} |k_{eff}^i - k_{crit}| \cdot w_2 + \sum_{i=1}^n \Delta \lim_1^i \cdot w_3 + \\ & + \sum_{i=1}^n \Delta \lim_2^i \cdot w_4 + \sum_{i=1}^n \Delta \lim_3^i \cdot w_5 + \Delta \lim_4 \cdot w_6 \end{aligned} \quad (3)$$

where

k_{EOR} : Obtained Effective Multiplication Factor at the end of cycle

k_{eff}^i : Obtained Effective Multiplication Factor in each burnup step

k_{crit} : Objective Effective Multiplication Factor

$\Delta \lim_1^i$: $\text{MFLPD}_{i,\lim} - \text{MFLPD}_{i,\text{obtained}}$

$\Delta \lim_2^i$: $\text{MAPRAT}_{i,\lim} - \text{MAPRAT}_{i,\text{obtained}}$

$\Delta \lim_3^i$: $\text{MFLCPR}_{i,\lim} - \text{MFLCPR}_{i,\text{obtained}}$

$\Delta \lim_4$: $\text{SDM}_{\text{obtained}} - \text{SDM}_{\lim}$

n : number of burnup steps for the control rod pattern.

For the above equation i denote each one of the burnup steps in which cycle length is divided. On the other hand, w_i , $i=1, \dots, 6$ are weighting factors, which are obtained with the statistical analysis previously explained. To obtain nuclear parameters SIMULATE3 [9] code was used.

In the two above cases, the main idea is to allocate fuel assemblies into the reactor core, taking into account two important outcomes. The first one is to verify the reactor security during the operating cycle, which is monitored by $\Delta \lim_k^i$ values in Equations (2) and (3). On the other case, it is necessary to reach the energy requirements, which is verified by $k_{eff,EOR}$ in the same equations. The difference between both Equations is the following: in Equation (1) Haling principle is applied, while in Equation (2) a control rod pattern and a k_{eff} target were used for the optimization process.

2.2.3 Control rod pattern design

Finally, the objective function used in this work for control rod pattern design is the following:

$$\max F_4 = w_1 |k_o - k_t| + w_2 \sum_{i=1}^{25} |P_{oi} - P_{ti}| + w_3 \cdot \Delta \lim_1 + w_4 \cdot \Delta \lim_2 + w_5 \cdot \Delta \lim_3 \quad (4)$$

where

k_o : current effective multiplication factor

k_t : target effective multiplication factor

P_{oi} : axial power distribution for node i

P_{ti} : target axial power distribution for node i

$\Delta \lim_1$: $MFLPD_{lim} - MFLPD_{obtained}$

$\Delta \lim_2$: $MAPRAT_{lim} - MAPRAT_{obtained}$

$\Delta \lim_3$: $MFLCPR_{lim} - MFLCPR_{obtained}$

Where w_i , $i=1, \dots, 5$ are weighting factors and $w_i > 0$ obtained with the statistical analysis previously explained. If the safety parameters (MFLPD, MAPRAT and MFLCPR) are satisfied their respective weighting factor is equal to zero. In this case, the minimization process only will be applied over the effective multiplication factor and the axial power distribution.

For this case, the control rod pattern design was divided in 12 burnup steps, in each burnup step is necessary to find an adequate set of control rod positions, trying to maintain reactor security and the criticality of the reactor. Again, the security is given by $\Delta \lim_k$ values, while the first term is for the criticality of the reactor. In this case a spectral shift strategy [10] was used during the optimization process.

2.3 Iterative process

To solve the four stages for the mentioned problem, an iterative process was applied. In Figure 2, a flowchart for the iterative process is shown.

Iterative process is as follows: in the first stage the bottom part of the fuel lattice for FB1 fuel batch (Figure 1) is built, which is designed applying a hybrid between scatter search and path relinking techniques, once this fuel lattice have been optimized, a local search (LS) is applied to build the second fuel lattice (for FB2 fuel assembly), taking into account the gadolinia content only. When two fuel lattices were optimized, the respective fuel assemblies are building (zones C and D for both assemblies), taking into account the same fuel lattice configuration, but adding some gadolinia rods in the those zones.

Once fuel assemblies were built, a seed fuel reload is obtained applying Haling Principle. In this case, some iterations are executed only, because in the first tests, it was seen that when seed fuel lattice is optimized enough, it was difficult to design control rod pattern in the first iteration of the internal loop. Next step is an internal loop, which can be executed until 5 times. Once seed fuel reload was designed, the obtained information is given to tabu search technique to generate control rod pattern. When control rod pattern was built, tabu search technique is applied again, but now to build fuel reload and taking into account the obtained control rod pattern.

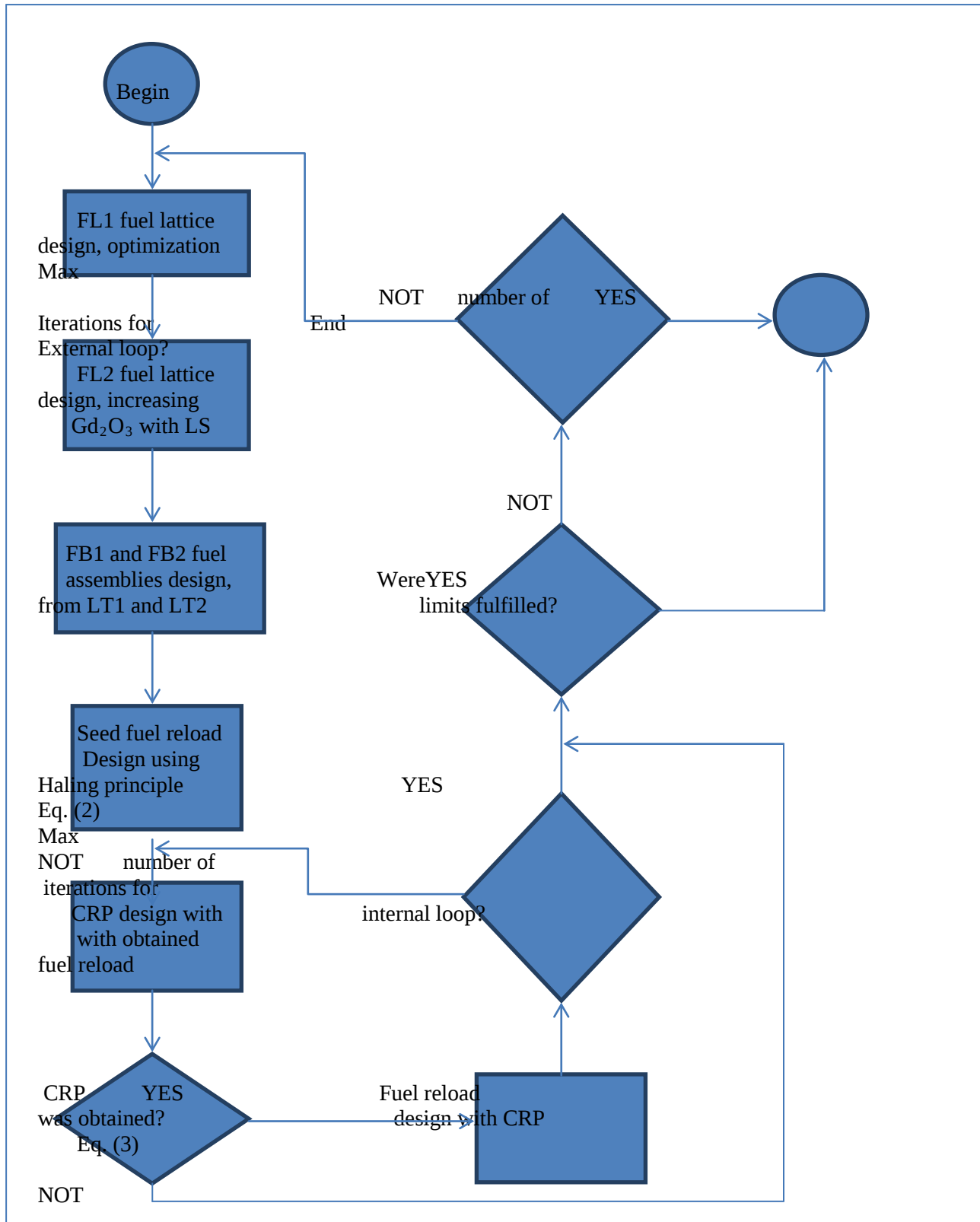


Figure 2. System flowchart.

If after 5 internal loop iterations, a good solution is obtained, it is to say, all nuclear parameters for the 4 stages are fulfilled, the system stop the iterative process. When some parameters are not fulfilled, the system starts the fuel lattice design. Due to the computational resources are very expensive, the number of iterations for the external loop is equal to 3.

3. Results

At this moment, the complete process has been executed few times, this is so due to the great quantity of needed computational resources, the three best results are shown only. Results are shown in the same order in which they were obtained: fuel lattice, seed fuel reload, control rod pattern and finally, fuel reload.

In Table I, the fuel lattice results are shown, in this case, the 6 designed fuel lattices of two fuel assemblies are shown. It is necessary to remember that, the zone B of fuel assembly FB1 was designed using a heuristic technique (SS+PR) and, the other 5 fuel lattices were optimized using a local search.

Table I. Fuel lattices results.

	Zone B		Zone C		Zone D	
	k_{∞}	LPPF	k_{∞}	LPPF	k_{∞}	LPPF
FL1 reference	1.148	1.201	1.121	1.222	1.079	1.205
FL1 example 1	1.152	1.193	1.117	1.230	1.069	1.283
Difference	400 (pcm's)	0.008	400 (pcm's)	0.008	1000 (pcm's)	0.078
FL1 example 2	1.152	1.194	1.126	1.215	1.090	1.283
Difference	400 (pcm's)	0.007	500 (pcm's)	0.007	1100 (pcm's)	0.078
FL1 example 3	1.153	1.190	1.105	1.199	1.060	1.294
Difference	500 (pcm's)	0.011	1600 (pcm's)	0.023	1900 (pcm's)	0.089
FL2 reference	1.099	1.254	1.058	1.305	1.004	1.307
FL2 example 1	1.107	1.230	1.063	1.244	1.006	1.251
Difference	800 (pcm's)	0.024	500 (pcm's)	0.061	200 (pcm's)	0.056
FL2 example 2	1.106	1.215	1.066	1.246	1.014	1.314
Difference	700 (pcm's)	0.039	800 (pcm's)	0.059	1000 (pcm's)	0.007
FL2 example 3	1.105	1.199	1.063	1.233	1.012	1.328
difference	600 (pcm's)	0.055	500 (pcm's)	0.072	800 (pcm's)	0.021

On the other hand, the next step was to design two fuel reloads, the first one when Haling principle was applied and then, the fuel reload obtained during the internal iterative process. In both cases the same three examples were considered. In Table II, both the fuel reload applying Haling principle and the last fuel reload for internal loop are shown. In each case, the difference (absolute value) between reference value and target value is included.

Finally, the obtained values for considered parameters for the optimized control rod pattern are shown, in this case, 12 burnup steps were considered and in the same way, the last configuration for the iterative process is shown. In Tables III-V these results are included for three obtained examples.

Table II. Fuel reloads results.

	Haling principle					Fuel reload + PBC				
	k_{eff} (EOC)	MFLPD	MFLCPR	MAPRAT	SDM	k_{eff} (EOC)	MFLPD	MFLCPR	MAPRAT	SDM
Fuel reload reference	0.9978	0.689	0.706	0.772	1.780	0.9973	0.966	0.834	0.790	1.780
Fuel reload example 1	0.9821	0.733	0.773	0.812	1.778	0.9991	0.824	0.788	0.901	2.650
difference ($ x $)	0.0157	0.044	0.067	0.04	0.002	0.0018	0.142	0.046	0.111	0.87
Fuel reload example 2	0.9833	0.711	0.764	0.773	1.783	0.9990	0.845	0.802	0.823	2.120
difference ($ x $)	0.0145	0.022	0.058	0.001	0.003	0.0017	0.121	0.032	0.033	0.34
Fuel reload example 3	0.9854	0.642	0.690	0.725	2.204	0.9993	0.759	0.804	0.759	1.710
difference ($ x $)	0.0124	0.047	0.016	0.047	0.424	0.002	0.207	0.03	0.031	0.07

Table III. Control rod pattern results, example 1.

Burnup step (MWD/T)	k_{eff}	MFLPD	MFLCPR	MAPRAT
0	1.0097	0.8890	0.8610	0.9110
1,000	1.0077	0.9250	0.8920	0.9150
2,000	1.0060	0.9210	0.8709	0.7810
3,000	1.0047	0.9079	0.8590	0.7929
4,000	1.0036	0.8569	0.8069	0.8539
5,000	1.0030	0.9120	0.8790	0.8650
6,000	1.0023	0.8740	0.8629	0.7950
7,000	1.0021	0.9039	0.8820	0.8539
8,000	1.0006	0.7620	0.7889	0.7960
9,000	0.9991	0.7059	0.7340	0.7900
10,000	0.9965	0.8610	0.9229	0.9079
10,896	0.9991	0.8249	0.9010	0.7889

Table IV. Control rod pattern results, example 2.

Burnup step (MWD/T)	k_{eff}	MFLPD	MFLCPR	MAPRAT
0	1.0099	0.9190	0.9049	0.9200
1,000	1.0076	0.9300	0.8439	0.9240
2,000	1.0057	0.9120	0.8640	0.9020
3,000	1.0046	0.9160	0.8849	0.8320
4,000	1.0036	0.9240	0.8759	0.8059
5,000	1.0029	0.9300	0.9060	0.8150
6,000	1.0023	0.8650	0.8679	0.8640
7,000	1.0021	0.8150	0.8010	0.8000
8,000	1.0009	0.8180	0.7770	0.8500
9,000	0.9989	0.8050	0.7699	0.8090
10,000	0.9968	0.8299	0.7979	0.8230
10,896	0.9990	0.8450	0.8230	0.8029

Table V. Control rod pattern results, example 3.

Burnup step (MWD/T)	k_{eff}	MFLPD	MFLCPR	MAPRAT
0	1.0099	0.8890	0.8209	0.8890
1,000	1.0076	0.9290	0.8470	0.9110
2,000	1.0060	0.9110	0.9110	0.9110
3,000	1.0044	0.9179	0.9170	0.9269
4,000	1.0035	0.9100	0.8629	0.8569
5,000	1.0031	0.9260	0.8939	0.9139
6,000	1.0022	0.9269	0.9070	0.8660
7,000	1.0020	0.9279	0.9269	0.8339
8,000	1.0009	0.8679	0.8730	0.8590
9,000	0.9990	0.7540	0.7530	0.8259
10,000	0.9960	0.9179	0.9139	0.9079
10,896	0.9993	0.7590	0.7599	0.8040

The evaluation of the four objective functions are very expensive, for this reason is very important to mention how many times the different objective functions were evaluated. In Table V these results are shown. In the same sense, it is important to note that each execution used three weeks in the complete process, using a Dell Workstation on LINUX platform.

Table V. Objective functions evaluations.

	Fuel lattice	Fuel assembly	Fuel reload Haling	Fuel reload (CRD)	Control rod pattern
--	--------------	---------------	--------------------	-------------------	---------------------

Example 1	26348	296	11688	148560	62388
Example 2	22598	296	12764	156740	60088
Example 3	23484	296	12058	149634	61262

4. Conclusions

A system to solve 4 designs in BWR nuclear fuel management area was shown. This system solves the mentioned designs in a coupled way. Even though, the consumed computational resources are expensive, the main advantage is that when iterative process has finished, a complete solution is obtained, from fuel lattice design until control rod pattern design. All stages of the process have communication between them.

At the beginning of the iterative process, the first results are fuel lattices for fuel assemblies. In this case, the obtained results for bottom part of the FB1 fuel assembly improved the reference values (see Table I). As it was mentioned, the other zones for fuel assemblies design were built with a local search when gadolinia was increased. From Table I, it can be seen that when a local search is applied, the obtained results never improved the reference values.

In the next step, when an internal loop is executed, a seed fuel reload was obtained. According to the obtained results, this fuel reload can be considered a worse fuel reload (Table II). However, it is important to say that the outcome in this part is to obtain a first fuel reload with Haling principle. During the realized tests, it was seen that when optimized fuel reload was obtained applying Haling principle, many times it was not possible to obtain the respective control rod pattern in the first iteration of the internal loop. For this reason, a few iterations were considered to obtain this fuel reload.

For finally results, some aspects must be analyzed, in the three cases k_{eff} is better than the reference values (Table II). However, in some cases (examples 2 and 3) not all thermal limits are lower than the reference values, even though, these obtained values are lower than the proposed limits values (0.9). In the same sense, in the example 3 all thermal limits are lower than the reference values, but, in this case the cold shutdown margin is greater than the reference value.

Based on all above, some changes have to be implemented in the system in order to fulfill all the proposed objectives. Some possible changes are either to adjust weighting factors or to modify local search in fuel lattice design, in order to improve the obtained results, particularly those related to energy requirements.

An advantage for this process is the following, when the process has been finished, a good complete solution is obtained: fuel lattices, fuel assemblies, fuel reload and the respective control rod patterns. A future work for this investigation can be addressed as follows: to modify the system with parallel tools, to reduce the real time and to implement a better optimization process for the other zones of the fuel lattices design.

5. Acknowledgments

The authors acknowledge the support given by Instituto Nacional de Investigaciones Nucleares through the research project CA-215, Consejo Nacional de Ciencia y Tecnología through the

research project CB-2011-01-168722 and to Departamento de Gestión de Combustible of the Comisión Federal de Electricidad of México.

6. References

- [1] Y. Kobayashi, E. Aiyoshi, “Optimization of Boiling Water Reactor Loading Pattern Using Two-Stage Genetic Algorithm”, *Nuclear Science and Engineering*, **vol.** 142, p. 119-139 (2002).
- [2] Alejandro Castillo, Juan José Ortiz, José Luis Montes, Raul Perusquía, “Fuel Loading and Control Rod Patterns Optimization in a BWR Using Tabu Search”, *Annals of Nuclear Energy*, **vol.** 34, p. 207-212 (2007).
- [3] Juan José Ortiz, Alejandro Castillo, José Luis Montes, Raúl Perusquía, “A new system to fuel loading and control rod pattern optimization in Boiling Water Reactors”, *Nuclear Science and Engineering*, **vol.** 157, p. 236-244 (2007).
- [4] Glover, F. “Scatter Search and Path Relinking”. In: D. Corne, M. Dorigo and F. Glover (Eds), *New Ideas in Optimisation*, Wiley (1999).
- [5] Laguna M., Martí R., *Scatter Search, Methodology and Implementations in C*, Kluwer Academic Publishers, Boston, USA (2003).
- [6] Glover F., “Tabu Search Part I”, *ORSA, Journal of Computing*, **vol.** 1, p. 190-206 (1968).
- [7] Rhodes, J., & Edenius, M., 2004. CASMO-4. A Fuel Assembly Burnup Program. User’s Manual. SSP-01/400 Rev 4. Studsvik Scandpower.
- [8] HalingRK, 1964. Operational Strategy for Maintaining an Optimum Power Distribution through Core Life. Proc. ANS Topl. Mtg. Nuclear Performance of Core Power Reactors, TID-7672. US Atomic Energy Commission.
- [9] Dean D. W. 2005. SIMULATE-3. Advanced Three-Dimensional Two-Group Reactor Analysis Code. User’s Manual. Studsvik Scandpower INC. SSP-95/15 - Rev 3.
- [10] Glasstone, S., Sesonske, A., *Nuclear Reactor Engineering, Reactor Systems Engineering*. Chapman & Hall, London (2004).
- [11] Castillo J. A., Alonso G., Morales L. B., del Valle E., “BWR fuel reloads design using a Tabu search technique”, *Annals of Nuclear Energy*, **vol.** 31, p. 151-161 (2004).
- [12] Castillo A, Ortiz JJ, Alonso G, Morales LB, del Valle E, “BWR Control Rod Design Using Tabu Search”, *Annals of Nuclear Energy*, **vol.** 32, p. 741-754 (2005).
- [13] Glover F., “Scatter Search and Star Paths: Beyond the Genetic Metaphor”, *OR Spektrum*, **vol.** 17, p. 125-137 (1995).
- [14] Glover F., “A template for Scatter Search and Path Relinking”, *Artificial Evolution, Lecture Notes in Computer Science*, **vol.** 1363, J.K. Hao, E. Lutton, E. Ronald, M. Schoenauer, D. Snyers (Eds.), p. 13-54 (1998).
- [15] Ortiz JJ, Requena I, “Azcatl-CRP: An Ant Colony-based System for Searching Full Power Control Rod Patterns in BWRs”, *Annals of Nuclear Energy*, **vol.** 33, p. 30-36 (2006).