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FEASIBILITY STUDY OF A SYSTEM FOR THE BWR CONTROL ROD PATTERN DESIGN BASED ON FUZZY LOGIC AND HEURISTICS

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ABSTRACT

This paper presents the development of a fuzzy logic control and heuristic based system for the control rod pattern (CRP) design of Boiling Water Reactors (BWR). At this stage of the study, very simple membership functions and fuzzy rules are defined to control the neutron multiplication factor (K) and the maximum relative nodal power (MRNP) by acting over the control rods relative movement. The Mamdani implication process is used to evaluate the membership functions. The variable K is controlled in order to bring the reactor to the critical state, and the MRNP is controlled to maintain the main thermal limits in the core under their design values. Several heuristic rules are implemented to govern the control rods' movement in the core. The system was tested with the cycle 5 of Laguna Verde Nuclear Power Plant using the CM-PRESTO simulator. The results obtained show that a very reasonable control rod programming can be achieved with a quite simple methodology. The obtained cycle length is comparable with that achieved with a Haling based simulation and the predicted by the cycle 5 design document.

1. INTRODUCTION

Control rod pattern (CRP) design is an important task of the cycle management of a BWR. It proposes the way the operator has to move the control rods to obtain the maximum energy from the core under the safety and flux constraints. On the other hand during the fuel reload pattern design stage, the control rod programming must be taken into account in order to obtain a real and optimum reload design. As part of our previous research in the in-core fuel management area, we have developed the SOPRAG system (François, 1999) to obtain improved fuel reload patterns for BWR using Genetic Algorithms. This system is based on a 2D methodology using the Haling technique to simulate the reload performance during the whole cycle. A new and improved version of SOPRAG is under development using a 3D methodology, an improved objective function taking into account all the thermal and reactivity constraints is being also implemented (Martín del Campo, 2001) and a control rod programming module is being developed to evaluate the proposed reload pattern instead of the Haling method. This last feature of the new system is the object of this paper.

Several works have been done for the BWR control rod programming since several years ago. Motada (1972) used the Method of Approximate Programming (MAP) limited to a simple 1D reactor model of one energy group. Afterwards, Kawai et al. (1976) using the MAP, developed the OPROD code based on a 3D BWR core simulator, the convergence of the MAP was the issue in this approach. Hayase and Motada (1980) included a heuristic search algorithm to improve the MAP algorithm. Kiguchi et al. (1984) developed a system to "optimize" the power distribution in the sense that it is the closest to a target one. They use a linear search algorithm with a simplified model based on sensitivity analyses of local power and thermal margins using a 3D simulator. On the side of the heuristic rules based systems, Zhong and Weisman (1984) developed a 3D computer code RODPRO for automatically generate a control rod program for BWR using a Control Cell Core (CCC) design. The system was based on heuristic rules to simplify complex theoretical approaches while eliminating trial and error studies. Fukusaki et al. (1987) developed a knowledge based system more flexible than the MAP based systems, in the sense that it can incorporate easily core design and operation policy changes by adding new rules. Lin and Lin (1991) showed that heuristic based expert systems can reproduce the experts' work for generate control rod patterns with the advantage of computational time savings. Finally Karve and Turinsky (1999) have shown the effectiveness of their CRP sampling capability added to the FORMOSA-B code, using heuristic rules based on common engineering practices used in industry.

The implementation of a control rod programming procedure in a system for reload pattern optimization, using stochastic algorithms search like genetic algorithms, needs to be very efficient since thousand of evaluations must be performed before to find an "optimal" solution. It must be also accurate in the sense that the proposed control rod pattern must be very close to the "best" CRP design, that allows the optimization system to obtain the better integral solution.

On the other hand, control methods use crisp and exact definitions to represent the operation of a system. In practice, however, it is not always easy to represent the crisp mathematical model of a system like the control of a BWR; such systems are mainly controlled by skilled human operators. Fuzzy logic theory (Zadeh, 1965) suggests a method to represent vague or fuzzy concepts and decision mechanisms. Mamdani and Assilian (1975) applied this theory to the design of fuzzy logic controllers for processes based on the control behaviors of a skilled human operator. The main behaviors of human operators are represented by linguistic rules. Therefore fuzzy logic offers several advantages that can be used for the CRP design problem:

- Fuzzy logic provides an environment to compute with words (operator's language), when there is no mathematical formula to express expertise.
- A fuzzy rule-based system is very easy to understand compared to that of the traditional rule-based approach.
- Fuzzy logic can handle approximate solutions efficiently.
- Fuzzy logic allows freedom in applying different composition techniques. Freedom comes from the membership (belief) function concept. The designer can incorporates his/her expertise, belief, or evidence into the inference mechanism by designing membership functions. The traditional rule-based systems operate based on exact match between a given situation and its rules.

- Fuzzy logic allows freedom in applying different implication techniques. Here, implication means the decision making process often symbolized by "THEN" clause. In traditional rule-based systems, "THEN" is a search process. When the left hand side of a rule is satisfied, a search is performed to find the corresponding action. In fuzzy logic, the implication process can be designed in any reasonable form to obtain the best approach for a given problem.
- The mechanics of fuzzy logic algorithms is different than that of the traditional rule-based systems. In fuzzy logic, all the rules are evaluated for a given input, therefore the speed of the algorithm is not a function of the number of inputs. On the other hand, the process speed of the traditional rule-based systems is a function of the input because of the search process. In some cases, the entire rule-based system must be searched to find out that there is no matching premise, thus there will be no action for a given input.
- Fuzzy logic algorithms are easy to implement. Fuzzy logic algorithms are not language dependent.

In the next sections, the implementation and the application to a real case of a simple fuzzy logic based control system for a typical BWR-CCC design are presented.

2. FUZZY LOGIC CONTROL SYSTEM

The main goal of the fuzzy logic control system (FLCS) is to act over the control rods axial relative movement to bring the neutron multiplication factor (K) to the critical state, and to maintain the maximum relative nodal power (MRNP) under a fixed value to assure that the main thermal limits in the core will be under the design values.

Fig. 1 shows the main components of the FLCS which are the CM-PRESTO 3D simulator (Scandpower, 1991) and the fuzzy logic controller (FLC) based on the FUZZLE software (Modico, 1997).

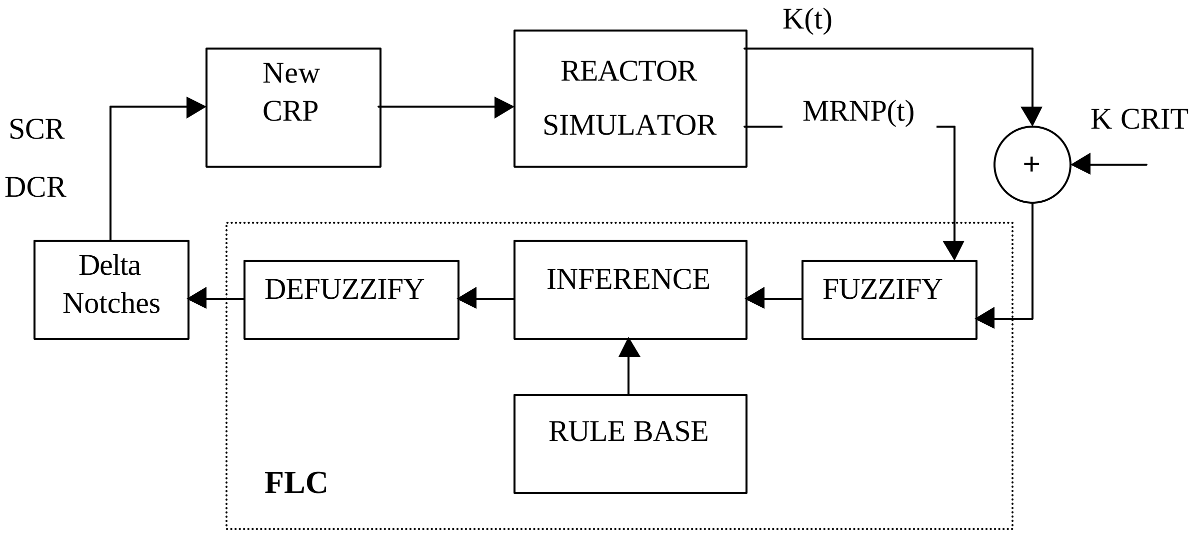

Fig. 1 Flow diagram of the Fuzzy Logic Control System

The fuzzy logic controller is composed by three parts. The FUZZIFY task where the variables are converted from crisp values obtained from the CM-PRESTO simulator into fuzzy values by mean of the membership functions. The INFERENCE task where the rules are combined to obtain a control action. Finally the DEFUZZIFY task where the output variables are converted from fuzzy values into crisp or scalar values.

2.1 Fuzzy Variables

Two types of fuzzy variables were defined for the system, the input variables and the action or output variables. The input variables are the neutron multiplication factor and the maximum relative nodal power as have already introduced. The action variables are defined as the increment or decrement in notches that will be applied to a control rod in order to achieve the core reactivity and to maintain the peak power under a limit value. The action values are the relative movement of the shallow control rods (SCR) and the relative movement of the deep control rods (DCR).

2.2 Fuzzification

A membership functions must be defined for each variable in the system in order to “fuzzify” them, it means to convert from a crisp value to a fuzzy value. In fuzzy logic the range or universe of a variable can be divided in several regions or fuzzy sets, as “low”, “medium” and “high”. For instance consider a variable X that can take any value between 1 and 10, it can be defined that the interval 1-5 is interpreted as “low”, the interval 3-8 as “medium” and the interval 7-10 as “high”. The definition of “low” or any other term solely depends on the user judgement. Such a judgement is formulated by a possibility distribution function, often taking values between 0 and 1, and is referred to as “membership function”. In FUZZLE, the shapes of the membership functions are piece-wise linear with 4 break points (coordinates) that include triangles and trapezoidal of any form. The maximum value of a membership function is equal to one.

2.2.1 Neutron multiplication factor

The membership function used for K is shown in Fig. 2. The range of this input variable was divided in three fuzzy sets: subcritical (SBC), critical (CRIT) and supercritical (SPC). Of course that a more detailed subdivision can be made, but for the purpose of this feasibility study this definition was considered acceptable. The bounds of the universe are 0.99 and 1.01.

- ❑ The breakpoints of the subcritical region are: 0.99, 0.99, 0.9985, 0.9995
- ❑ The breakpoints of the critical region are: 0.9985, 0.9995, 1.0005, 1.0015. It means that the membership function “CRIT” must yield the maximum value 1, at the location in the universe between 0.9995 and 1.0005 which represents “CRIT” the best. In other words, the reactor will be critical at 1.0 ± 0.0005
- ❑ The breakpoints of the supercritical region are: 1.0005, 1.0015, 1.01, 1.01

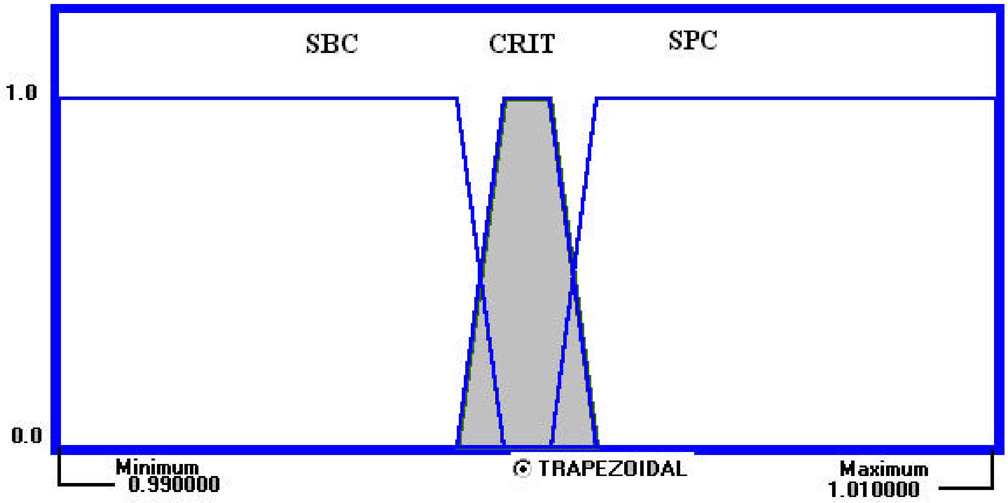

Fig. 2 Membership function of K

2.2.2 Maximum relative nodal power

The membership function used for MRNP is shown in Fig. 3. The range of this input variable was divided in three fuzzy sets: low power (LP), normal power (NP) and high power (HP). The bounds of the universe are 1.5 and 3.0. The maximum value assigned for the "normal" power is 2.25 (1.5 x 1.5), which is a conservative value that must assure that the main thermal limits: the maximum lineal heat generation rate (MLHGR), the ratio of the average planar lineal heat generation rate (RAPLHGR) and the minimum critical power ratio (MCPR) must be under their limit design values.

- The breakpoints of the low power fuzzy set is: 1.5, 1.5, 1.85, 2.1
- The breakpoints of the normal power fuzzy set: 1.85, 2.1, 2.25, 2.5
- The breakpoints of the high power fuzzy set: 2.25, 2.5, 3.0, 3.0

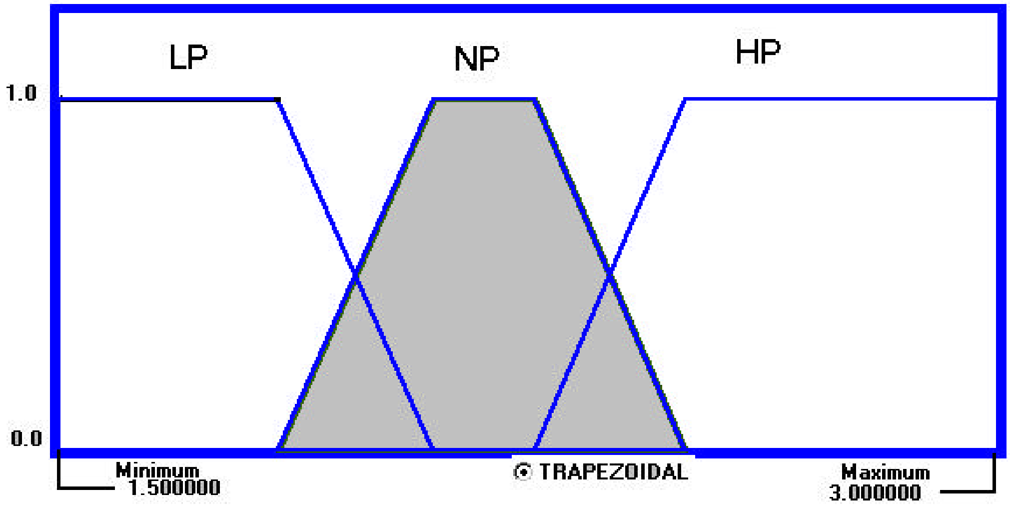

Fig. 3 Membership function of MRNP

2.2.3 Control rod relative movement

Two membership function were used for the relative movement of the control rods. One is used to control the MRNP, which are in most of the cases the so called shallow control rods (SCR) (in the case that the axial power profile is top peaked, the SCR can move along the core length). The other membership function is to control the core reactivity which are the deep control rods (DCR). The whole axial length was divided in two zones. The shallow rods are allowed to move from 24 notches of withdrawn to 48, nevertheless it is preferable that they move from 32 to 48. The deep rods can move from 2 to 24 notches of withdrawn, however they must preferably move from 4 to 16 notches. The fully inserted control rod (zero notches of withdrawn) is forbidden. Three fuzzy sets were used for these membership functions: negative (NEG), zero (ZERO) and positive (POS). The bounds of the universe are 0 and 24. A negative value of the action variable means that the rod or group of rods must be inserted, then a negative reactivity is added, on the opposite, a positive value means that the rods must be extracted, adding a positive reactivity to the core. Figure 4 shows the membership function for the "shallow" control rods, where the breakpoints are:

- For the negative fuzzy set: 0, 0, 8, 10
- For the zero fuzzy set: 8, 12, 16
- For the positive fuzzy set: 14, 16, 24, 24

Figure 5 shows the membership function for the "deep" control rods, where the breakpoints are:

- For the negative fuzzy set: 0, 2, 10, 12
- For the zero fuzzy set: 8, 12, 16
- For the positive fuzzy set: 12, 14, 22, 24

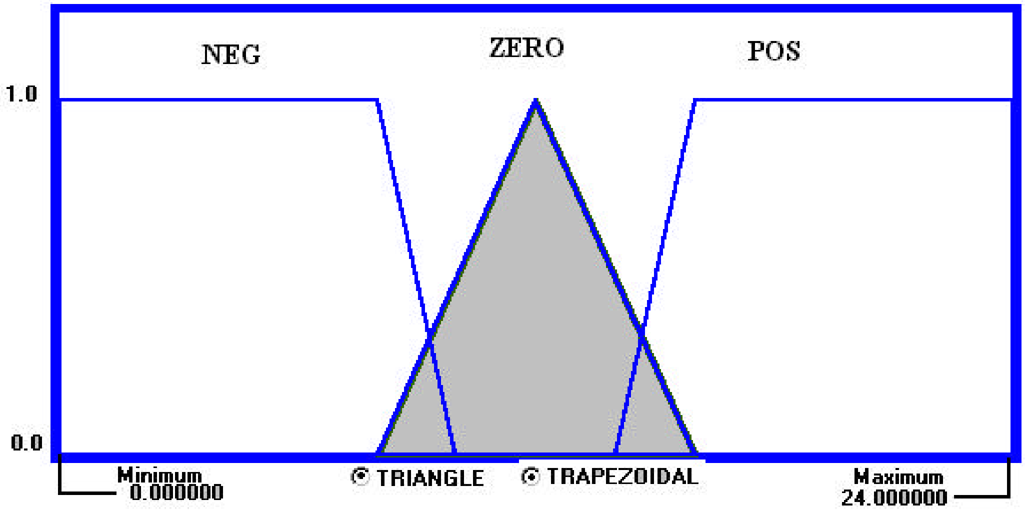

Fig. 4 Membership function of SCR

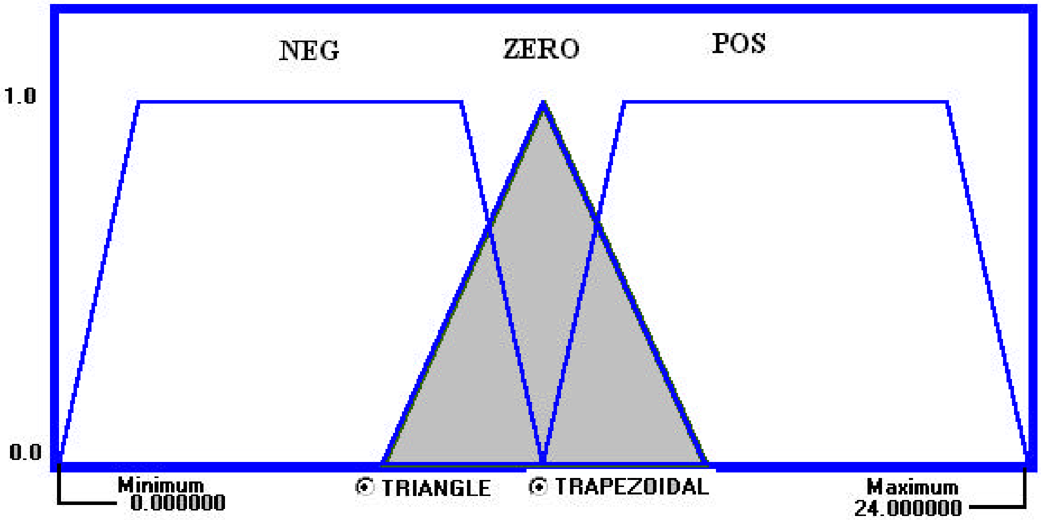

Fig. 5 Membership function of DCR

It must be pointed out that the real zero movement of the control rod is located at the value 12 of the membership function. This is done because FUZZLE does not allow negative values in the range of the membership functions.

2.3 Fuzzy Rules

In a fuzzy logic controller, the dynamic behavior of the fuzzy system is characterized by a set of linguistic description rules. A fuzzy control action consists of IF-THEN statements. The IF portion is the antecedent and the THEN part is the consequent. In this study, control rules are chosen as follows:

IF X is Ai OR/AND Y is Bi THEN Z is Ci

Where X and Y are process variables, Ai, Bi and Ci are fuzzy sets and Z is the control action of the rule.

Examples of rules used in this study are:

IF K_is_SBC .THEN. DCR_is_POS
IF K_is_SPC .THEN. DCR_is_NEG
IF MRNP_is_HP .THEN. SCR_is_NEG
....

Rules can be written in the fuzzy associative memory (FAM) form, for the deep control rods we have:

K

		SBC	CRIT	SPC
MRNP	LP	POS	ZERO	NEG
	NP	POS	ZERO	NEG
	HP	POS	ZERO	NEG

DCR

2.4 Inferencing

The evaluation of membership functions (sometimes call cuts or clipping) for a given numerical value is done in this step. The reactor variables are computed with the CM-PRESTO simulator and the degree of membership of each value is determined; these computed values can be a member of more than one fuzzy set. The rules are combined in order to obtain a control action and the degree of fulfillment (DOF) of each and every rule is obtained. The DOF of the premises (conditionals) is the level in which the consequent membership function are clipped. In a simple fuzzy rule such as:

IF X is A THEN Y is B

the evaluation of the antecedent fuzzy variables (X is A) directly produces a DOF value for this rule. The DOF value is used to evaluate (clip) the consequent fuzzy variable (Y is B). The Mamdani implication process was used to evaluate the membership functions in this study (Modico, 1997).

2.5 Defuzzzification

In this step a crisp value for the action variable is obtained from the process described in the previous step (clipping). In this study the center of gravity approach was used, which is one of the most common techniques. The center of gravity of the final shape is obtained by cutting the membership function of the consequent fuzzy variable (action variable) with the results of the rule composition.

3. CONTROL ROD PATTERN DESIGN HEURISTICS

In addition to the fuzzy rules used in the fuzzy logic control system, heuristic rules must be implemented in the system in order to take advantage of the design and operational experience in BWR control rod programming and direct the system to a realistic tool. In particular the CCC strategy was used in this study with critical search to a target eigenvalue for a fixed water flow. General knowledge rules are:

- The eigenvalue must be in the range of ± 0.0005 dK of the target eigenvalue.
- MLHGR, RAPLHGR and MCPR design limits must be met.
- Try to use the minimum quantity of control rods in the core.
- A bottom peaked axial power shape is desirable during some earlier portion of the cycle.

- To shift the power peak toward the bottom of the core, try to keep the deep rods as deep as possible and the shallow rods as shallow as possible.
- At beginning of cycle (BOC), the position of the first deep rods is determined by the location of the fuel having the highest MRNP with all rods out.
- Use the pattern of the previous burn-up step as the initial pattern for the current step.
- Try to move as minimum as possible the rods from one step to another.
- No shallow rods is desirable. Reduce as much as possible their utilization.
- The position of the shallow rods is determined by the location of the fuel having the highest axial power peak in the bottom part of the core (nodes 1 to 8), that produces a violation of the MLHGR or the RAPLHGR.
- Then MCPR violation is removed with deep rods.
- No intermediate rods is desirable. Reduce as much as possible their utilization.
- Intermediate rods can be used to remove thermal limits violation, mainly in the half part of the cycle.
- Reduce as much as possible the deep-shallow rod exchange. Two of these exchanges (equidistant) may be enough for a 12 to 18 months cycle.
- The exchange is the most effective when the deep control rods can be completely withdrawn.
- At the end of cycle (EOC) all the control rods must be withdrawn.

Specific rules of the system used in this study are:

- The initial position of the deep rods is 10 notches of withdrawn.
- The initial position of the shallow rods is 40 notches of withdrawn.
- Shallow rods are allowed to move from 24 notches of withdrawn to 48, nevertheless it is “preferable” that they move from 32 to 48.
- Deep rods can move from 2 to 24 notches of withdrawn, however they must “preferably” move from 4 to 16 notches.
- The fully inserted control rods (zero notches of withdrawn) are forbidden.
- The range of influence (ROI) concept, introduced by Karve and Turinsky (1999), which takes into account an active control rod and its surrounding 16 fuel assemblies, is used to determine the control rod group that will be used to control the MRNP variable.
- A group and subgroup classification type of the control rods (Karve, 1999) is done as follows:

```
--  --  --  --
22  --  12  --  --
--  --  --  --  --  --
11  --  21  --  12  --
--  --  --  --  --  --
23  --  11  --  22  --
```

This quarter core representation has eight core symmetry, the active CCC control rods are those of the sequence A2. The first digit in the number “xx” means the group number, the second digit is the subgroup number. For example the control rods 21 belongs to the group 2 and subgroup 1. The following rules apply:

- The control rods of the same group and subgroup move together (symmetry).

- The control rods of the same group move to the same axial region if it is needed. For example if rods 11 are inserted at any deep position then the rods 12, if they have to be inserted, they must be in a deep position too. This rule can not be followed at the latest part of the cycle, near to the all rods out condition.
- For a group of control rods, the priority of the movement of the subgroups is 1, 2, etc. For example for the group 2, the movement of the rods 21 are preferred to 22, and 22 to 23.

4. APPLICATION TO LAGUNA VERDE NUCLEAR POWER PLANT

The methodology was tested with the cycle 5 of Laguna Verde Nuclear Power Plant – Unit 1 (LVNPP-U1), which is a BWR with 444 fuel assemblies and 109 control rods. The full power cycle length of this cycle reported in the cycle management report is 9151 MWd/MT (Alonso, 1995). The CM-PRESTO model has been validated for LVNPP applications (François, 2001). The reactivity and thermal limit values used in the test are: K target = 0.997 at the en EOC and 1.0 at other burn-up steps. The MRNP must be < 2.25, the MLHGR must be < 463 W/cm, the RAPLHGR must be < 0.98 and the MCPR must be > 1.35.

4.1 Control Rod Pattern at BOC

Figure 6 shows the steps followed to obtain the control rod pattern at BOC.

--	--	--	--		
--	--	--	--	--	
--	--	--	--	--	--
10	--	--	--	--	--
--	--	--	--	--	--
--	--	10	--	--	--

K= 1.00685
P= 2.1068
MLHGR= 436.9
RAPLHGR= 0.92
MCPR= 1.73

--	--	--	--		
--	--	--	--	--	
--	--	--	--	--	--
4	--	--	--	--	--
--	--	--	--	--	--
--	--	4	--	--	--

K= 1.00462
P= 2.2121
MLHGR= 458.9
RAPLHGR= 0.967
MCPR= 1.73

--	--	--	--		
--	--	--	--	--	
--	--	--	--	--	--
4	--	10	--	--	--
--	--	--	--	--	--
--	--	4	--	--	--

K= 0.99668
P= 2.0879
MLHGR= 438.4
RAPLHGR= 0.914
MCPR= 1.79

--	--	--	--		
--	--	--	--	--	
--	--	--	--	--	--
4	--	14	--	--	--
--	--	--	--	--	--
--	--	4	--	--	--

K= 0.9985
P= 2.0067
MLHGR= 421.2
RAPLHGR= 0.878
MCPR= 1.79

--	--	--	--		
--	--	--	--	--	
--	--	--	--	--	--
4	--	16	--	--	--
--	--	--	--	--	--
--	--	4	--	--	--

K= 0.99923
P= 1.9744
MLHGR= 414.4
RAPLHGR= 0.864
MCPR= 1.78

--	--	--	--		
--	--	--	--	--	
--	--	--	--	--	--
6	--	16	--	--	--
--	--	--	--	--	--
--	--	6	--	--	--

K= 1.0001
P= 1.9365
MLHGR= 406.4
RAPLHGR= 0.847
MCPR= 1.77

Fig. 6 Steps to obtain the control rod pattern at BOC

At BOC the core was controlled only with shallow control rods, these rods were moved into their “preferred” bounds (4 – 16 notches). The thermal limits and the reactivity target were met.

4.2 Cycle 5 Control Rod Pattern

The control rod programming for LVNPP cycle 5 obtained in this study is presented in Fig. 7. The obtained cycle length is 9230 MWd/MT, which is comparable with the cycle length (9151 MWd/MT) of the design document and very close to the cycle length obtained with a Haling calculation (9266 MWd/MT).

0
MWd/T

--	--	--	--		
--	--	--	--	--	
--	--	--	--	--	--
6	--	16	--	--	--
--	--	--	--	--	--
--	--	6	--	--	--

K= 1.0001
P= 1.9365
MLHGR= 406.4
RAPLHGR= 0.847
MCPR= 1.77

1000
MWd/T

--	--	--	--		
--	--	--	--	--	
--	--	--	--	--	--
8	--	14	--	--	--
--	--	--	--	--	--
--	--	8	--	--	--

K= 0.9997
P= 1.7392
MLHGR= 370.8
RAPLHGR= 0.775
MCPR= 1.74

2000
MWd/T

--	--	--	--		
--	--	--	--	--	
--	--	--	--	--	--
4	--	16	--	--	--
--	--	--	--	--	--
--	--	4	--	--	--

K= 1.00019
P= 1.7702
MLHGR= 380
RAPLHGR= 0.81
MCPR= 1.73

3000
MWd/T

--	--	--	--		
4	--	--	--	--	
--	--	--	--	--	--
--	--	10	--	--	--
--	--	--	--	--	--
4	--	--	--	4	--

K= 1.0004
P= 2.0038
MLHGR= 421.7
RAPLHGR= 0.903
MCPR= 1.52

4000
MWd/T

--	--	--	--		
2	--	--	--	--	
--	--	--	--	--	--
--	--	2	--	--	--
--	--	--	--	--	--
2	--	--	--	2	--

K= 1.00011
P= 2.2143
MLHGR= 455.4
RAPLHGR= 0.976
MCPR= 1.49

5000
MWd/T

--	--	--	--		
2	--	16	--	--	
--	--	--	--	--	--
10	--	--	--	16	--
--	--	--	--	--	--
2	--	10	--	2	--

K= 1.00002
P= 2.2333
MLHGR= 452.5
RAPLHGR= 0.97
MCPR= 1.44

6000
MWd/T

--	--	--	--		
2	--	16	--	--	
--	--	--	--	--	--
10	--	--	--	16	--
--	--	--	--	--	--
2	--	10	--	2	--

K= 0.99972
P= 1.9641
MLHGR= 416.8
RAPLHGR= 0.894
MCPR= 1.44

7000
MWd/T

--	--	--	--		
12	--	16	--	--	
--	--	--	--	--	--
10	--	--	--	16	--
--	--	--	--	--	--
2	--	10	--	12	--

K= 1.0005
P= 2.0905
MLHGR= 418.8
RAPLHGR= 0.905
MCPR= 1.47

8000
MWd/T

--	--	--	--		
12	--	16	--	--	
--	--	--	--	--	--
44	--	--	--	16	--
--	--	--	--	--	--
2	--	44	--	12	--

K= 0.99955
P= 2.0819
MLHGR= 416.7
RAPLHGR= 0.879
MCPR= 1.42

9000
MWd/T

--	--	--	--		
--	--	--	--	--	
--	--	--	--	--	--
--	--	--	--	--	--
--	--	--	--	--	--
--	--	--	--	--	--

K= 0.9987
P= 2.0774
MLHGR= 416
RAPLHGR= 0.872
MCPR= 1.56

9230
MWd/T

--	--	--	--		
--	--	--	--	--	
--	--	--	--	--	--
--	--	--	--	--	--
--	--	--	--	--	--
--	--	--	--	--	--

K= 0.99656
P= 2.0322
MLHGR= 407
RAPLHGR= 0.857
MCPR= 1.56

Fig. 7 Control rod programming for LVNPP cycle 5.

The results show that the deep rods were used during almost all the cycle, which is a good practice; shallow rods appeared only at the end of the cycle. One deep-shallow rod exchange was done at 3000 MWd/MT. A second exchange was done at 5000 MWd/MT although it was not completely successful because of MRNP constraints. Deep rods had to be inserted at 2 notches in order to control the MRNP at 4000 MWd/MT, which is a not preferred situation according with the heuristic rules. The obtained control rod pattern is a good one, however it does not represent an "optimal" pattern. An optimization algorithm can be added to improve the results.

5. CONCLUSIONS

A methodology based on heuristic rules and the fuzzy logic technique was developed for the control rod pattern design of BWR's. The feasibility to use these techniques was studied for a typical BWR core under the control cell core strategy. The study and the application to LVNPP cycle 5 proved that the system can be a very useful tool to be incorporated to a reload pattern optimization system based on Genetic Algorithms. Improvements in the heuristic and fuzzy rules and in the membership functions must be done in order to optimize the proposed control rod pattern and to have an automated and efficient system. An objective function can be added to obtain the maximum energy in the cycle under the reactivity and thermal limits constraints, and an option for the criticality search with water flow must be added to take advantage of spectral shift in BWR's. One fuzzy variable can be added for each thermal limit: MLHGR, RAPLHGR and MCPR, instead of the MRNP in order to have a better tracking of their behavior. Finally more fuzzy sets can be added to the membership functions to improve the efficiency and accuracy of the fuzzy logic controller.

ACKNOWLEDGMENTS

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