Azcatl-CRP: An ant colony-based system for searching full power control rod patterns in BWRs

Juan José Ortiz a,*, Ignacio Requena b,1

a Dpto. Sistemas Nucleares, ININ, Carr. Mexico-Toluca Km. 36.5, Salazar, Edo. de Mexico, Mexico
b Dpto. Ciencias Computación e I.A. ETSII Informática, University of Granada, C. Daniel Saucedo Aranda s/n, 18071 Granada, Spain

Received 12 May 2005; received in revised form 15 August 2005; accepted 15 August 2005
Available online 7 October 2005

Abstract

We show a new system named AZCATL-CRP to design full power control rod patterns in BWRs. Azcatl-CRP uses an ant colony system and a reactor core simulator for this purpose. Transition and equilibrium cycles of Laguna Verde Nuclear Power Plant (LVNPP) reactor core in Mexico were used to test Azcatl-CRP. LVNPP has 109 control rods grouped in four sequences and currently uses control cell core (CCC) strategy in its fuel reload design. With CCC method only one sequence is employed for reactivity control at full power operation. Several operation scenarios are considered, including core water flow variation throughout the cycle, target different axial power distributions and Haling conditions. Azcatl-CRP designs control rod patterns (CRP) taking into account safety aspects such as \( k_{\text{eff}} \) core value and thermal limits. Axial power distributions are also adjusted to a predetermined power shape.

1. Introduction

The obtaining of energy in a nuclear reactor is a complex process in which two aspects must be considered in order to optimize it. First, optimization in the placing of the fuel bundles in the reactor core (in order to get the maximum energy within the safety margins). Second, optimization of control rod patterns (CRPs) in order to safety aspects will be fulfilled. In previous works, we have considered the first one (see Ortiz and Requena, 2004a,b). Now, we consider the second aspect, also for boiling water reactors (BWR).

Control rod patterns at full power in BWRs is a very complex problem. Safe operation and efficient fuel bundles burning are characteristics of a good operation strategy. The purpose of the CRP optimization is to assign axial positions of control rod in order to adjust the effective multiplication factor (\( k_{\text{eff}} \)) to a target \( k_{\text{eff}} \), to maximize the minimum critical power ratio (MCPR) and the maximum linear heat generation rate (MLHGR) margins and to minimize the differences between a target axial power distribution (TAPD) and the current axial power distribution (APD). Haling (1964) says that if the axial power distribution is kept constant in all the cycle, then power peaks are minimized. In order to maximize cycle length, low water core flow is used in first burnup steps and then increased towards end of the cycle (EOC). This operation strategy is named spectral shift.

Motoda et al. (1973) have developed a system to find optimal CRPs which works with two iterative loops. In the first one, a TAPD is used to find optimal CRPs; in the second one, at EOC, if there are control rods inserted in the core, then the TAPD is modified and the first loop is repeated. OPROD system (Kawai et al., 1976) works similarly to Motoda’s system, and uses a modified Haling APD (this is his TAPD). The TAPD is kept constant in all burnup steps in OPROD and Motoda’s system.

Expert systems have been designed to find optimal CRPs. Fukuzaky et al. (1988) developed a system with...
500 rules. Lin and Lin (1991) developed an expert system with 71 rules. Finally, Ortiz and Castro (1995) developed an expert system named DPB with seven rules, which was applied to cycle two of Laguna Verde Nuclear Power Plant (LVNPP) in Mexico.

Taner et al. (1992) developed a two step system. In the first one, a set of optimal exposure-dependent Haling APDs is proposed and in the second step, optimal CRPs are found. In this system, the optimal exposure-dependent Haling APD is designed using the spectral shift concept. Spectral shift is an operation strategy which can be used to extend the length of the cycle that can be accomplished in two ways: by controlling the core axial burnup distribution with appropriate CRPs and by controlling the core flow. At the beginning of the cycle (BOC), when core flow is reduced or the power is peaked toward the bottom of the core (with CRPs), the water starts boiling at lower axial elevation, and therefore the core average void density is increased. So, $^{238}$U fission and plutonium production and fission are increased (neutron energy spectrum hardening). Towards EOC, the core flow is increased and the APD becomes top-peaked (spectrum softening) providing extra reactivity to extend the cycle length. Finally, Montes et al. (2004) show GACRP to optimize CRPs in BWRs using genetic algorithms.

In this paper, we show a new system to optimize CRPs, named Azcatl-CRP, where Azcatl stands for Ant in nahuatl, an ancient mexican language. Azcatl-CRP uses the ant colony system (ACS) (Dorigo and Gambardella, 1997) to find CRPs which minimize the differences between TAPDs and APDs in each burnup step. Azcatl-CRP is tested with LVNPP transition and equilibrium cycles. Cycle length is divided in burnup steps for which a CRP is proposed in each one in order to satisfy restrictions.

LVNPP fuel reloads follow control cell core (CCC) (Specker et al., 1978) load strategy, which permits to simplify CRPs designs. The LVNPP reactors have 109 control rods divided in four sequences. So, it is possible to reduce the number of control rods to operate the reactor. The problem complexity can be reduced by considering an eighth core symmetry and only 5 control rods in CRP design.

The requirements for good CRPs are:

1. MCPR and MLHGR margins have to be optimized.
2. $k_{\text{eff}}$ value must be adjusted to a target $k_{\text{eff}}$ value in all cycle.
3. APD in all burnup steps have to be adjusted to TAPD.

2. Ant colony systems for control rod pattern design

The ant colony system algorithm (ACS) (Dorigo and Gambardella, 1997) is inspired in the way that a real ant colony builds shortest paths between food sources and its nest. While walking, ants deposit an amount of pheromone; probabilistically, each ant prefers to follow a path rich in pheromone. Paths poor in pheromone are erased by evaporation, while paths rich in pheromone are kept.

An artificial ant builds a tour (or solution for a given problem) using pheromone trails deposited by other ants. A characteristic that do not have real ants is environment information; for example, a real ant does not know if a direction is shorter than other to go to the food. In the artificial model, we give some environment information in order to have a more efficient method. A real ant moves in a continuous environment, while an artificial ant moves in discrete states.

Artificial ants work as follows. Each ant (there are $M$ ants in the colony) builds a solution by choosing a state transition according to the state transition rule (STR). Then, the local pheromone updating rule (LPUR) is applied to deposit an amount of pheromone in old state–new state trails. When all ants complete their solutions (or visit all states), the global pheromone updating rule (GPUR) is applied to deposit an amount of pheromone in states belonging to the best solution. The process is iterated until pheromone trails does not change in various successive iterations.

In our problem, each ant jumps from a control rod to another control rod; all ants follow the same itinerary: control rod 1, control rod 2, control rod 3, …, control rod $N$. For each control rod, an ant will choose an axial position according to STR and it will deposit pheromone in the axial position selected using LPUR.

Each control rod can be located in 25 axial positions labeled [0, 2, 4, 6, …, 44, 46, 48]. When axial position is 0, control rod is fully inserted in the core; while axial position 48 means control rod is withdrawn. Rules for ACS in the CRP problem are:

State transition rule (STR) for CRP is as follow. For ith control rod, the ith axial position can be chosen according to

$$u = \begin{cases} \frac{s}{\tau(i,s)} \cdot [A(i,s)]^\beta = \max \{\frac{\tau(i,r)}{[A(i,r)]^\beta} \} & \text{if } q \leq q_0, \\ \frac{s/p(i,s)}{\max \{p(i,r)\}} & \text{otherwise,} \end{cases}$$

$$p(i,u) = \frac{\tau(i,u) \cdot [A(i,u)]^\beta}{\sum_{u=1}^{N} \tau(i,u) \cdot [A(i,u)]^\beta},$$

where $\tau(i,u)$ is the pheromone accumulated in ith axial position for ith control rod, $A(i,u)$ is an heuristic information on the convenience of ith axial position for ith control rod; $\beta$ is a constant greater than zero; $N$ is the amount of valid axial positions, and the parameter $q_0$ determines the relative importance of exploitation versus exploration. If $q \leq q_0$ ($q$ is a random number with $0 < q < 1$), then the ant chooses the new state according to Eq. (1) (exploitation); otherwise, the ant chooses its new state according to Eq. (2) (exploration).

Local pheromone updating rule (LPUR) for CRP problem is

$$\tau(i,u)^{\text{new}} = (1 - \rho) \cdot \tau(i,u) + \rho \tau_0,$$
where \( \rho \) is the pheromone evaporation rate (0 < \( \rho \) < 1) and \( \tau_0 \) is the pheromone amount deposited by the ant.

Global pheromone updating rule (GPUR) for CRP problem is

\[
\tau(i, u)^{\text{new}} = (1 - \rho) \cdot \tau(i, u) + \rho / F,
\]

where \( F \) is the current cost of the best solution generated by all ants. Only axial positions (ith positions) belonging to the best CRP (ith control rods) receive an extra pheromone trail.

Ant colony system applied to CRP problem works as follow (for each burnup step):

1. Set \( \tau_0 \) and \( q_0 \) values and ants amount in the colony.
2. Each ant assigns axial positions for all control rods in the core using STR.
3. Axial positions assigned by the ant receive pheromone trail using LPUR.
4. Repeat steps 2 and 3 for all ants in the colony.
5. When all ants have generated their CRPs, and they are evaluated by a core simulator. Axial positions belonging to the best CRP receive an extra pheromone trail using GPUR.
6. Steps 2–5 are repeated until a strong pheromone trail is obtained.

A strong pheromone trail produces that ants follow it and any new trail is not explored. This means that the process must be stopped.

We have 25 possible axial positions and 5 control rods, therefore we define a [25, 5] pheromone matrix and a [25, 5] matrix of the convenience value for each axial position. According to STR, axial position with the greatest \( \tau A \) product will be chosen.

Dorigo recommends to use the following values for the involved parameters in the rules for the travel salesman problem: \( \beta = 2, \ q_0 = 0.9, \ \rho = 0.1, \ M = 10, \ \tau_0 = (n^*L_{mn})^{-1} \), where \( L_{mn} \) is the cost for a valid solution. We used those values for CRPs problem.

Function \( A(i, u) \) for convenience of ith control rod in ith axial position was proposed according to our experience in control rod pattern design. We propose the following equation:

\[
A(i, u) = \begin{cases} 
T(\text{LHGR}, u, i) \text{ if } (T(\text{LHGR}, u, i) \leq 1.0) \\
\text{and } T(\text{LHGR}, u, i) < S(\text{CPR}, u, i) \\
\text{and } V_p(u, i) < 0, \\
S(\text{CPR}, u, i) \text{ if } (S(\text{CPR}, u, i) \leq 1.0) \\
\text{and } T(\text{LHGR}, u, i) > S(\text{CPR}, u, i) \\
\text{and } V_p(u, i) < 0, \\
\exp|R(u, i)| - 1 \text{ if } (T(\text{LHGR}, u, i) > 1.0) \text{ and } (S(\text{CPR}, u, i) > 1.0) \\
\text{and } V_p(u, i) < 0, \\
1/V_p(u, i) \text{ if } V_p(u, i) > 0. 
\end{cases}
\]

Functions \( T(\text{LHGR}, u, i) \), \( S(\text{CPR}, u, i) \), \( R(u, i) \) and \( V_p(u, i) \) are the followings:

\[
T(\text{LHGR}, u, i) = \exp\left( \frac{\text{LHGR}_{\text{MAX}} - \text{LHGR}_{\text{LIM}}}{\text{LHGR}_{\text{LIM}}} \right),
\]

\[
S(\text{CPR}, u, i) = \exp\left( \frac{\text{CPR}_{\text{LIM}} - \text{CPR}_{\text{MIN}}}{\text{CPR}_{\text{LIM}}} \right),
\]

\[
R(u, i) = \text{ValBC}(u, 48) - \text{i[ValBC}(u, 48) - \text{ValBC}(u, 0)]/48,
\]

\[
V_p(u, i) = \begin{cases} 
\sqrt{i/18} \text{ if } 1.1 \text{ TAPD}(i) < \text{APD}(u, i) \text{ and } (i < 18), \\
\sqrt{i/48} \text{ if } 1.1 \text{ TAPD}(i) < \text{APD}(u, i) \text{ and } (i > 18), \\
\text{and } (k_{\text{eff}} > 1.004), \\
0 \text{ otherwise.}
\end{cases}
\]

\( \text{LHGR}_{\text{MAX}} \) is the greatest value of linear heat generation rate in the nearest four fuel channels around ith control rod in ith axial plane. \( \text{CPR}_{\text{MIN}} \) is the lowest value of critical power ratio, in the nearest four fuel channels around ith control rod in ith axial plane. These values are calculated by CM-PRESTO (Scandpower, 1995) simulator at the beginning of burnup step with all control rods out. \( \text{LHGR}_{\text{LIM}} \) is the maximum core LHGR value permitted and \( \text{CPR}_{\text{LIM}} \) is the minimum core CPR value permitted.

Eq. (9) calculates \( k_{\text{eff}} \) value when ith control rod is assigned in ith axial position. ValBC(u, 48) and ValBC(u, 0) are \( k_{\text{eff}} \) values when control rod is fully withdrawn and fully inserted, respectively. Those values are calculated at the beginning of burnup step by core simulator. TAPD(i) is the target power in ith axial position, and APD(\. \text{ and } APD(u, i) \text{ is the average power in ith axial position in ith control rod neighborhood.}

Function \( F \) in Eq. (4) is

\[
F(k_{\text{eff}}, \text{MCPR}, \text{MLHGR}, P) = C + G(k_{\text{eff}}) + H(\text{MCPR}) + I(\text{MLHGR}) + J(P),
\]

\[
G(k_{\text{eff}}) = \begin{cases} 
w_i(k_{\text{eff}} - k_{\text{targ}}) \text{ if } (k_{\text{eff}} - k_{\text{targ}}) > \delta k, \\
0 \text{ else,}
\end{cases}
\]

\[
H(\text{MCPR}) = \begin{cases} 
1.45w_2/\text{MCPR} \text{ if } \text{MCPR} < 1.45, \\
0 \text{ else,}
\end{cases}
\]

\[
I(\text{MLHGR}) = \begin{cases} 
w_3\text{MLHGR}/400 \text{ if } \text{MLHGR} > 400\text{W/cm,} \\
0 \text{ else,}
\end{cases}
\]

\[
J(P) = w_4 \sum_{i=1}^{25} (\text{APD}^i - \text{TAPD}^i)^2,
\]

where \( C \) is an arbitrary constant that is introduced in order the function to be positive; \( k_{\text{targ}} \) is objective value of \( k_{\text{eff}} \), taken as 1.0; \( \delta k \) is a tolerance for \( k_{\text{eff}} \) adjustment; \( \text{TAPD}^i \) is target APD in each of the 25 axial nodes in which reactor core is divided and \( \text{APD} \) is APD in ith axial position. \( w_i \) are constants empirically determined which have the purpose of giving or removing importance to associated variables.

\( w_1 \) values involved in Eqs. (11)-(14) are \( w_1 = 7000, \ w_2 = 2, \ w_3 = 5, \ w_4 = 1 \). \( C \) constant of Eq. (10) was determined in 10 and finally \( \delta k = 0.001 \).
3. Azcatl-CRP system

Flow diagram in Fig. 1 shows the actions followed by Azcatl-CRP to propose CRPs. At the beginning of each burnup step, core simulator CM-PRESTO is used to calculate control rod worths and thermal limits values and their location. Then, ACS rules are applied to create M CRPs and they are evaluated using core simulator. If the best CRP is not successful then ACS rules are applied until the pheromone trail does not change. If CRP is successful then a burnup step is made with an exposure length of 1000 MWD/T. The process is repeated until EOC is reached. The CRP pheromone trail found in previous burnup step can be used in next burn up step as an initial CRP.

In Fig. 1, when information flow comes from “Local Minimum?” question, the pheromone matrix is restarted.

4. Experiments

When a fuel reload pattern is repeated through several cycles, eventually all cycles will have the same core characteristics (thermal limits values, $k_{eff}$ value, core mean burnup, etc.). These cycles are named equilibrium cycles, while cycles with core characteristics non constant are denominated transition cycles. To test Azcatl-CRP system, we used transition and equilibrium cycles of LVNPP.

The reference value for transition cycle length is 9920 MWD/T and a Haling calculation for target $k_{eff}$ is 9610 MWD/T. In our first experiments water core flow was kept fixed at 100% through the cycle and we used three different TAPDs. In Montes et al. (2004) you can see a description of these TAPDs. The first one is calculated with a Haling calculation (HAPD). The second one is calculated with CM_PRESTO at BOC, all control rods out and no fuel depletion (BOC-APD). HAPD and BOC-APD were kept fixed throughout all burnup steps. Third APD is calculated with CM-PRESTO as follows. At first burnup step a BOC-APD is calculated and a CRP is proposed; for next burnup step, fuel depletion is made and a new APD is calculated similarly to BOC-APD. BOC-APD, CRP proposal and fuel depletion are repeated until EOC is reached (STEPS-APD).

Table 1 shows a comparison between cycle lengths (first column) and average (second column) and maximum (third column) power peaks obtained with CRPs using HAPD, BOC-APS and STEPS-APD as TAPDs and reference cases. Figs. 2–4 show APDs obtained with CRPs proposed by Azcatl-CRP system using HAPD, BOC-APD and STEPS-APD as TAPD, respectively.

We can see that the greatest cycle length obtained using Azcatl-CRP, is in BOC-APD and STEPS-APD cases, being this length 10,300 MWD/T. Cycle lengths obtained by Azcatl-CRP are greater than reference ones. In Figs. 2–4, we can see that APDs are very well adjusted to TAPDs.

The 9000–10,000 APD is the best adjusted to HAPD, while 0–1000 APD is the best adjusted to BOC-APD since they were specifically so designed. In HAPD and BOC-APD cases, APDs are constrained to adjust to a fixed APD. But, APD depends on axial burnup distribution, so, if axial burnup distribution depends on CRPs then it is not consistent to adjust APDs constants. Therefore, STEPS-APD case is a better way to design APDs.

Fig. 5 shows a pheromone convergence graph for a control rod (pheromone level of 25 axial positions) through 60 iterations. We can see that at the beginning of iteration process, position 42 receives high pheromone levels; then position 32 receives pheromone, while pheromone in position 42 evaporates. A similar graph can be obtained for all control rods in each burnup step.

These results demonstrate the ability of Azcatl-CRP to design CRPs, so an 18 months equilibrium cycle was used.
Fig. 2. Axial power distributions obtained with Haling APD.

Fig. 3. Axial power distributions obtained with BOC APD.

Fig. 4. Axial power distributions obtained with STEPS-APD.
Montes et al. (2001) to study the ability of Azcatl-CRP system to design CRPs varying core water flow. Its length is 11,846 MWD/T, which includes 10,896 MWD/T at full power operation, being the remaining cycle time for increase core flow and coastdown operation strategies. The neutron effective multiplication factor ($k_{\text{eff}}$) value at EOC is 0.9926. The burnup for a Haling calculation for this target $k_{\text{eff}}$ is 9880 MWD/T which means that it should be necessary to extend coastdown length to reach the cycle length. So, if burnup length at full power operation is maximized (with appropriate CRPs), then the coastdown length will be minimized.

In the next experiments, we worked with variable core water flow for Haling, BOC and STEPS APDs. We used four different core water flow schemes. In the first one, core water flow was fixed at 85% from 0 to 10,000 MWD/T; then it was increased to 100% until EOC was reached (Case 85%). In the second one, core water flow was fixed at 90% from 0 to 10,000 MWD/T and then increased to 100% until EOC was reached (Case 90%). In the third scheme, core water flow was fixed to 94% from 0 to 10,000 MWD/T and increased to 100% until reaching EOC (Case 94%). Finally, a scheme with core water flow at 100% through all cycle was used (Case 100%).

Table 2 shows a comparison between cycle length, average axial power peak and maximum axial power peak for different studied cases and for a reference one (Haling calculation). Spectral Shift has the characteristic that an APD peaked in the core bottom increases the cycle length. We can see that STEPS-APD cases have the greatest cycle lengths and that the shortest cycle lengths correspond with Haling APDs. Also, the greatest axial power peaks correspond to STEPS-APD, while the lowest axial power peak corresponds to HAPD.

Another way to increase cycle length is working with low core flow at first burnup steps, which is shown in Table 2. For different cases, cycle lengths are extended in average 451.25, 696.25 and 833.75 MWD/T, for Haling, BOC and STEPS APDs, respectively. In 85% core flow case, cycle length extension is 733.3 MWD/T, in average; while in 100% core flow case, the average is 595 MWD/T. This suggests that APDs design is more important than core flow variation.

5. Conclusions

It has been shown that the new ant colony system-based Azcatl-CRP system, is a good tool for designing CRPs for BWRs. Azcatl-CRP was tested using a transition cycle of LVNPP and demonstrated its capability to design safe and efficient CRPs. Three different TAPDs were proposed and Azcatl-CRP found CRPs that improve the cycle length compared to Haling calculation and reference CRPs. Afterward, Azcatl-CRP was tested using an equilibrium cycle for three APDs and four core water flow schemes. For this cycle the system was capable of designing good CRPs.
Azcatl-CRP improves cycle length from 18 to 33 days at full power in equilibrium cycle. Spectral shift operation has a strong presence in this cycle, while for a transition cycle with lower spectral shift, cycle extension is about 12 full power days with respect to the reference value.

Azcatl-CRP requires about 30 iterations for each burnup step to design CRPs, that is to say, 600 CRPs evaluations with CM-PRESTO. In average, about 8 h are necessary to design CRPs for an operation cycle.

GACRP system (Montes et al.) was tested with the same equilibrium cycle used in this paper. So, we can see that Azcatl-PBC gives us better results than GACRP.

Although we have concluded that TAPDs are more important to maximize cycle length, for future work we would like to add core water flow in function $A(i, u)$. Eq. (5) will change to take into account core water flow in order to maximize $k_{eff}$ at the end of each burnup step.

Acknowledgments

We are grateful to our fuel management group colleague, Raúl Perusquía del Cueto, for his important contributions to this paper and Guillermo Duque y Mojica for his comments. This research has been partially supported by Project TIC2002-04330-C02-02 of the DGICYT, MECD, Madrid, Spain, and a credit-grant from Mexico’s Instituto Nacional de Investigaciones Nucleares (ININ) and the Bank of Mexico.

References


