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IN-CORE FUEL MANAGEMENT METHOD FOR PWR REACTORS USING A FIRST ORDER PERTURBATION THEORY

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Abstract

The object of this study is to develop a computational program to automatically determine a low neutron leakage core loading pattern for a pressurized water reactor (PWR) in a process of in–core fuel management.

The proposed method makes use of the Bi–Dimensional, Two–Group First Order Perturbation Theory to find out which binary fuel element interchange should be made in order to obtain a low core neutron leakage. The fuel management is performed automatically by the modified CITATION computer code. Tests of the radial peaking factor during the fuel cycle are made by burnup calculation. No burnuble poison , and no soluble boron were considered.

The method was applied in first core of Angra–I, brazilian PWR, where the core was considered with 1/8 symmetry, having 3 enrichment zones. After 10 trials, a core configuration which gives the minimum neutron leakage was obtained. All these cases spent about 8 min. CPU time in an IBM–4381 machine.

1 – INTRODUCTION

In the last years several researchs have examined in–core fuel management problem with the purpose to increase the fuel cycle and reactor lifetime (today near 30 years), and consequently to reduce the cost of electrical energy from nuclear power plants /1,2,3/.

The reactor lifetime is basically defined by its pressure vessel lifetime Thus reducing the fast neutron fluence in the pressure vessel walls will increase the reactor lifetime The fast neutron fluence is proportional to the neutron leakage from the core, and thus in this work we propose an algoritm to reduce this leakage through a scheme of fuel management Any reduction in neutron leakage results in a reactivity increasing , thus allowing extend the cycle and reduces fuel cycle cost

The proposed method makes use of a bi–dimensinal, two–group energy, First Order Perturbation Theory (FOPT) /4/ to find out, in a fast way, which binary fuel element shuffling should be made in order to obtain a leakage reduction, based on the behavior of peaking factor (PF) as function of reactivity variation The analysis based on the behavior of peaking factor to reduce leakages is due to the fact that an increase in the reactivity implies in an increase in the PF (keeping as constraint its design limit) and as direct consequence there will be reduction in the core leakage The method uses HAMMER–TECHNION/5/ AND CITATION /6/ codes The CITATION code was modified to automatically perform the fuel managemenet through the use of FOPT and also to calculate the real and adjoint neutron fluxes required by FOPT The code also has a burnup capability that can be used to check power peak factor through the fuel cycle

2 – FIRST ORDER PERTURBATION THEORY

The first order perturbation theory (FOPT) is applied in the in–core fuel managemenet to predict the radial peak factor behavior due to binary shuffling of the fuel elements The FOPT merits are due to its capability to determine, in a fast way, the possible candidates for a shuffling, by calculating the reactivity change due to small perturbation in the core without solving the diffusion equation It is important to be sure that the perturbation induced by the shuffling is small in order to the method be valid

From the two group diffusion equation , one can write

$$\begin{bmatrix} -\nabla D_1\nabla + \Sigma_{a1} & 0 \\ -\Sigma_{s12} & -\nabla D_2\nabla + \Sigma_{a2} \end{bmatrix} \begin{bmatrix} \phi_1 \\ \phi_2 \end{bmatrix} = \frac{1}{k} \begin{bmatrix} \nu_1\Sigma_{f1} & \nu_2\Sigma_{f2} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \phi_1 \\ \phi_2 \end{bmatrix}$$

or

$$\mathbf{M}\,\phi = \frac{1}{k}\,\mathbf{F}\,\phi, \qquad (1)$$

where, D is diffusion coefficient, Σ a macroscopic cross section and k the multiplication factor

A perturbation on any of the macroscopic nuclear parameter, D, Σ_a, $\nu\Sigma_f$ corresponds a change on $\mathbf{M}$, and $\mathbf{F}$ matriz , so

$$\mathbf{M}' = \mathbf{M} \pm \delta\mathbf{M} \qquad \text{and} \qquad \mathbf{F}' = \mathbf{F} + \delta\mathbf{F}\ , \qquad (2)$$

and the equation (1) becomes

$$\mathbf{M}'\phi = \frac{1}{k}\,\mathbf{F}'\phi, \qquad (3)$$

where

$$\frac{1}{k'} = \frac{1}{k + \delta k} = \frac{1}{k\,(1 + \frac{\delta k}{k})}\ , \qquad (4)$$

Since the perturbation is assumed to be small, the first order approximation can be applied to obtain

$$(1 + \frac{\delta k}{k})^{-1} \cong 1 - \frac{\delta k}{k}\ , \qquad (5)$$

and the equation (4) becomes

$$\frac{1}{k'} \cong \frac{1}{k} - \frac{\delta k}{k^2} \qquad (6)$$

The corresponding first order reactivity change is given by

$$\delta\rho \cong \frac{\delta k}{k^2} \quad , \tag{7}$$

and from the equation (3)

$$\delta\rho \cong \frac{\frac{1}{k} \langle \phi^+, \delta F \phi \rangle - \langle \phi^+, \delta M \phi \rangle}{\langle \phi^+, F \phi \rangle} \quad , \tag{8}$$

where ϕ^+ is adjoint flux and ϕ the real flux.

3 – FUEL MANAGEMENT PROCEDURES

A reference core loading pattern is used to begin the calculation. Homogeneized fuel element cross section in two group were determined as a function of burnup utilizing HAMMER–TECHNION code. Real and adjoint neutron fluxes are calculated for the reference core loading using the two group, two–dimensional diffusion theory code (CITATION). The candidates for the fuel shuffling are chosen through the FOPT and the fuel element management is made by modified CITATION code, where the reactivity change and PF behavior are determined for all possible binary shufflers.

The process is then repeated until a configuration that gives a minimum core neutron leakage is found. The burnup calculation verify if the constraints are satified during the fuel cycle. This scheme was repeated several cycles until a equilibrium cycle is obtained. Figure 1 shows a simplified flowchart of the procedure.
The fuel management procedures allows some options and restrictions, such as:

- the center fuel element is treated separatly ;
- a binary shuffling can not induce large perturbation. The code has an option , a variable DKMAX, to restrict the limits of the perturbation ;

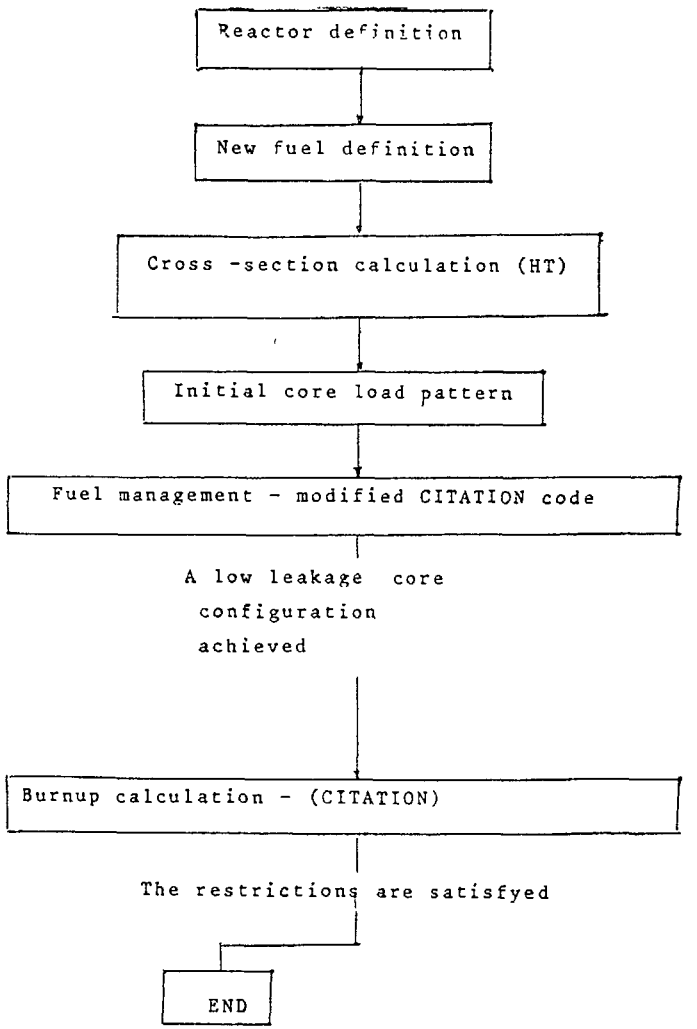
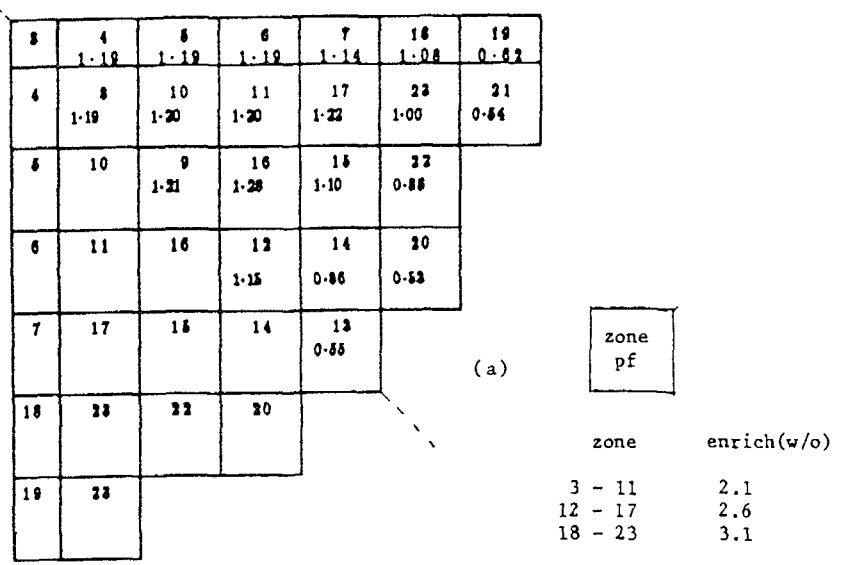


Figure 1 - Flowchart of the fuel management



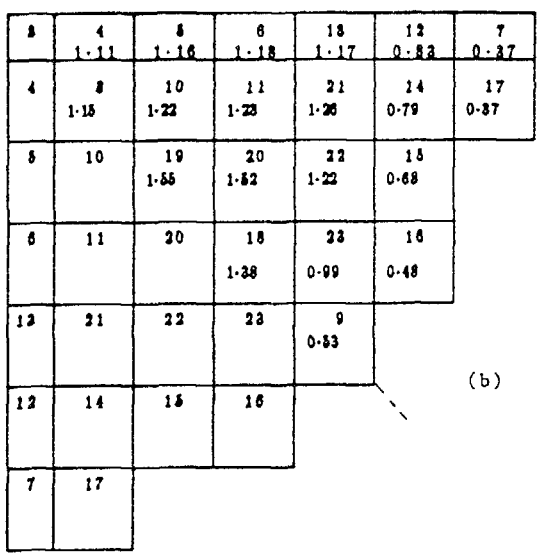


Figure 2- Beginning of the first cycle

(a) loading pattern before fuel management

(b) loading pattern after fuel management (low leakage core)

– PF is restricted by design constraint since the minimization of neutron leakage (or the maximization of reactivity) and power peaking are opposite functions;

– the restriction on fuel elements changes are given by reactivity perturbation constraint.

4 – TESTS AND RESULTS

The first core of Angra–I, brazilian PWR was selected as test case in this study. Figure 2(a) shows a 1/4 core for the beginning of cycle. The calculation was done by considering 1/8 symmetry and 3 enrichment zones (2.1, 2.6 and 3.1 w/o). No burnuble poison, soluble boron or control rods were considered. The calculations were made for several fuel cycles, until the equilibrium cycle was obtained. At each fuel cycle, one–third of the more burned fuel element are discharged and new fuel elements (3.3 w/o fixed enrichement) are loaded. The design constraint for PF was fixed in 1.6.

Table 1- Core Neutron Leakage and Reactivity Change - First Core (BOC)

Conf	FP	Leakage (neut./s)	I	J	$\Delta\rho_{ij}$	$\Delta\rho$
0	1,282	$8{,}114\ 10^{16}$	16	20	$2{,}44\ 10^{-3}$	$2{,}30\ 10^{-3}$
1	1,415	$8{,}092\ 10^{16}$	9	13	$1{,}73\ 10^{-3}$	$1{,}62\ 10^{-3}$
2	1,440	$8{,}076\ 10^{16}$	13	19	$1{,}45\ 10^{-3}$	$1{,}38\ 10^{-3}$
3	1,565	$8{,}062\ 10^{16}$	12	18	$5{,}93\ 10^{-4}$	$5{,}44\ 10^{-4}$
4	1,589	$8{,}057\ 10^{16}$	18	7	$3{,}34\ 10^{-4}$	$3{,}06\ 10^{-4}$
5	1,532	$8{,}057\ 10^{16}$	17	21	$2{,}15\ 10^{-3}$	$2{,}04\ 10^{-3}$
6	1,504	$8{,}037\ 10^{16}$	15	22	$1{,}24\ 10^{-3}$	$1{,}31\ 10^{-3}$
7	1,501	$8{,}023\ 10^{16}$	7	13	$1{,}14\ 10^{-3}$	$1{,}19\ 10^{-3}$
8	1,514	$8{,}016\ 10^{16}$	23	14	$2{,}01\ 10^{-4}$	$1{,}31\ 10^{-4}$
9	1,531	$8{,}016\ 10^{16}$	18	13	$2{,}01\ 10^{-4}$	$1{,}31\ 10^{-4}$
10	1,553	$8{,}014\ 10^{16}$				

I,J : identification of shuffled fuel element

$\Delta\rho_{ij}$: reactivity change estimated - FOPT

$\Delta\rho$: reactivity change calculated- CITATION

Table 1 shows the results obtained for the first cycle. After 10 trials a core configuration which gives the minimum neutrons leakage was obtained, as shown in figure 2(b). In this case the power peak factor was increased from 1.282 to 1.553 and the neutron leakage reduced from 8.114 E+16 to 8.014E+16 n/s.

5– CONCLUSION

The modified CITATION code including FOPT can minimize the core neutron leakage with power peaking constraint for a PWR at BOC.

The results presented in section 4 demonstrate the efficience of the method to determine a low leakage core loading pattern.Also the method shows to be fast to select the possible candidate for shuffling. The CPU time was around 8 minutes for 10 trials in an IBM–4381 machine. To improve the computer time it is planned to use a nodal code, instead of CITATION. Also, to increase the potential of the system ,would be interesting to include an economic calculation module.

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