OPTIMIZATION STUDY FOR LOADING OF THORIUM BUNDLES IN 700 MWe PHWR INITIAL CORE

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ABSTRACT
PHWRs need continuous on-power refueling. The refueling is done in such a way that power shape is flattened and full power can be drawn. If the initial core of 700 MWe PHWR is loaded with all fresh Natural Uranium fuel, only about 88 % Full Power can be drawn from reactor during initial days of operation due to large peaking in channel powers. It is possible to load few Thorium bundles at selected locations to operate the reactor at full power. Finding the best possible locations is, however, a fairly complex and massive combinatorial optimization problem. The locations of Thorium bundle in each fuel channel are selected such that they are driven out of the core at the first refueling of that channel. An evolutionary optimization technique based on Estimation of Distribution Algorithm (EDA) is used to determine the optimum Thorium loading pattern.

Keywords: Thorium, Optimization, Estimation of distribution Algorithm

INTRODUCTION
An advanced version of Indian Pressurized Heavy Water Reactor (PHWR), 700 MWe PHWR, is to be commissioned in near future. PHWRs are based on Natural Uranium (NU) fuel and Heavy water as moderator and coolant. These reactors need continuous on-power refueling. The refueling is done in such a way that power shape is flattened and full power can be drawn. If the initial core of 700 MWe PHWR is loaded with all fresh Natural Uranium fuel, only about 88 % Full Power can be drawn from reactor during initial days of operation due to large peaking in channel powers. It is possible to load few Thorium bundles at selected locations to operate the reactor at full power. Finding the best possible locations is, however, a fairly complex and massive combinatorial optimization problem. The locations of Thorium bundle in each fuel channel are selected such that they are driven out of the core at the first refueling of that channel. An evolutionary optimization technique based on Estimation of Distribution Algorithm (EDA) is used to determine the optimum Thorium loading pattern. The overall aim of the optimization is to maximize K-effective and get 100% full power without violating operational and safety parameters such as maximum permissible bundle power, channel power, channel power peaking factor and permitted reactivity worth in shut-down system. While choosing the locations of Thorium bundles in the core, the following considerations are taken into account:

1) $K_{\text{eff}}$ is maximum so that the pre-fueling period of the reactor becomes longer leading to better fuel economy.
2) Reactor power is close to 100%FP.
3) Channel power peaking factor (CPPF) is less than limiting value.
4) Maximum bundle power is less than the bundle power limit.
5) Maximum channel power is less than the limiting value.
6) Sufficient reactivity worth in the shutdown systems.

ALGORITHM USED
There are total 392 fuel channels (from A to W in Y-direction and 1 to 22 in X-direction), having 12 bundles in each, in 700 MWe reactor core. The $392 \times 12 = 4704$ fixed fuel bundle locations will generate a huge search space for loading of few tens of thorium bundles. This requires parallel
computing facility. In order to generate the solution on single processor, effort has been made to reduce the search space. One octant i.e. 53 fuel channels are considered for loading of Thorium bundles at 9th position of the fuel bundle as shown in Figure 1.

Estimation of Distribution Algorithm (EDA) is used as optimization algorithm to solve the fresh core loading pattern generation problem. EDA [1&2] is an optimization algorithm, which is based on estimation of distribution and sampling to generate new candidate solutions as shown in Figure 2. The objective function to be maximized has been defined using penalty method [2] to take care of constraints as follows:

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\text{Fitness} = K_{\text{eff}} - F_1 - F_2 - F_3 - F_4 - F_5
\]

Where \( K_{\text{eff}} \) is effective multiplication factor and \( F_1, F_2, F_3, F_4, F_5 \) are penalties due to reactor power, channel power, bundle power, channel power peaking factor and worth of shutdown system as described in reference [2]. The objective function defined as ‘Fitness’ is maximized in subsequent generations (or iterations).

A 2-group neutron diffusion code in 3-D geometry to evaluate the Fitness of given configuration has been developed and used [2]. It is based on finite difference approximation. The homogenized two energy group cross-sections for NU and Thorium bundles were obtained by neutron transport code CLUB [3].

**RESULT**

The performance of an EDA highly depends on how well it estimates and samples the probability distribution. Univariate Marginal Distribution Algorithm (UMDA) assumes no interaction among variables. The probability distribution is estimated using UMDA [1]. The Probability Distribution Function (PDF) was generated using 30% dominated individuals of the population size. The population size is taken as 90. Alpha is chosen 0.05.

The fitness function variation with generation number is shown in Figure 3. The evolution of the objective function ‘Fitness’ corresponding to the average of all 90 candidates ‘Fit(avg)’, best among all 90 candidates ‘Fit(max)’ and average of selected 30 candidates ‘Fit(select)’ is shown there. The generated fresh core loading pattern was having 24 Thorium bundles. 4 Thorium bundles have been loaded in each of the fuel channel J05, L05, J18 and L18 at 9th position to
increase the worth of shutdown system. Thus the final loading pattern consists of 28 Thorium bundles as shown in Figure 4.

CONCLUSIONS

Thorium is a pure absorber and choosing suitable locations for Thorium in a loading pattern by manual intuition is not possible. Estimation of Distribution Algorithm is successfully used to generate suitable fresh core loading pattern for 700 MWe PHWR. There are 28 Thorium fuel bundles in the loading pattern. The initial core excess reactivity at 0 FPD is such that the refueling requirement will start after about 115 FPD. The maximum bundle power and channel power peaking factor remains within specified limit allowing 100%FP reactor operation. All the core parameters satisfy operational and safety criterion for 100%FP reactor operation.

REFERENCES