DEVELOPMENT OF A GRAPHICAL INTERFACE COMPUTER CODE FOR REACTOR FUEL RELOADING OPTIMIZATION

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ABSTRACT: This report represents the results of an institute project performed in 2007. The aim of this project is to develop a graphical interface computer code that allows refueling engineers to design fuel reloading patterns for research reactor using simulated graphical model of reactor core. Besides, this code can perform refueling optimization calculations based on genetic algorithms as well as simulated annealing. The computer code was verified based on a sample problem, which relies on operational and experimental data of Dalat research reactor. This code can play a significant role in in-core fuel management practice at nuclear research reactor centers and in training.

1. Introduction

After a time of operation, a reactor must be refueled. Because of the unsymmetrical distribution of fuel burnup over the reactor core, a decision on how many fuel bundles and what fuel bundles to be refueled must be based on the solution of the problem of in-core fuel management optimization.

For a very long time after the first nuclear power reactor was launched into critical and put into operation, only two traditional methods of fuel reloading having been adopted were those of 'out-in' pattern and checkerboard pattern [1]. These initial reloading methods are assured to give the flat radial power distribution over the reactor core. The existence of only a few of methods for fuel reloading for a long time reflects somewhat the complexity and difficulty of this typical problem in reactor area. Since 1980 researches into this problem have increasingly developed, resulting in much optimistic progress in the process of this matter. An apparent consequence resulting from the past researches is a change in the fuel reloading strategy from following the out-in scheme to adopting the low-leakage patterns. The out-in scheme, by which fresh fuels are loaded into outermost core positions, flattens the radial power density distribution while the low-leakage patterns allow the arrangement of fresh fuels into non-periphery positions to extend the cycle length.

For nearly four decades research into the problem of in-core fuel management optimization has increasingly developed, resulting in a perspective progress [2-14]. Recent research works have been usually based on stochastic methods like GA [5-12], simulated annealing method [2-5,13,14], etc. as well as combinations of these methods with heuristic rules [5]. Turinsky [15] overviewed the development of nuclear fuel management optimization capabilities for PWRs and BWRs ranging from the employment of experience-based rules to the usage of mathematical approaches.

Besides, development of graphical interface reactor calculation programs combined with heuristic rules also allows the more convenient manual preparation of fuel LPs at many centers. This approach is of great interest to fuel managers because of its intuitive, concrete and easy to understand features. Furthermore, stochastic methods often reach near global optimal solutions but not exact optimum, so graphical interface reactor calculation programs can be used to move towards better solutions from the solutions of stochastic methods.

2. Orientation of works

Principal characteristics of a reactor such as k_{eff}, neutron flux distribution can be determined by solving the following multigroup neutron diffusion theory equations:

$$-D_{r,g}\Delta\Phi_{r,g} + (\Sigma_{a,r,g} + \sum_{g'}\Sigma_{s,r,g\to g'})\Phi_{r,g} = \sum_{g'}(\Sigma_{s,r,g'\to g} + \frac{\chi_g(\nu\Sigma)_{f,r,g'}}{k_{eff}})\Phi_{r,g'}$$

Power peaking factor PPF is determined based on the neutron flux distribution. Each global reactor calculation provides neutron parameters needed for optimal calculations. Graphical representation of reactor on computer screen together with its neutron parameters can help refueling engineers perform simulated fuel exchanges in computer model to find out optimal fuel reloading patterns according to their experience. A graphical interface computer code has been developed in this project to make the above idea become practical. It means that this program can help a refueling engineer to design manually refueling patterns using simulated model of the reactor.

The code includes programme modules written independently in languages Visual Fortran and Visual Basic, running on PCs. This version of the code can perform global reactor calculation, automatically searching fuel reloading patterns that maximize the effective multiplication factor and minimize the power peaking factor within rigorous constrains and design manually optimal refueling configurations using graphical representation of reactor in two-dimensional geometry. The reactor calculation involves the finite difference diffusion theory representation of neutron transport theory [16], treating three space dimensions with arbitrary groups. The radial geometric mesh options in reactor calculation include slab, cylinder, hexagonal and triangular. The flowchart of the code, named REFUELOP, is shown in fig. 1. The code includes three principal modules CITALIB, OPTIVN and SIMULATE and an additional. CITALIB is modified based on the CITATION reactor calculation code [16], module OPTIVN written in Visual Fortran is an optimization programme, and SIMULATE written in Visual Basic and module RECONFIG written in Visual Fortran is graphical interface modules.

3. Results and discussion

Calculations were performed to verify the computer program. The program was used to design optimal refueling patterns of the Dalat reactor for its second cycle. At that time, all the 89 existing fuel bundles in the core were unchanged; only 11 beryllium rods, which have the same shape and size as the fuel bundles, at the core periphery were replaced by 11 fresh fuel bundles. fig. 2 presents the arrangement of 100 fuel bundles in the core after 11 beryllium rods were replaced by fresh fuel bundles. This core configuration defines the base LP, in which the fuel bundles are assigned by the same number as the core positions. The number on the upper line in a cell indicates core position. Fuel burn-up BU = $\Delta m^5/m^5_0$ (where Δm^5 is spent amount of fuel U^{235} and m^5_0 initial amount in a fuel bundle) in units of percentage is indicated by the number on the lower line.

From the base configuration, refueling calculations were carried out by using the simulated models of the reactor core on computer screen. Exchanges of fuel bundles on the simulated models were done by clicking mouse on the **Fuel shuffle** menu. After a fuel exchange, a global reactor calculation was performed by clicking on the **Preinput** and **Estimate** menus. Calculated results are presented on computer screen. Adapted to the result of genetic algorithm optimization [11], calculations with 11 fuel exchanges compared to the base configuration were performed using the simulated model of the reactor and the results are presented in table1.

After 11 fuel exchanges, the optimal fuel pattern has k_{eff} = 1.061468 and PPF = 1.361876. This is the optimal fuel pattern found out by genetic algorithm optimization with the 11 limited numbers of fuel shuffles [11].

Because genetic algorithm is a stochastic search, it likely find out near global optimum but not exact optimum solution in almost cases. So, in this case we proposed 3 binary exchanges more in order to move towards better solution. This proposal is based on the inherent advance of the symmetry of fuel burnup distribution over the reactor core. Results are presented on the last three rows of table 1. It can be seen that the parameters of the final optimal pattern are better (with k_{eff} = 1.065086 and PPF = 1.331527). A significant decrease in PPF through the last three exchanges is due to the final fuel configuration (fig. 3) has a more symmetrical distribution of fuel burnup than the optimal genetic algorithm solution.

4. Conclusion

This is a computer code for refueling optimization based on modern methods taking advance on the development of computer science. This code runs on PCs with XP Windows. This code can apply to research reactors and helps refueling engineers to establish refueling patterns, analyze reactor core configurations directly using graphical representative of the reactor on computer screen.

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Table 1: K_{eff} and PPF in refueling process

No.	Fuel exchange	K_{eff}	PPF
	0	1.060453	1.374156
1	1 ↔ 50	1.060828	1.374205
2	2 ↔ 33	1.061212	1.372689
3	3 ↔ 58	1.061664	1.375163
4	4 ↔ 68	1.062037	1.374655
5	5 ↔ 34	1.062558	1.375359
6	12 ↔ 51	1.062948	1.377114
7	67 ↔ 89	1.063486	1.364327
8	44 ↔ 96	1.063994	1.363218
9	32 ↔ 97	1.064245	1.363708
10	28 ↔ 99	1.064249	1.363613
11	57 ↔ 100	1.064768	1.361876
Sum		$\Delta\rho$ (%) = 3.82	ΔPPF (%) = 0.01228
12	35 ↔ 99	1.064788	1.363209
13	43 ↔ 97	1.064974	1.331632
14	20 ↔ 66	1.065086	1.331527
		$\Delta\rho$ (%) = 0.028	ΔPPF (%) = 0.030349

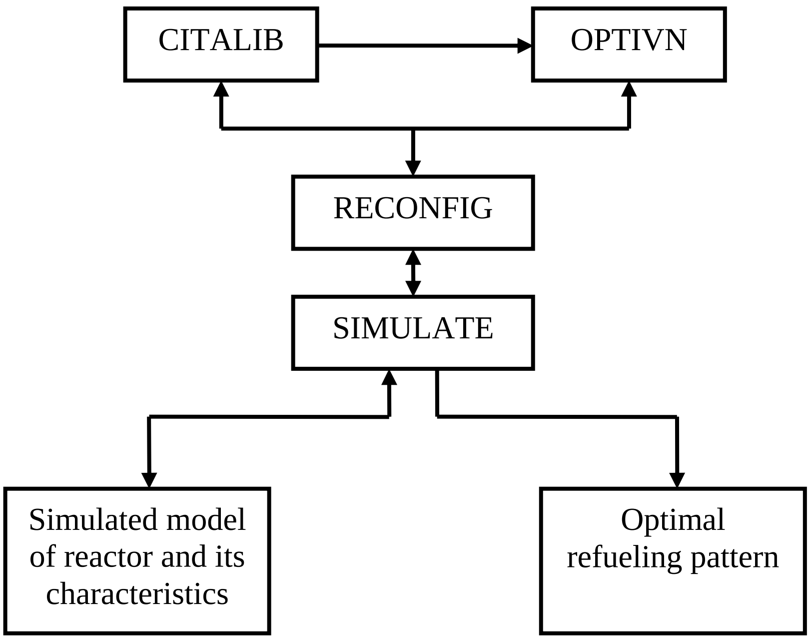


Fig. 1: Flowchart of the computer code REFUELOP

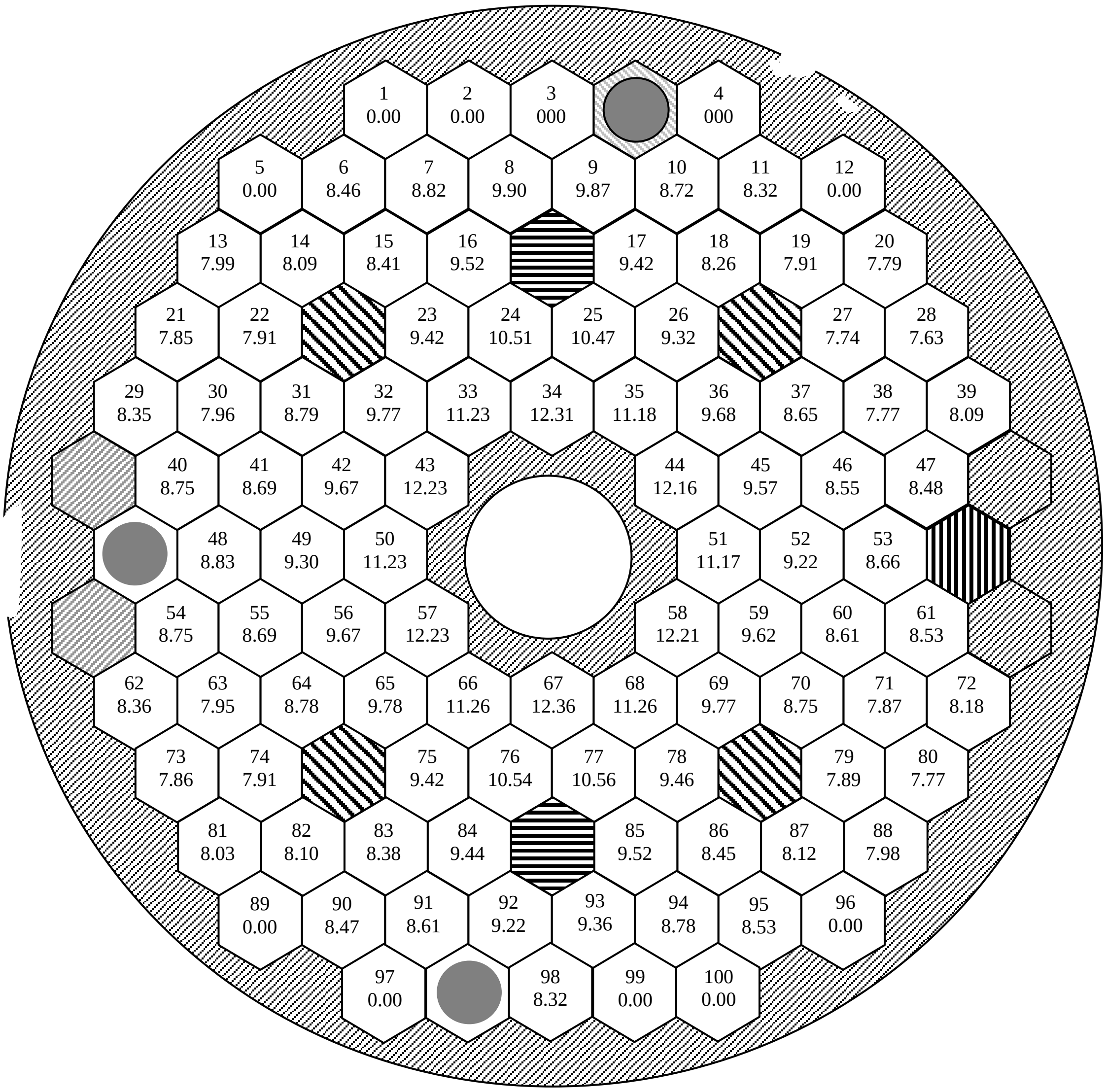
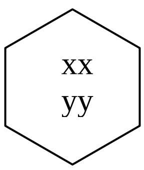


Fig. 2: Arrangement of fuel bundles in the sample problem.



xx: Bundle index
yy: Fuel burnup in dimension %

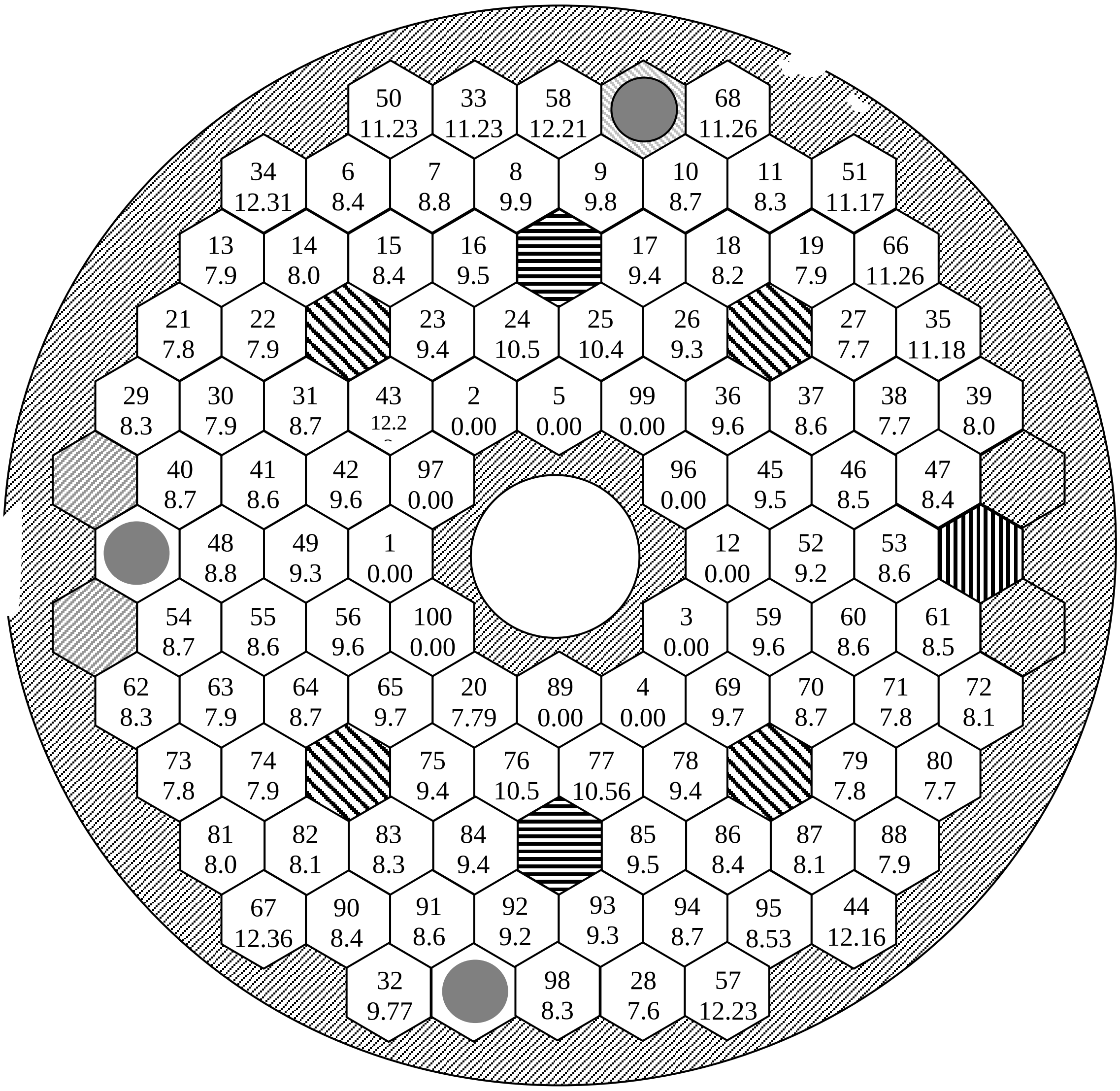


Fig. 3: Optimal refueling patterns with k_{eff} = 1.065 and PPF = 1.332.