STUDY ON IN-CORE FUEL MANAGEMENT AND OPTIMIZATION FOR URANIUM ZIRCONIUM HYDRIDE RESEARCH REACTOR

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ABSTRACT

In this paper the in-core fuel management and optimization of refueling loading pattern for the uranium zirconium hydride research reactor is studied and a set of practicable valuable code packages in engineering is developed. The scattering mechanism of H in ZrH is studied by the general scattering law. Considering the acoustic (DEBYE spectrum) and optic (GAUSS spectrum) model of hydride zirconium, its frequency spectrum distributing function is given, the scattering law and the scattering kernel in the thermal region of H in ZrH are also obtained. Then in accordance with the structure and the form of the 69-group library of WIMS the microscopic cross-sections of H in ZrH and Er are prepared. A few-group neutron macroscopic cross section for all types of cells are generated using WIMS-D/4. The global core analysis is performed using SIXTUS and CITATION. The excess reactivity, neutron flux, power distribution and power peaking factors are studied. The code package HEX-ICFM is encoded for the in-core fuel management. Finally, the orthogonal design model and the program HEX-ORTH is developed for the optimization of refueling loading pattern for the uranium hydride zirconium reactor. In order to reduce the fuel cost, the loading patterns of four cycles are calculated with the objective function $Max(K_{eff}^{BOC})$. The calculated results demonstrate that HEX-ORTH can give out automatically the optimum refueling plan and higher objective values.

1. INTRODUCTION

The uranium zirconium hydride research reactor is developed in China since 1980. The first Uranium Zirconium Hydride research reactor was completed and went critical in July 1990. It attained to full power in January 1991 and pulsing operation in March 1991[1]. The 2MW Uranium Zirconium Hydride research reactor with hexagonal geometry core configuration is being designed at present.

There are two important points should be considered in the uranium zirconium hydride research reactor physics calculation. The mechanism of thermal neutron scattering of H in ZrH is different from H in water [2]. The proper scattering cross-section should be used for the calculation in UZrH fuel. Another case is the core configuration is hexagonal. The core is calculated using hexagonal nodal or differential diffusion code.

To complete the design of China Uranium Zirconium Hydride research reactor, the scattering mechanism of H in ZrH is studied by the general scattering law. Considering the acoustic (DEBYE spectrum) and optic (GAUSS spectrum) model of hydride zirconium, its frequency spectrum distributing function is given, the scattering law and the scattering kernel in the thermal region of H in ZrH are also obtained. Then in accordance with the structure and the form of the 69-group library of WIMS the microscopic cross-sections of H in ZrH and Er are prepared. A few-group neutron macroscopic cross section for all types of cells are generated using WIMS-D/4. The global core analysis is performed using SIXTUS and CITATION. The excess reactivity, neutron flux, power distribution, power peaking factors are studied. The code package HEX-ICFM is encoded for the in-core fuel management. Finally, the orthogonal design model and the program HEX-ORTH is developed for the optimization of refueling loading pattern for the hexagonal research reactor. In order to reduce the fuel cost, the loading patterns for four cycles are calculated with the objective function $Max(K_{eff}^{BOC})$. The calculated results demonstrate that HEX-ORTH can give out automatically the optimum refueling plan and higher objective values.

In this paper the in-core fuel management and optimization of refueling loading pattern for the uranium zirconium hydride research reactor is studied and a set of code packages are developed.

2. STUDY ON THE SCATTERING LAW OF H IN ZRH

2.1 SCATTERING LAW FOR ZIRCONIUM HYDRIDE

The nuclear analytical model of scattering law and scattering kernel calculation for uranium zirconium hydride reactor is studied [3,4]. The differential inelastic scattering cross section is given by:

$$\frac{d^2\sigma_{in}(E_0 \to E,\mu,T)}{d\Omega dE} = \frac{\sigma_b}{4\pi T}\left(\frac{E}{E_0}\right)^{\frac{1}{2}} \exp\left(-\frac{\beta}{2}\right) S(\alpha,\beta,T) \qquad (1)$$

where σ_b is the bound cross section of H atom, α、β are dimensionless variables, $S(\alpha,\beta,T)$ is scattering law, is equal to $S(\alpha,\beta)T$, E_0, E is initial and final neutron energy, μ is scattering angle, T is temperature, in eV and *in* represents inelastic scattering. The scattering law $S(\alpha,\beta)$ is solved as follows:

$$S(\alpha,\beta)=\frac{1}{2\pi}\int_{-\infty}^{\infty} e^{i\omega t} X(\alpha,t)dt \tag{2}$$

where $X(\alpha,t)$ is intermediate scattering function.

$$X(\alpha,t) = exp[\alpha WG(t)] \tag{3}$$

where $$G(t) = \gamma(t) - \gamma(0) \tag{4}$$

$$\gamma(t)=T\int_{-\infty}^{\infty}\frac{f(|\omega|)e^{\frac{\omega}{2T}}}{2\omega\sinh(\frac{\omega}{2T})}e^{i\omega t}d\omega \tag{5}$$

$$\gamma(0)=T\int_{-\infty}^{\infty}\frac{f(|\omega|)e^{\frac{\omega}{2T}}}{2\omega\sinh(\frac{\omega}{2T})}d\omega \tag{6}$$

where T is temperature, in eV, ω is frequency, in eV.

We found it is very important to select the correct frequency $f(\omega)$ in the calculation of scattering law from the above formulas. The scattering kernel of ZrH has been studied by GA in 1960s. The theoretical partial differential cross sections curve for inelastic neutron scattering of hydride zirconium is derived by means of the SUMMIT code[3]. The frequency distribution of hydride zirconium was used only acoustic model in earlier research works. Considering the acoustic (DEBYE spectrum) and optic (GAUSS spectrum) model of hydride zirconium, its frequency distributing function $f(\omega)$ is studied in this work.

$$f(\omega)=W_1\times f_1(\omega)+W_2\times f_2(\omega) \tag{7}$$

where $f_1(\omega)$ is DEBYE spectrum, $f_2(\omega)$ is GAUSS spectrum.

With the combination of DEBYE and GAUSS spectrum, the frequency of H in ZrH is obtained. The weight fractions of DEBYE and GAUSS spectrum are compared. The weight of DEBYE spectrum is determined from 1/91 to 1/360. The weight of GAUSS spectrum can be selected from 90/91 to 359/360. The combination of the acoustic and optic spectrum weights is satisfied for the calculation of scattering law.

2.2 SCATTERING CROSS SECTION CALCULATION

The scattering law in the thermal region of H in ZrH is obtained by GASKET[4]. The scattering cross section calculation code SMP for ZrH is encoded using the inelastic scattering cross section and elastic scattering section equations[5]. The double differential scattering cross sections are calculated by scattering law using this code. The double differential inelastic scattering cross section of H in ZrH vs neutron energy shows the calculation results agree very well with the reference [3]. The scattering kernel $\sigma_l(E_0 \rightarrow E)$ of hydrogen bound in zirconium hydride is provided by SMP code in the standard form of WIMS cross section library.

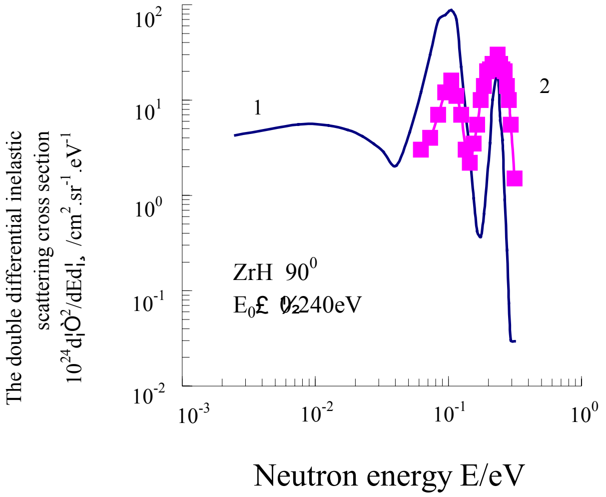

Fig.1 The double differential inelastic scattering cross section of H in ZrH vs neutron energy
1: this work 2: reference [3]

Then in accordance with the structure and the form of the 69-group library of WIMS the microscopic cross-sections of H in ZrH is processed from ENDFB-VI files using NJOY.

These two libraries are compared and evaluated. These two libraries are suitable for the cell calculation of uranium zirconium hydride reactor.

3. CODE PACKAGE OF FUEL MANAGEMENT

3.1 CORE CONFIGURATION

The full power of China uranium zirconium hydride reactor being designed is 2MW. It is a light water reactor cooled by natural convection. The core configuration is hexagonal. In total there are 211 locations in the core, which can be filled either by fuel elements or other components like control rods, graphite rods, neutron source, etc. Elements are arranged in 9 hexagonal rings: A, B, C, D, E, F, G, H and I, having 1, 6, 12, 18, 24, 30, 36, 42, and 42 locations respectively. The distance between locations is 43mm. There is a big water channel in the center of the core consisting of 13 cells. Six control rods are used in the core: regulating (D10), compensating (B1, B2), safety (A1, A2), and transient (M). Their locations are indicated in Fig.2. Two stainless steel rods are used as absorbers to reduce the higher excess reactivity. The control rods are fueled-follower type. Similar to the fueled-follower control rods, the transient rod consists of the absorber part and of the so-called air follower. When the fueled-follower control rod is fully withdrawn, the fueled part is in the active part of the core, while the upper absorber leaves the core completely. The same is true for the air follower. 101 fuel elements are used in cycle 1 core configuration. The horizontal cross section for the first cycle is presented in Fig.2. Composition of material used in the uranium zirconium hydride reactor core showed in table I.

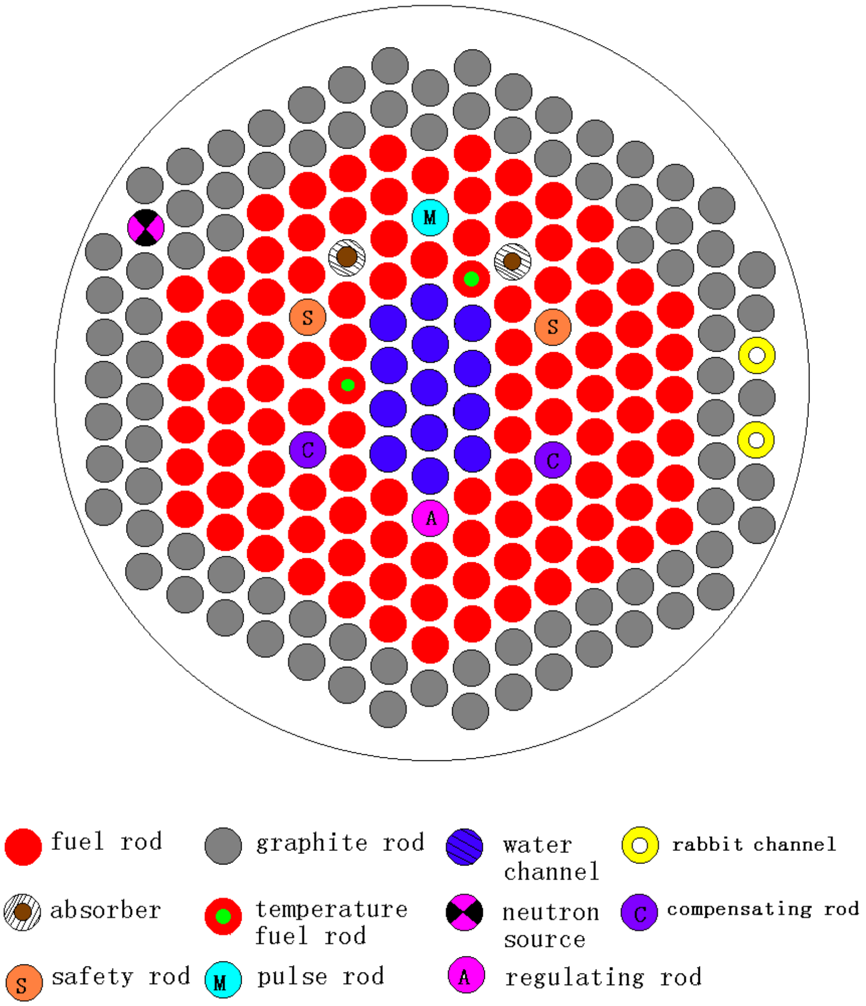

Fig.2 The x-y midplane of the core configuration for cycle 1

Table I. Composition of core material

Material	Density (g/cm^3)	Element	Weight Fraction
Fuel and fueled-follower (19.75% enriched)	6.179	^{235}U ^{238}U ^{nat}Zr ^{1}H	0.0234609 0.0938442 0.8671729 0.0155218
Zirconium rod	6.44	^{nat}Zr	1.00000
Graphite rod	1.65	^{12}C	1.00000
Absorber(B^{4}C)	1.815	^{10}B ^{11}B ^{12}C	0.13690 0.64588 0.21722
Stainless steel cladding	7.9	^{nat}Cr ^{55}Mn ^{nat}Fe ^{nat}Ni	0.19023 0.02002 0.69585 0.09390

3.2 CODE PACKAGE FOR CORE CALCULATION

The code package of uranium zirconium hydride reactor physics calculation is developed. The cell parameters are calculated using WIMS-D/4 code and the library including the data of H in ZrH[6]. The core diffusion calculation is performed using CITATION[7] and SIXTUS[8]. The calculating models of different kinds of cell are discussed. The results of the cell calculation are satisfied and it shows that the calculation models of cell in the core are correct[6].

Table II. The first cycle calculation results for China uranium zirconium hydride reactor

Burnup step/EFPD	K_{eff} without control rod	*Fxy* and its location	Critical K_{eff}
0	1.055652	1.466 C11,C3	0.9907183
2.0	1.032651	1.455 C10	1.001672
10.0	1.028288	1.462 C10	1.000635
20.0	1.025357	1.465 C9	0.9995521
30.0	1.023163	1.465 C9	0.9986155
120.0	1.009315	1.414 C9	1.006476

The in-core fuel management code HEX-ICFM is encoded on the basis of SIXTUS code[9]. To check the accuracy and reliability of the code package, the critical K_{eff} and the value of the control rod of China pulsed reactor are calculated. The first cycle calculation of China 2MW uranium zirconium hydride reactor is computed using HEX-ICFM. The excess reactivity, neutron flux, power distribution, power peaking factors and control rods worths are studied. Table II presents the effective multiplication factor K_{eff}, power peaking factor and its location in different burn-up steps for cycle 1. The power distribution for cycle 1 is shown in Fig.3. The hot spot is found physically at he fuel position C3 and C11 with a power peaking factor of

1.466 for the fresh core. The results are satisfied.

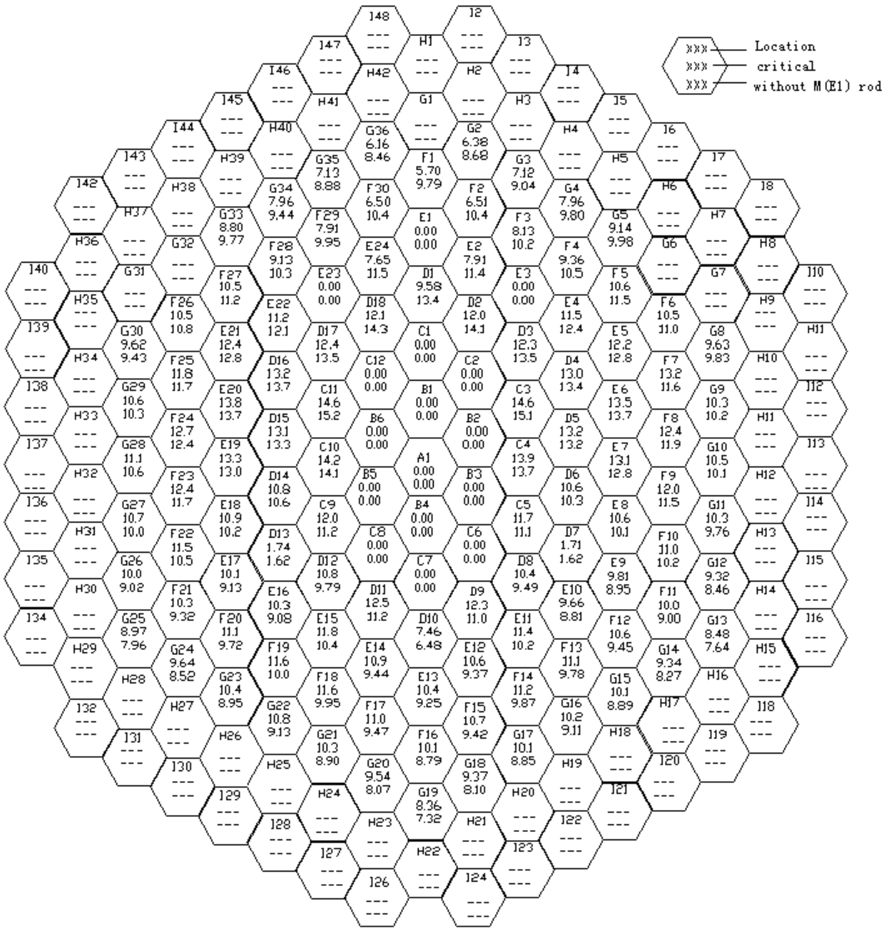

Fig.3 Radial power factor (×10^{-1}) distribution in critical state and with M(E1) rod out

4. OPTIMIZATION OF REFUELING LOADING PATTERN

4.1 DESCRIPTION OF OBJECTIVE FUNCTION

In core fuel management optimization concerns the arrangement of fuel rod within the reactor core over an operating cycle so that the great economic benefit or maximize neutron flux density in the reactor channels while satisfying operational constraints. Because the uranium zirconium hydride fuel rods are more expensive than ordinary uranium oxide fuel rods, $Max(K_{eff}^{BOC})$ is selected as a objective function to get maximum cycle length. An orthogonal design method is provided for the optimization of refueling loading pattern, which is popular in mathematical statistics [10,11].

The first 3 cycles of 2MW China uranium zirconium hydride reactor are calculated using HEX-ICFM. The cycle life is 120 EFPD for cycle 1 with 101 fresh fuel elements and 5 fueled-follower control rods. Two stainless absorbing rods are replaced by two fresh fuel elements in the end of cycle 1. 101 former burned fuel elements, 5 former burned fueled-follower control rods and 2 fresh fuel elements are used in cycle 2. It has a same big water channel as cycle 1, consisting of 13 cells. The burning life of cycle 2 is 130EFPD. Two fresh fuel rods are loaded into ring G in the end of cycle 2. The ring C is filled with burned fuel rods and the water channel consists of ring A and ring B. The core configuration of cycle 3 is showed in fig.4. The cycle length is 100EFPD for cycle 3. The detailed description is given in [9].

There are 110 fuel rods including 5 fueled-follower control rods are used in the first three cycles of 2MW China Uranium Zirconium Hydride research reactor. 30 fresh fuel rods can be used in the future operation. The goal of the optimization is to found an optimization model in order to get the maximization burning life with all of 105 burned fuel rods and 30 fresh fuel rods. The designed maximum burn-up of the fuel element for 2MW China Uranium Zirconium Hydride research reactor is 35000MWd/tU.

We consider the refueling loading pattern optimization problem is $Max(K_{eff}^{BOC})$, that is the maximization burning life.

The objective function $Max(K_{eff}^{BOC})$ subject to the following constraints:

(1) The full operation power of the reactor is 2MW. 105 fuel rods and 5 fueled-follower control rods are used. The locations of the control rods are not altered
(2) The maximum discharge burn-up of fuel rod is 35000.00MWd/tU
(3) The radial power peaking factor of fuel element $F_{XY} \leq 1.65$
(4) The refueling cycle life > 20 days
(5) The fueled-follower control rods are not replaced by fresh one until their burn-up reach the limited value 35000MWd/tU.

4.2 OPTIMIZATION MODEL

There are 105 fuel rods in China uranium zirconium hydride reactor core. The application of direct optimization method to the fuel replacement has not proven practical. A major reason is the extremely large number of variables that must be considered if over hundred fuel rods are accounted for throughout the lifetime. There are 105! types of core configuration according to all of the fuel rods arrangement for 2MW China Uranium Zirconium Hydride research reactor. The orthogonal optimum model is used in the refueling loading pattern calculation.

The fuel rods are divided into 18 groups according to their burn-up levels and the core geometry is divided into 18 uniform regions according to their locations in order to simplify the optimization problem. Each group of fuel rods has 6 fuel rods from group 1 to group 17. There are 3 fuel rods in the group 18 whose burn-up is the maximum in the all of 105 fuel elements. Each region of fuel rod locations has 6 locations from region 1 to region 17. Region 18 has 3 locations G8, G20, G32. The 3 fuel rods of group 18 are arranged in the region 18, outermost ring G8, G20, G32 because of their higher burn-up value. The fuel rods of group 18 and locations of region 18 are not considered in orthogonal optimization model. The optimization problem is becoming 17 factors (locations of fuel rods) and 17 levels (burn-up of fuel rods) orthogonal design problem. Here the 17 factors in the orthogonal problem represent the 17 regions of fuel rod locations. The 17 levels in the orthogonal problem represent the 17 groups of fuel rods. That means the 102 fuel rod locations in the core are divided into 17 uniform regions and 102 fuel rods are divided into 17 groups according to their burn-up. The 17 regions of core configuration are given in Fig.4. Region 1 locations (factor 1) are in the innermost ring C and region 17 (factor 17) is in the outermost ring G. The burn-up of group 1 fuel rods (level 1) is the lowest and the bur-up of group 17 is the highest.

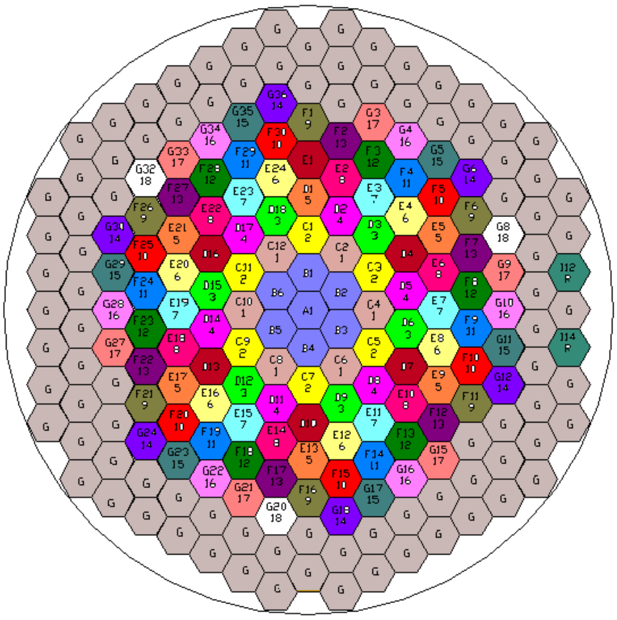

Fig.4 17 Divided regions of Core Configuration for Orthogonal Design Method
A1,B1-B6: water channel D4,D7,D13,D16: fueled-follower control rod E1: pulse rod
R: rabbit channel G: graphite rod 1-18 groups: fuel rods and their locations

The orthogonal table of the fuel rods in the core is constructed. The orthogonal method make the optimization problem very simple. The orthogonal refueling loading patterns of 17 factors and 17 levels is only provided 17×17=289 kinds of core configuration, which can represent all 105! kinds of core configurations. Each refueling loading pattern consists of 17 groups fuel rods in 17 regions arrangements respectively. It is easier to find the optimum refueling loading plan using the orthogonal model. The optimum core configuration is obtained by analyzing the following equation.

$$S_i = \frac{1}{n}\sum_{j=1}^{n}(K_i^j)^2 - \frac{1}{n^2}(\sum_{l=1}^{n^2} x_l)^2 \qquad (8)$$

where, *i* represents the factor (*i*th region of the core) , *j* represents level (*j*th group of fuel rods), x_l is the objective value of experiment (refueling loading pattern) *l*. *n* is the number of experiments, that is the number of the core refueling loading pattern. K_i^j is the sum of total *j* level's objective value at factor *i*. The value of *Si* represents the objective function value. We select the optimum loading pattern whose *Si* is the biggest and satisfied for the constraints conditions in the same time.

The orthogonal optimization for in-core fuel management is performed by the following steps:
(1) The factors and levels are designed at first. The fuel rod locations of the core are divided into different regions (factors). The fuel rods are divided into different groups (levels).
(2) The orthogonal experiment table is constructed according to the number of factor and level.
(3) The orthogonal experiment, i,e. the different kinds of the core orthogonal designed configuration is calculated using diffusion code. The objective function value of each core pattern is obtained.
(4) The objective value is analyzed using equation (8).
(5) The optimum loading pattern is obtained which satisfied the constraint conditions.

4.3 OPTIMUM RESULTS

A program named HEX-ORTH is encoded using the above orthogonal model. The loading patterns of China pulsed reactor from cycle 4 to cycle 8 are optimized using HEX-ORTH. The optimization loading patterns of the core are obtained as the objective function is $Max(K_{eff}^{BOC})$. The calculated results demonstrate that HEX-ORTH can give out the optimum refueling plan and higher objective values automatically.

The refueling loading pattern for core configuration of 4th cycle is given in table III . The lifetime of the core operation can last 20EFPD with optimum loading pattern. The four optimum results calculated using HEX-ORTH are summarized in Table IV. The cycle life is totally 205EFPD from cycle 4 to cycle 8. The results are satisfied for the design of in-core fuel management optimization. The maximization cycle lifetime is obtained. The orthogonal optimization model can be used for other objective function, for example $Max(\phi_{A1})$ to get the maximum neutron flux in center water channel.

Table III. Optimum loading pattern for cycle 4

State	Fuel rods location	Factor	Level

							(location)	(fuel rod)
Pre-optimization	C10	C8	C4	C6	C12	C2		1
Optimum results	G3	G9	G15	G21	G27	G33	17	
Pre-optimization	D15	D18	C3	D6	D8	D2		2
Optimum results	G6	G12	G18	G24	G30	G36	14	
Pre-optimization	D5	D17	C9	D3	E18	C5		3
Optimum results	G5	G11	G17	G23	G29	G35	15	
Pre-optimization	D11	E20	E8	E16	D9	E10		4
Optimum results	G4	G10	G16	G22	G28	G34	16	
Pre-optimization	C1	E17	E6	E15	E11	E9		5
Optimum results	F2	F7	F12	F17	F22	F27	13	
Pre-optimization	C7	F23	E22	E21	F24	E4		6
Optimum results	F5	F10	F15	F20	F25	F30	10	
Pre-optimization	E5	F22	F9	F19	E23	F8		7
Optimum results	F1	F6	F11	F16	F21	F26	9	
Pre-optimization	E3	F20	F13	F10	E14	F12		8
Optimum results	F3	F8	F13	F18	F23	F28	12	
Pre-optimization	F25	F18	E12	F14	G28	F21		9
Optimum results	F4	F9	F14	F19	F24	F29	11	
Pre-optimization	F7	G27	F27	F5	G23	F11		10
Optimum results	D1	E5	E9	E13	E17	E21	5	
Pre-optimization	F28	G29	G22	F17	G26	F26		11
Optimum results	E4	E8	E12	E16	E20	E24	6	
Pre-optimization	F4	E13	F15	G16	G15	G24		12
Optimum results	E2	E6	E10	E14	E18	E22	8	
Pre-optimization	E24	E2	G10	F6	G30	G21		13
Optimum results	E3	E7	E11	E15	E19	E23	7	
Pre-optimization	G11	G14	G17	F29	G12	G9		14
Optimum results	C2	C4	C6	C8	C10	C12	1	
Pre-optimization	F16	F3	G8	D1	G20	G18		15
Optimum results	C1	C3	C5	C7	C9	C11	2	
Pre-optimization	G34	G4	F30	G33	G5	F2		16
Optimum results	D3	D6	D9	D12	D15	D18	3	
Pre-optimization	G3	F1	G32	G6	E19	E7		17
Optimum results	D2	D5	D8	D11	D14	D17	4	
Pre-optimization	C11	D14	D12					18
Optimum results	G8	G20	G32				18	

Table IV. Optimization results using HEX-ORTH

Cycle	Refueling pattern	Cycle life	Average Discharge Burn-up

		/ EFPD	/ MWd/tU
Cycle 4	No fresh rods, locations of burned fuel rods exchanging (Table III)	20	34414.00
Cycle 5	Loading 6 fresh fuel rods	74	34228.20
Cycle 6	Loading 4 fresh fueled-follower control rods	59	34029.00
Cycle 7	Loading 12 fresh rods	32	34498.10
Cycle 8	Loading 12 fresh rods	20	34999.20

5. CONCLUSIONS

The in-core fuel management and optimization for China Uranium Zirconium Hydride research reactor is studied in the paper. The code package for in-core fuel management of hexagonal geometry core HEX-ICFM is developed. The reactor core physical calculation is performed using code package HEX-ICFM. The excess reactivity, neutron flux, power distribution and power peaking factors are calculated. An optimum model is studied using orthogonal design method. The optimization core loading pattern is calculated using code package HEX-ORTH. The results are satisfied and used in the design of China 2MW Uranium Zirconium Hydride research reactor. The research results can be used to in-core fuel management and optimization of refueling design not only for the uranium hydride zirconium reactor but also for the other kinds of research reactors.

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