Preliminary study of the tight lattice pressured heavy water reactor loaded with Pu/U and Th/U mixed fuels

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Abstract To improve nuclear fuel utilization efficiency and prolong fuel cycle burn-up, a tight pitch lattice pressured heavy water reactor was investigated as an alternative of next generation of power reactors. It is shown that the high conversion ratio and negative coolant void reactivity coefficient are challenges in the reactor core physics designs. Various techniques were proposed to solve these problems. In this work, a tight pitch lattice and mixed fuel assemblies pressured heavy water reactor concept was investigated. By utilizing numerical simulation technique, it is demonstrated that reactor core mixed with Pu/U and Th/U assemblies can achieve high conversion ratio (0.98), long burn-up (60 GWD/t) and negative void reactivity coefficients.

Keywords High conversion ratio, Tight lattice, Pressured heavy water reactor, Pu/U assembly, Th/U assembly, mixed core

CLC numbers TL32, TL423 A

1 INTRODUCTION

Nuclear power has been demonstrated to be a safe, economic and benign energy source for the reduction of the global warming, about 21% of electricity in the world is generated by nuclear energy presently. Commercial power reactors are mainly composed of light water reactors and heavy water reactors, so called thermal neutron reactors. Determined by the physics characteristics, thermal reactors have some disadvantages such as large reactivity burn-up swing, low burn-up and poor fuel utilization efficiency.

Uranium is a potential and abundant nuclear source. In thermal reactor, only small fraction of the fuel is utilized. LMFBR (Liquid Metal Fast Breeder Reactor) can use these sources effectively, but its commercial application seems still unable to be solved at present because of various difficulties.

To improve nuclear fuel utilization efficiency and extend fuel cycle burn up are the challenge to the nuclear power system of next generation. The high conversion reactor concept by reducing coolant fraction was studied by many scientists and institutes.[1,2] Tight lattice mixed fuel Pressured Heavy Water Reactor (PHWR), to be discussed in this paper, is an alternative for this objective. The tight lattice PHWR is based on presently matured technology and very similar to PWR (Pressured Water Reactor). Heavy water is used as coolant to replace light water and the neutron spectrum in the core is much harder

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Manuscript received date: 2001-04-16

than in LWR (Light Water Reactor). MOX (Mixed Oxide of Pu/U) and Th/U oxide fuel assemblies mixed core concept was investigated to reduce coolant void reactivity coefficient. To study and demonstrate its practicality, the numerical simulation method was used to calculate the cell and core physics characteristics. It is shown that the mixed fuel tight lattice PHWR has many advantages, such as small burn-up reactivity swing, high conversion ratio, long burn up, satisfactory safety, reduction of the production of minor actinides, long lived fission products and other radioactive waste.

2 REACTOR LATTICE ANALYSIS

In tight lattice PHWR physics calculations, computer codes SRAC95[3] and WIMS/TDB were used to calculate the cell neutron spectrum, burn-up, few-group constants and power distribution. SRAC95 is a reactor physics code system developed by JAERI. The system consists of several 107-group nuclear data libraries (based on JENDL-3.2, ENDF/B-6, etc.) and various numerical modulars, such as collision probability (PIJ) calculation modular, ultra-fine energy group resonance absorption (PEACO) calculation modular, Sn transport (ANISN, TWOTRAN) calculation modulars, diffusion calculation (CITATION) modular, and burn-up calculation modular. The code system is applicable to core analyses of various types of nuclear reactors.

The WIMS/TDB code system was developed on the basis of WIMS/D4.[4] 69-group nuclear data library was updated and extended based on ENDF/B-6 and CENDL-2. By checking with several lattice benchmarks, the calculation accuracy with the new library was improved. TDB is a three-dimensional, few-group, finite difference code for solving the neutron diffusion equation. With the help of burn-up-dependent few-group constants generated with WIMS, TDB can calculate the *Keff*, pin power distribution, fuel rod temperature distribution, and power density peaking factor. The code is very fast and suitable for the LWR calculation. Because of the computer environmental limitation, WIMS/TDB is used for reactor core calculation, whereas SRAC95 for verification of lattice computation in this research.

The numerical data for the tight lattice PHWR cell is given in Table 1, which refer to design data of commercial power reactors. The fuel composition is given in Table 2. To study plutonium loaded lattice, two types of fuel, MOX and transuranics (TRU), were considered. The composition of plutonium and minor actinides was taken from commercial PWR spent fuel with burn-up 32.5 GWD/t and ten years cooling.

Table 1 Tight lattice PHWR lattice data

Fuel rod diameter /cm	0.82
Cladding diameter /cm	0.95
Cladding material	Zr-4
Coolant	Heavy water
Lattice geometry	Square

The effective multiplication factor of the tight lattice PHWR varies with the lattice pitch. From Figs.1, 2 and 3, it is clear that the effective multiplication factor and conversion ratio increase with the lattice pitch reduction for the MOX and TRU fuel. It means that the tight lattice or small coolant volume fraction is benefit for neutron utilization.

Table 2 Pu and MA isotopics fraction (wt%)

Isotope	MOX	TRU
^{239}Pu	60.00	51.48
^{240}Pu	25.02	21.46
^{241}Pu	9.18	7.85
^{242}Pu	5.80	5.01
^{237}Np	0.0	8.17
^{241}Am	0.0	5.01
^{243}Am	0.0	1.02

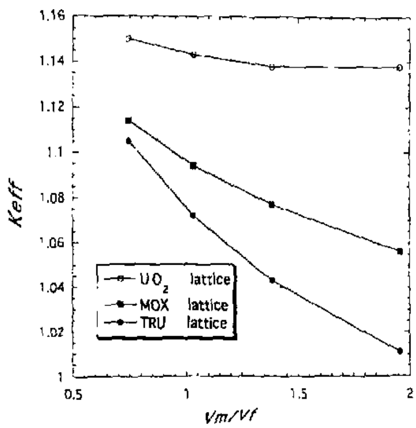


Fig.1 *Keff* variation with *Vm/Vf*

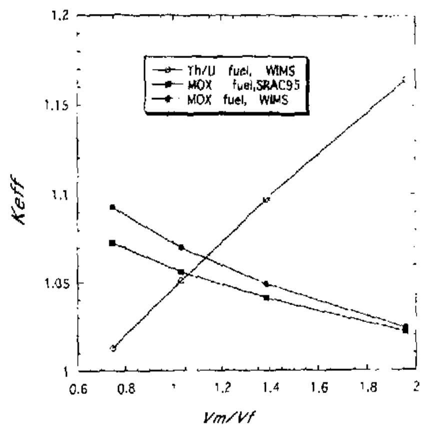


Fig.2 *Keff* variation with *Vm/Vf*

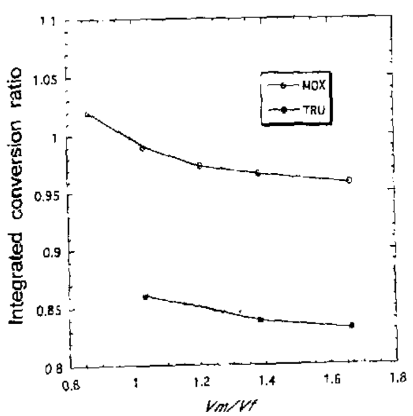
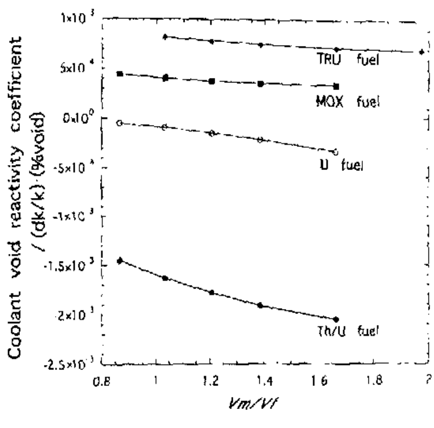


Fig.3 Conversion ratio variation with *Vm/Vf*



In tight lattice PHWR, the coolant temperature reactivity coefficient is very small, therefore, its effect can be neglected. The fuel temperature reactivity coefficient varies with the fuel composition and lattice pitch. MA (Minor Actinides) will reduce the fuel temperature coefficient and in the situation studied, the fuel temperature reactivity coefficient is negative.

The coolant void reactivity coefficient in the tight lattice PHWR is positive for plutonium and TRU fuel, but negative for ^{235}U and Th/^{233}U fuel (Fig.4). For nuclear reactor safety, it is necessary to study a tight lattice PHWR core with high conversion ratio and negative void reactivity coefficient.

Following the accumulation of fission product and heavy nuclides, the reactivity coefficient for fuel temperature and coolant void is increased somehow in the tight lattice PHWR.

The burn-up reactivity swing is small for tight lattice PHWR (Fig. 5), especially for the lattice loaded with MA.

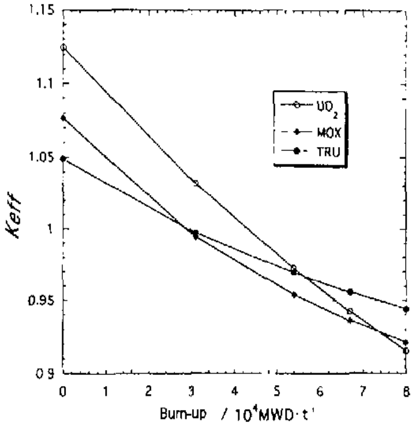


Fig.5 *Keff* variation with burn-up

3 MOX AND Th/U LOADED TIGHT LATTICE PHWR

MOX and Th/U fueled tight lattice PHWR core was studied in this work. Homogeneous TRU and MOX fuels have large and positive coolant void reactivity coefficients, therefore the MOX and Th/U mixed core was investigated to keep the coolant void reactivity coefficient negative.

Two reactor physics calculation code systems, SRAC 95 and WIMS/TDB, were utilized for the simulation of the tight lattice PHWR and the burn-up-dependent few-group data were calculated with WIMS, power and temperature distribution with TDB. The few-group nuclear data, conversion ratio, and temperature coefficient were checked by SRAC95/CITATION.

The height of reactor active core is 366 cm. The core is composed of 193 fuel assemblies, as described in Fig.6. There are 129 MOX assemblies and 64 Th/U assemblies. Each assembly consists of 17× fuel or non-fuel lattices. The MOX assembly has one non-fuel lattice and the Th/U assembly has 25 non-fuel lattices. The control rod is inserted in Th/U assemblies. The data for the tight lattice PHWR core are given in Table 3.

M5	T2	M1	T1	M1	T3	M2	M4
T2	T4	T1	M1	T2	M2	M2	M3
M1	T1	M1	T1	M1	T3	M3	M4
T1	M1	T1	M1	T2	M2	M4	M3
M1	T2	M1	T2	M2	T3	M3	
T3	M2	T3	M2	T3	M4	M4	
M2	M2	M3	M4	M3	M4		
M4	M3	M4	M3				

Total 193 FA

M—MOX assembly T—Th/U assembly

1~5—cycle number

Fig.6 3400MWt tight lattice PHWR core diagram (1/4 core)

A tight lattice pitch of 1.05 cm was considered in this work. The fuel rod and zircaloy cladding outer diameters are 0.82 cm and 0.95 cm, respectively, refer to a typical PWR's fuel rod data. The ratio of the lattice coolant to fuel volume is 0.7455. The fuel composition is described in Table 4. Four-batch (MOX assmbly) and three-batch (Th/U assembly) fuel management strategies were studied for the core, with 400 EFPD per cycle. A low leakage loading pattern was investigated. The 3rd and 4th cycle assemblies were located at the core periphery, the fresh and 2nd cycle assemblies were located at the core center mixed with Th/U assemblies. At the discharged burn-up, the conversion ratio is 1.00 for MOX assembly and 0.94 for Th/U assembly, respectively. The core average integrated conversion ratio is about 0.98.

Table 3 Tight lattice PHWR core description

Total power/MWt	3400
Fuel assembly number:	
MOX fuel	129
Th/U fuel	64
Total	193
Assembly configuration	17×17
Fuel rods/assembly:	
MOX fuel	288
Th/U fuel	264
Active core length/cm	366
Enrichment	
MOX/%	14.60
(Th/U)/%	8.26
Fuel loading:	
MOX/t	74.7
(Th/U)/t	31.4
Fuel rod diameter/cm	0.82
Cladding diameter/cm	0.95
Lattice pitch/cm	1.05
Cycle length/EFPD	400
Discharge burn-up/(GWD/t)	60
Power peaking factor:	
BOC	2.18
EOC	2.09
Maximum fuel temperature:	
BOC/°C	1834
EOC/°C	1837

Table 4 Tight lattice PHWR fuel composition (10^{24} atom·cm^{-3})

Isotope	MOX	Th/U
^{238}U	1.980×10^{-2}	0.0
^{239}Pu	2.030×10^{-3}	0.0
^{240}Pu	8.432×10^{-4}	0.0
^{241}Pu	3.078×10^{-4}	0.0
^{242}Pu	1.944×10^{-4}	0.0
^{232}Th	0.0	2.00×10^{-2}
^{233}U	0.0	1.40×10^{-3}

4 COOLANT VOID REACTIVITY COEFFICIENT

The reactors with a hard spectrum are usually puzzled by the positive void reactivity coefficient. This issue is a cooperative effect of the neutron spectrum shift, neutron leakage change and nuclear cross-section variation.

The coolant void reactivity coefficient is strongly dependent on the core buckling and so small core dimension with high leakage will decrease the void worth, as described in Fig.7. Large buckling will make much more neutron leakage from the reactor core in high void fraction situation, then the void reactivity coefficient is reduced.

The void reactivity coefficient is also dependent on fuel composition. ^{233}U and ^{235}U loaded core has a negative or small coolant void coefficient, MA and plutonium loaded core has a positive the void coefficient. Hence the core mixed with suitable fuel assemblies can adjust void reactivity coefficients. In MOX and Th/U mixed core, because of different characteristics of ^{232}Th, ^{233}U and Pu cross-sections, the void the reactivity coefficient in reactor core can be reduced (Fig.8).

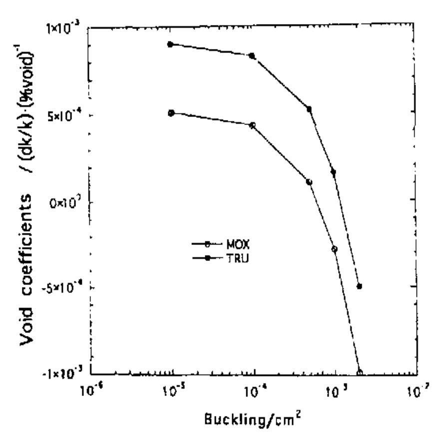


Fig.7 Void reactivity coefficient variation with buckling

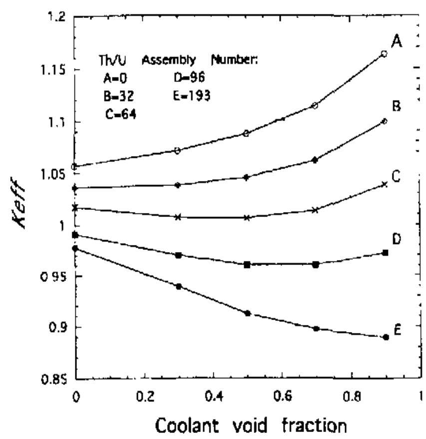


Fig.8 Keff variation with Th/U assembly number

Reducing the core height and using seed-blank techniques are effective methods to decrease the void reactivity coefficient for the tight lattice high conversion reactors. On the other hand, these techniques will aggravate the power distribution and require plutonium separation from blanket. The mixed core of MOX and Th/U assemblies can void these disadvantages.

5 CONCLUSION AND DISCUSSION

The tight lattice PHWR concept was simulated with modern reactor physics calculation codes and analyzed in the present work. It shows some good characteristics for this type of reactors. For MOX fuels, it can achieve a high conversion ratio of about 1.00, with burn-up 60 GWD/t, two times of PWR's. Abundant thorium source can be utilized at high efficiency. The tight lattice PHWR can be used to burn military and reactor plutonium, reduce plutonium accumulation and environmental impacts. The total plutonium in the reactors is almost self-consistent, therefore, plutonium separation is not necessary. It can prevent its military usage.

Tight lattice PHWR system structure is similar to PWR's and the heavy water coolant technique is also very matured, therefore, the tight lattice PHWR is very practical without severe technical, manufacture and license issues. The existing experience and long burn-up will make the tight lattice PHWR very attractive on the economic viewpoint.

Compared with the commercial LWR, the tight lattice MOX and Th/U mixed PHWR possesses some safe characteristics (small reactivity burn-up swing, large and negative fuel temperature coefficient, etc.). These characteristics will assure the reactor operation. Even if control rod clusters were extracted out of the core, the reactor could be controlled by the fuel temperature coefficient.

Based on the above calculation and discussion, we can conclude that the tight lattice PHWR has the important characteristics for the next generation of nuclear power reactors. Future studies of the concept should be focused on fuel management in detail, fuel cycle economic evaluation, as well as reactor transient analysis.

Acknowledgement

We are grateful to Mr. Hironobu UNESAKI in Research Reactor Institute, Kyoto University for comments of SRAC95 code application.

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