STUDY OF CHARACTERISTICS OF TH-U CYCLE IN CANDU SCWR

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Abstract

The flexibility of CANDU technology allows the use of different fuel cycles including various uranium-driven thorium cycles. Direct self-recycle method and heterogeneous cycle modes with supercritical water as coolant were studied for $(U,Th)O_2$ CANFLEX fuel bundle. Lattice pitch and enrichment of driver fuel were treated as independent variables, taking account of coolant void reactivity, fuel burnup, and linear power uneven factor. In the end, appropriate cycle mode and parameters of bundle were chosen for $(U,Th)O_2$ cycle in CANDU SCWR. Calculations were processed by the two-dimensional multigroup neutron transport code WIMS-AECL release 3.1.2.1.

1. Introduction

With the design of pressure tube and fuel channel model, CANDU type reactor has particular advantages in using super-critical water as coolant. It's easier and safer to keep high pressured super-critical water inside the pressure tube compared to rectangular shaped lattice. Heavy water with much lower pressure and higher density is still used as moderator to keep a high neutron economy. On the other hand, Thorium has inherent advantages on material and neutron physics property, and China has a great abundance of Thorium resource. Besides, CANDU technology provides flexibility for fuel cycles including thorium cycles. This work studies lattice physics and Th-U cycle characters in CANDU SCWR with WIMS-AECL code (ENDF/B-VI library).

Based on informed researches, three proposals are provided for Thorium cycle in CANDU reactor. They are mixed-core model, mixed-bundle model and mixed-fuel model. Mixed-bundle model was adopted in work of this paper, using UO_2 fuel rods on the outer two circles as driver fuel, and ThO_2 rods on the centre position and inner circle in a CANFLEX bundle. Under this model, a feasible direct self-recycle method was researched, which means after an irradiation cycle, placing the bundle outside the core for some time until ^{233}Pa converting to ^{233}U sufficiently, then combining ThO_2 rods with fresh UO_2 rods into a new bundle, and putting the new mixed bundle into the core for the next cycle.

Geometric parameters of an ACR-700 CANFLEX bundle remained except lattice pitch value, which was altered from 20cm to 30cm to check the relevant change of coolant void reactivity (CVR) under critical calculation. Linear power uneven factor and burnup depth were also checked under the scoping of lattice pitch and enrichment of driver rods to get appropriate parameters of bundle assembly. Cycles with different driver rods enrichment were studied.

2. Model Description

As mentioned above, this work uses CANFLEX bundle as basic assembly model. Super-critical light water is used as coolant, and heavy water as moderator. The bundle length is 49.53cm. In each bundle, there are 43 rods which are arrayed as 1, 7, 14, 21 on number from inside out. Materials of cladding, pressure tube, calandria tube and gas are ZircIV, Zr25Nb, ZircII alloy and CO_2 respectively. The cross section of fuel bundle is shown in Figure 1.

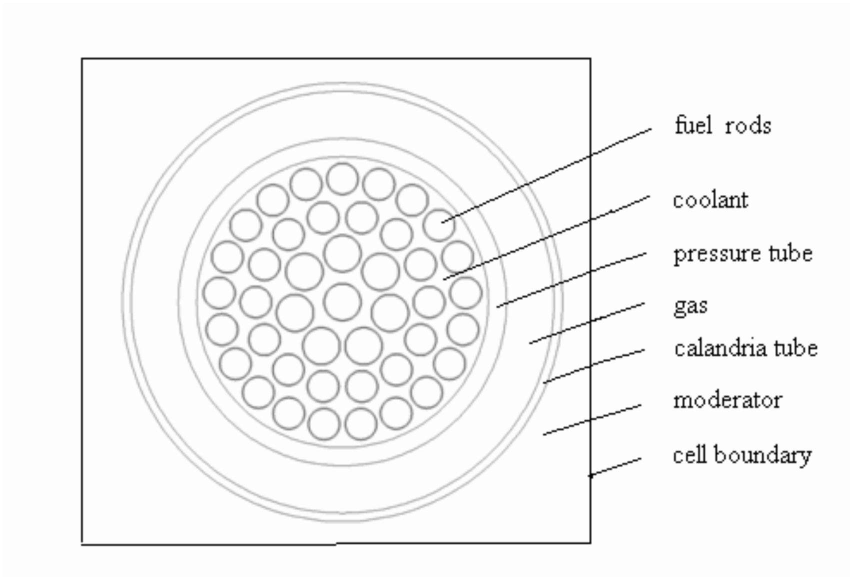

Figure 1 Cross section of CANFLEX fuel bundle

With a symmetric cosine power distribution, channel power 8.5MW and inlet temperature 350℃[1], a distribution of coolant density and coolant temperature could be obtained along the channel under a certain pressure 25MPa. Results are obtained via the thermal-hydraulic code CFX. Coolant density and temperature distributions along the channel are shown in Figure 2. Coolant parameters needed in later calculation and analysis are gotten from Figure 2.

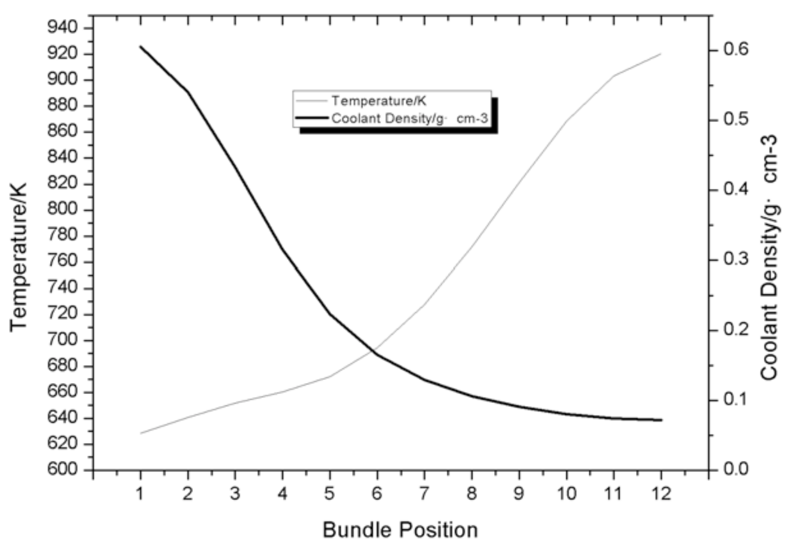

Figure 2 Coolant density and temperature distribution along channel

3. Lattice Parameters Scoping

In this part, lattice properties including coolant void reactivity, burnup depth and power distribution in the radial direction are studied. As a result, high enrichment of driver UO_2 and big lattice pitch are suggested to achieve a deep burnup and even power distribution. However, a small lattice pitch should be chosen to the benefit of negative coolant void reactivity. Proper values of lattice pitch and enrichment are given in the end.

3.1 Coolant Void Reactivity

In CANDU reactor design, coolant void reactivity (CVR) is defined as the reactivity increment when coolant water is totally replaced by void. So CVR could be calculated by

$$\Delta\rho = \rho_{void} - \rho_{cool} = \frac{1}{k_{cool}} - \frac{1}{k_{void}}, \quad (1)$$

where k_{cool} and k_{void} are infinite multiplication factors with and without coolant. CVR on three bundle positions in a channel are calculated under different lattice pitch and driver UO_2 enrichment. All these calculations are processed at zero burnup.

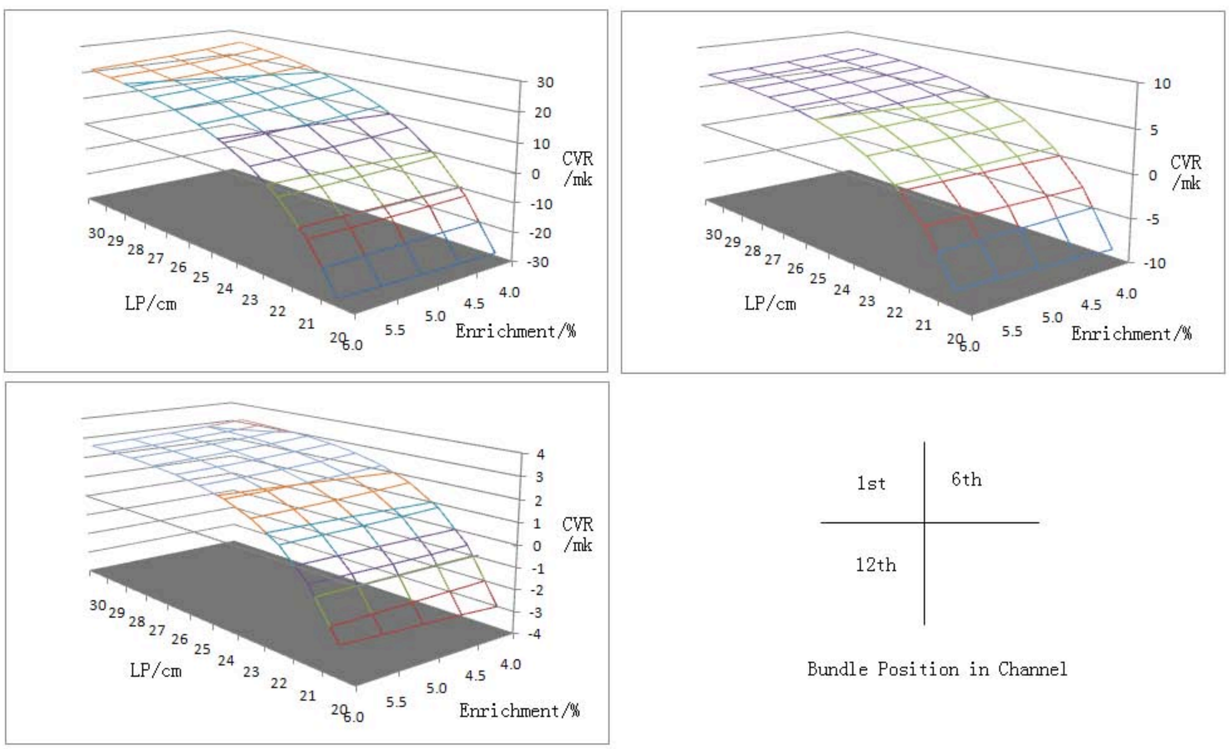

Figure 3 CVR at Three Channel Positions under Lattice Pitch and Enrichment Scoping

In Figure 3, bundle position numbers correspond to the bundle positions in Figure 2. Comparing three diagrams in Figure 3, we could find that absolute values of CVR are higher at positions close to channel inlet, and much lower at positions close to channel outlet. This is because density of super-critical water changes a lot through the channel. According to Figure 3, CVR has a same variation trend at the three positions: It increases with the increasing of lattice pitch, and changes much more slowly with the increasing of driver fuel enrichment. What we concern most is to maintain the CVR value negative, so proper value of lattice pitch should be chosen. Based on the lattice pitch scoping result, lattice pitch should be set to 21.5cm or less. So during later burnup calculations, a range from 20.0cm to 21.5cm is used for lattice pitch.

3.2 Burnup

During burnup calculation for a CANDU reactor, an integrated infinite multiplication factor is used[2]. It is defined as

$$\int k_{\inf} = \frac{\int k_{\inf} \mathrm{d}t}{\int \mathrm{d}t} \tag{2}$$

At the end of burnup, $k_{\inf}$ may be smaller than 1, but as long as integrated infinite multiplication factor is above 1, the bundle could stay in the reactor and don't need to be refuelled. We used the value 1.04, so burnup calculations stopped when integrated infinite multiplication factor decreases to 1.040.

Burnup results under different lattice pitch and enrichment value is shown in Figure 4. Coolant parameters are from the 6th bundle in Figure 2. Power is set to 30.0MW/(t • HE).

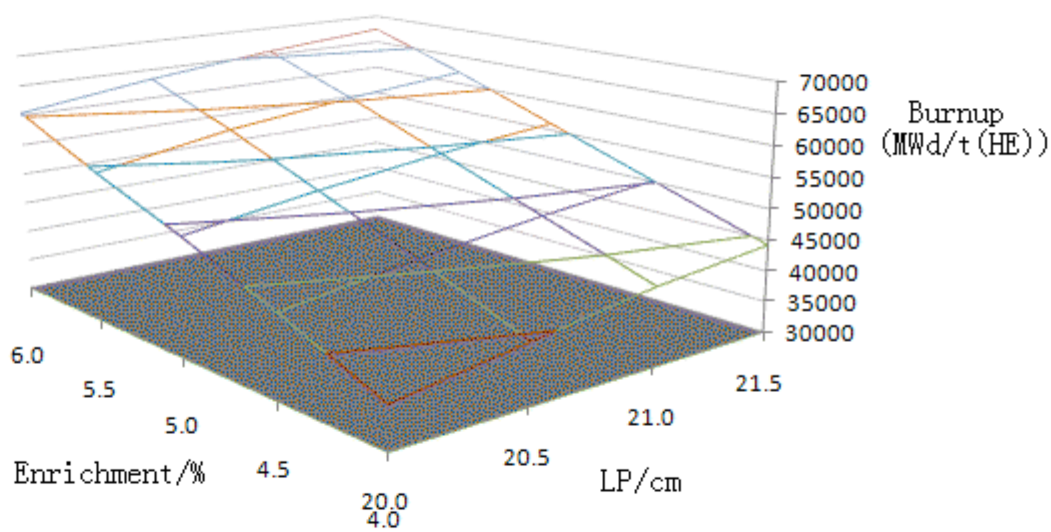

Figure 4 Burnup under Lattice Pitch and Enrichment Scoping

When the lattice pitch is in the range of that shown in Figure 4, it is an undermoderated lattice, so $k_{\inf}$ increases with the increasing of lattice pitch, and so is burnup. A higher burnup is achieved with a higher enrichment of driver fuel.

3.3 Radial Power Distribution

For a CANFLEX bundle, fuel rods in different circles are under different moderated conditions. So a linear power uneven factor is used to measure bundle power distribution at radial direction. Linear power uneven factor is defined as ratio of the maximum rod power to the minimum one. For a CANFLEX bundle with ThO_2 rods and super-critical water here, it is found that during first cycle of thorium fuel, the maximum linear power density is from rods in the outermost circle and the minimum power is from the centre ThO_2 rod. Radial power distributions at the end of burnup series are graphed as Figure 5.

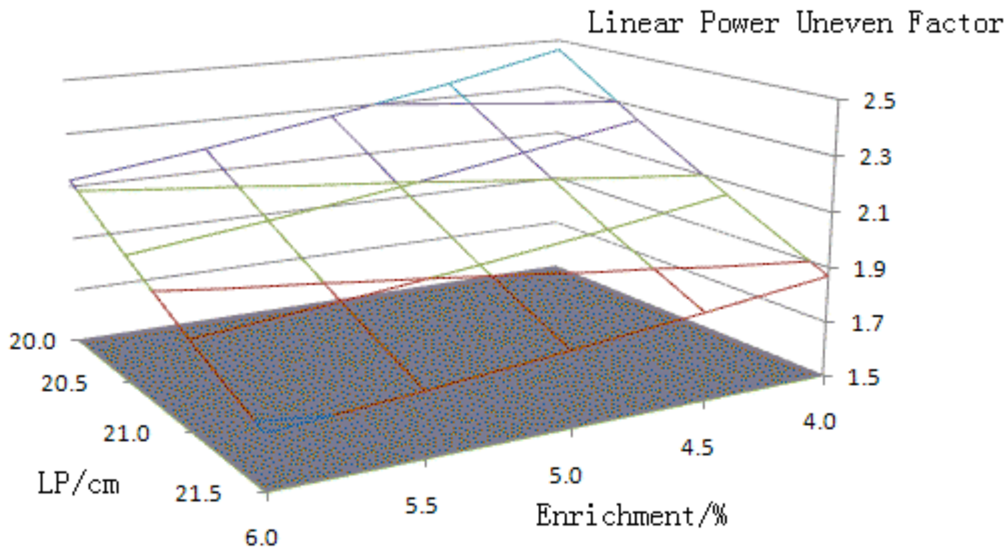

Figure 5 Linear power uneven factor under Lattice Pitch and Enrichment Scoping

According to Figure 5, a lower linear power uneven factor value could be obtained with a bigger lattice pitch and higher enrichment. In ThO_2 rods, ^{232}Th converts to fissile isotope ^{233}U during burnup process, and high flux profits accumulation of ^{233}U. The more ^{233}U is accumulated, the more power is produced from ThO_2 rods. So an evener distribution could be achieved when lattice pitch or enrichment is enhanced. Here radial power distribution at exit burnup is analysed, however the difference between the power in the outer rings and the inner rings is much bigger for fresh fuel, because fresh ThO_2 rods produce very little power. During following cycles, radial power difference would not change so much as in the first cycle, because ^{233}U quantity in ThO_2 rods almost reaches a balanced state at the end of first burnup cycle, which would be analysed in section 4.

3.4 Conclusion

A lattice pitch under 21.5cm could make sure the CVR is negative. Considering an even power distribution and deep burnup under a fixed enrichment of driver fuel, lattice pitch value should not be too small. So lattice pitch could be chosen from 20.0 to 21.5cm. To be on the safe side, burnup is controlled under an upper limit in reactor fuel management, so enrichment doesn't need to be too high. Based on Figure 4, burnup could reaches to 55,000MWd/(t • HE) with enrichment 5.0% and lattice pitch 21.0cm. So in the first cycle, driver fuel enrichment could be set to 5.0% or less.

4. Studies on Thorium Cycle Method

Direct self-recycle method is studied for thorium cycle. After each cycle, the burned bundle is placed out of the core for 140 days (almost 5 half-lives of ^{233}Pa), and then ThO_2 rods are discharged from the bundle and combined with fresh UO_2 rods to a new bundle. The goal integrated infinite multiplication factor is still set to 1.040.

4.1 Using Driver Fuel with Fixed Enrichment

During each cycle, enrichment of driver rods is 5.0% and lattice pitch is 20.0cm. Three cycles are processed.

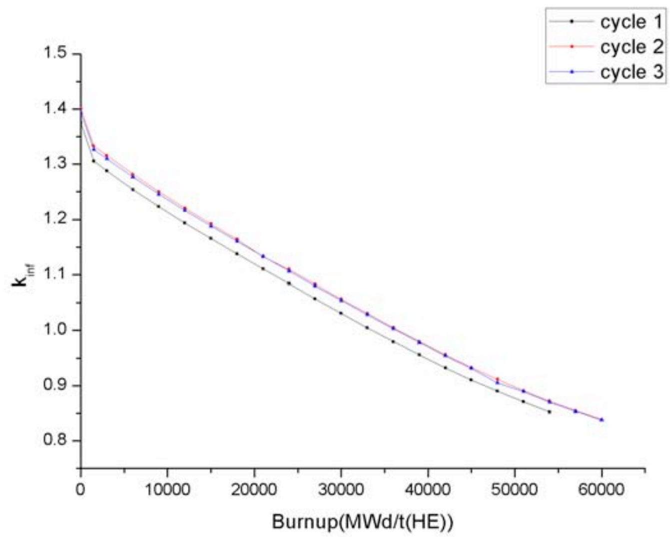

Figure 6 Variation of k_{inf} ,All Cycles with 5.0% UO_2 Driver Rods

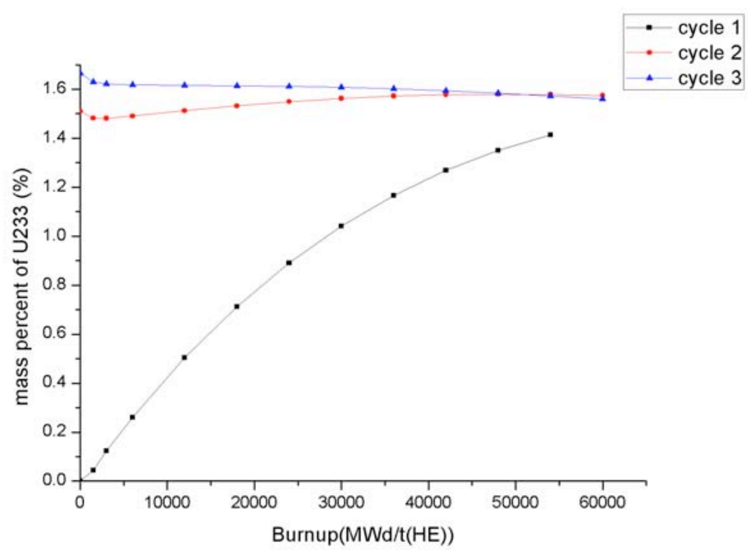

Figure 7 Variation of ^{233}U Density, All Cycles with 5.0% UO_2 Driver Rods

Figure 6 shows the variation of k_{inf} with burnup in each cycle. Lines end when integrated infinite multiplication factor decreases to 1.040. Because of the contribution of accumulated ^{233}U in ThO_2 rods, k_{inf} in cycle 2 is higher than that in cycle 1, and cycle 2 provides a deeper burnup than cycle 1. In cycle 3, k_{inf} varies almost the same way as cycle 2, that's because ^{233}U quantity in ThO_2 rods reaches a balanced state. This could be verified in Figure 7, which shows the mass percentage of ^{233}U in the second circle rods.

4.2 Using Driver Fuel with Different Enrichment in Cycles

Since the accumulation of ^{233}U induces an increment of k_{inf} in cycle 2, so a lower enrichment of driver fuel could be used in the second and following cycles. Here in cycle 2 and cycle 3, 4.5% UO_2 rods are used as driver fuel. In the first cycle, 5.0% UO_2 rods are still used as driver fuel. Variation of k_{inf} in this case is shown in Figure 8.

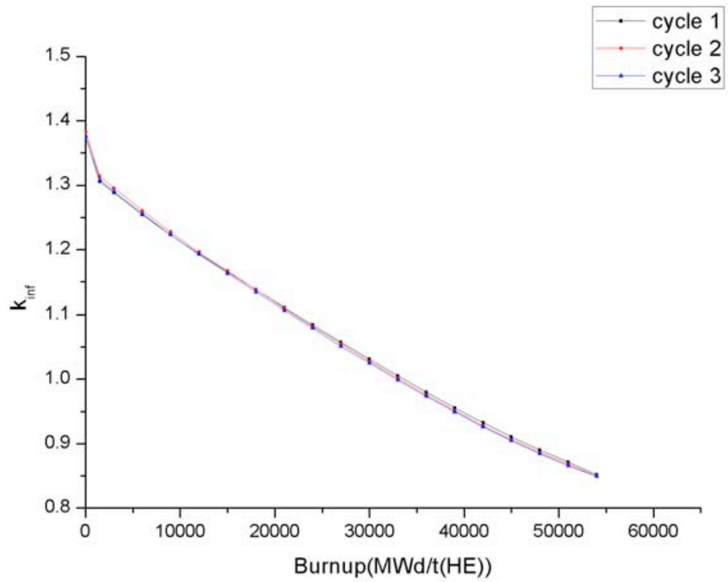

Figure 8 Variation of k_{inf} , 1st Cycle with 5.0% ^{235}U Driver Rods, Other Cycles 4.5%

As enrichment of driver fuel adjusted to 4.5% in second and third cycles, k_{inf} gets lower in these cycles (compared to Figure 6), and a deep burnup could still be reached. A similar k_{inf} behaviour and a same burnup in each cycle provide convenience to reactor fuel management. Behaviour of ^{233}U density is almost same as Figure 7. This means enhancing driver fuel enrichment in the second and third cycles could not raise ^{233}U percentage.

4.3 Conclusion

As ^{233}U is fully accumulated in the first cycle, driver fuel with lower enrichment could be used in following. In direct self-recycle method, using an enrichment of 5.0% in first cycle and 4.5% in following cycles could reach similar k_{inf} and burnup.

5. References

[1] Yu Jiyang,Wang Songtao,Jia Baoshan, “Development of sub-channel analysis code for CANDU-SCWR”, *Progress in Nuclear Energy*, Vol. 49, Iss. 4, 2007, pp.334-350.

[2] P.G. Boczar,P.S.W Chan,G.R. DYCK, “Recent advances in thorium fuel cycles for CANDU reactor”, IAEA TCM on Utilization of Thorium Fuel, Vienna, Austria, 1999.