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The utilization of thorium for long-life small thermal reactors without on-site refueling

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Abstract

Thorium cycle has many advantages over uranium cycle in thermal and intermediate spectrum nuclear reactors. In addition to large amount of resources in the world which up to now still not utilized optimally, thorium based thermal reactors may have high internal conversion ratio so that they are very potential to be designed as long-life reactors without on-site refueling based on thermal spectrum cores. In this study preliminary study for application of thorium cycle in some of thermal reactors has been performed.

We applied thorium cycle for small long-life high temperature gas reactors without on-site refueling. Calculation results using SRAC code show that 10 years lifetime without on-site refueling can be achieved with excess reactivity of about 10% dk/k.

The next application of thorium cycle has been employed in long-life small and medium PWR cores without on-site refueling. Relatively high fuel volume fraction is also applied to get relatively hard spectrum, small size, and high internal conversion ratio. In the current study we have been able to reach more than 10 years lifetime without on-site refueling for 20–300 MWth PWR with maximum excess reactivity of a few %dk/k.

The last application of thorium cycle has been employed in long-life BWR cores without on-site refueling. Relatively high fuel volume fraction is applied to get relatively hard spectrum, small size, and high internal conversion ratio. In the current study we have been able to reach more than 10 years lifetime without on-site refueling for 100–600 MWth BWR with maximum excess reactivity of a few %dk/k.

Keywords: Thorium cycle; Long-life thermal reactors; High internal conversion ratio; SRAC code; Hard spectrum; Excess reactivity

1. Introduction

Thorium cycle in general has better conversion ratio than uranium cycle in the thermal spectrum. In this study, thorium cycle is used to extend the thermal reactor operation cycle without on-site refueling. Basically we have to adjust the moderating ratio and fuel enrichment to be able to improve internal conversion ratio. And by geometrical optimization process we can get the design of small long-life high temperature gas cooled reactors (HTGR) without on-site fueling, small long-life pressurized water reactors (PWR) without on-site fueling, and small boiling water reactors (BWR) without on-site fueling.

2. Design concept

In order to extend the refueling cycle without excessive reactivity swing in high temperature gas cooled reactors we need reactor core with high internal conversion ratio, in general around unity. In thermal reactors such as HTGR, proper combination of ^{232}Th–^{233}U cycle gives high possibility to achieve such objective. Adjusting moderation ratio by appropriately setting the graphite moderator and fuel composition is one of important strategy to get harder neutron spectrum so that much better conversion ratio can be reached.

Here we performed many parametric surveys to understand the influence of many parameters such as moderating ratio,

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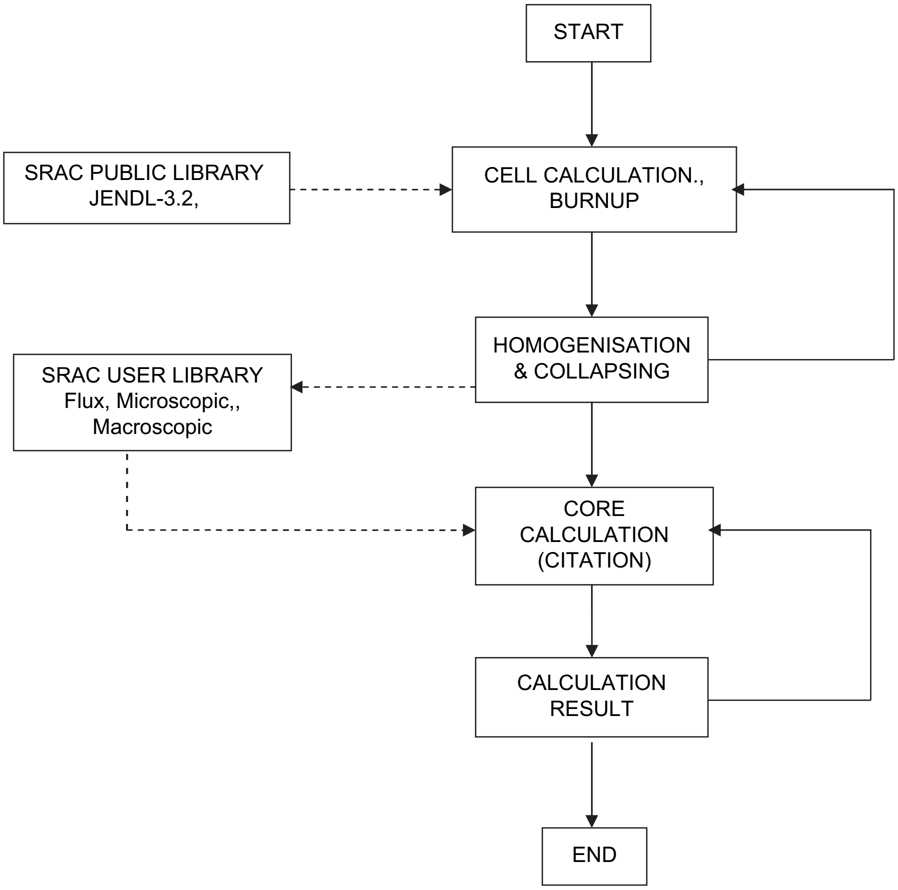

Fig. 1. Computation scheme in this study.

fuel enrichment, linear power, etc. to the infinite multiplication factors pattern during burn-up. Using the results of parametric survey we can then perform optimization in the core level.

Similar approach is used for long-life small pressurized water reactors without on-site refueling and long-life small long-life BWR without on-site refueling and here we apply tight lattice concept to get small core with relatively high internal conversion ratio.

3. Computational method

For computation method we used SRAC code system to calculate cell calculation and cell burn-up. Whole core

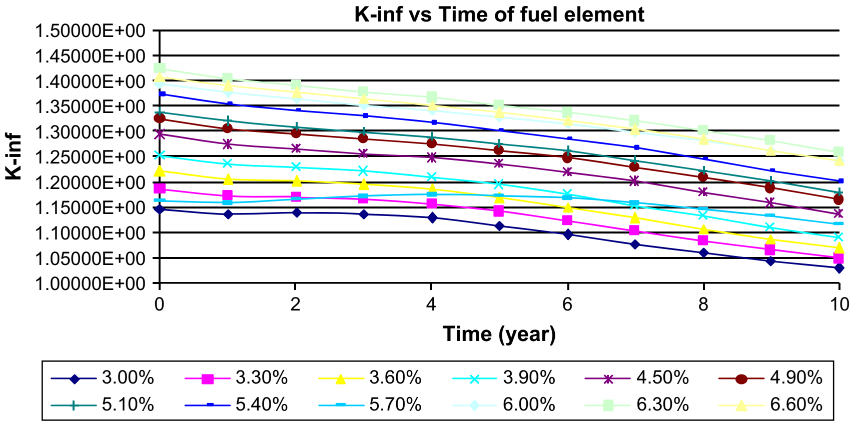

Fig. 2. Infinite multiplication change during burn-up for various enrichment of ^{233}U in the fuel.

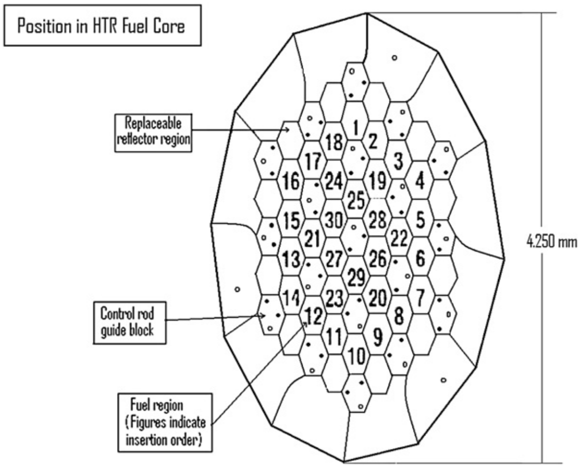

Fig. 3. Core lay-out of small long-life high temperature gas cooled reactors without on-site refueling.

Table 1

One example of core level optimization results of long-life small high temperature gas cooled reactors without on-site refueling

Position of fuel block (from above)	Fuel characteristics	No. of fuel zone			
		1	2	3	4
1	Uranium-233 enrichment (wt%)	5.4	6.0	6.3	6.6
	Number of fuel pins	33	33	31	31
	Type of burnable poisson	H-I	H-I	H-I	H-I
2	Uranium-233 enrichment (wt%)	4.5	5.1	5.7	6.0
	Number of fuel pins	33	33	31	31
	Type of burnable poisson	H-II	H-II	H-II	H-II
3	Uranium-233 enrichment (wt%)	3.6	4.5	4.9	5.1
	Number of fuel pins	33	33	31	31
	Type of burnable poisson	H-II	H-II	H-II	H-II
4	Uranium-233 enrichment (wt%)	3.0	3.3	3.6	3.9
	Number of fuel pins	33	33	31	31
	Type of burnable poisson	H-I	H-I	H-I	H-I
5	Uranium-233 enrichment (wt%)	3.0	3.3	3.6	3.9
	Number of fuel pins	33	33	31	31
	Type of burnable poisson	H-I	H-I	H-I	H-I

calculation is performed using CITATION or FI-ITBCH codes. For SRAC code system calculation the calculation scheme is shown in Fig. 1.

When we calculate the whole core calculation using FI-ITBCH code, interpolation for linear power parameter is performed to get relatively accurate results with optimal computation time.

4. Simulation results and discussion

4.1. Small long-life high temperature gas cooled reactors without on-site refueling

Fig. 2 shows the results of cell-burn-up parametric survey for different fuel enrichments (^{233}U) during 10 years burn-up without refueling.

From Fig. 2 it is shown that in general higher enrichment gives longer lifetime but also higher reactivity swing. Core enrichment of 3% gives smaller infinite multiplication constant drop after 10 years of burn-up. This trend can be thought as an influence of higher internal conversion ratio in fuel with lower enrichment ^{233}U Fig. 3.

As the next steps we performed core optimization and as one of the optimal results we can see the combination shown in Table 1 as follows.

So as shown in the above table we used various values of fuel enrichment (^{233}U) in core optimization. The effective multiplication factor change during burn-up for the above core configuration is shown in Fig. 4.

Fig. 4 shows that during 10 years of burn-up without refueling, the core composition shown in Table 1 in which 30 column of fuel were filled give excess reactivity of about 12% dk/k.

4.2. Small long-life pressurized water reactors (PWR) without on-site refueling

Similar method to that of long-life HTGR was applied to the long-life PWR without on-site refueling. After some optimizations we get the following pattern for 100 MWth long-life PWR without on-site refueling based on thorium cycle. Fig. 5

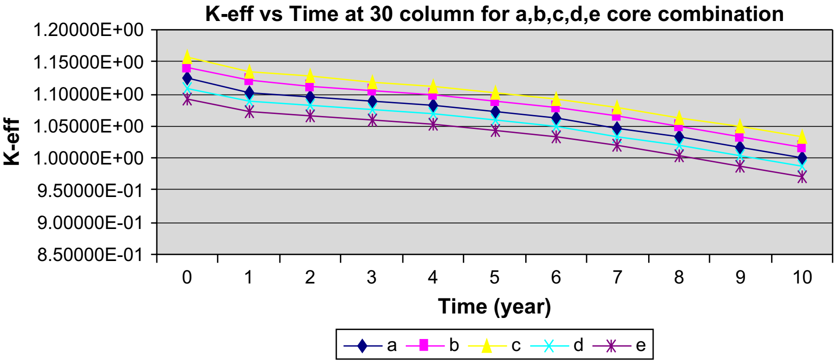

Fig. 4. Effective multiplication factor change during burn-up and the combination shown in Table 1 correspond to the 'a' line.

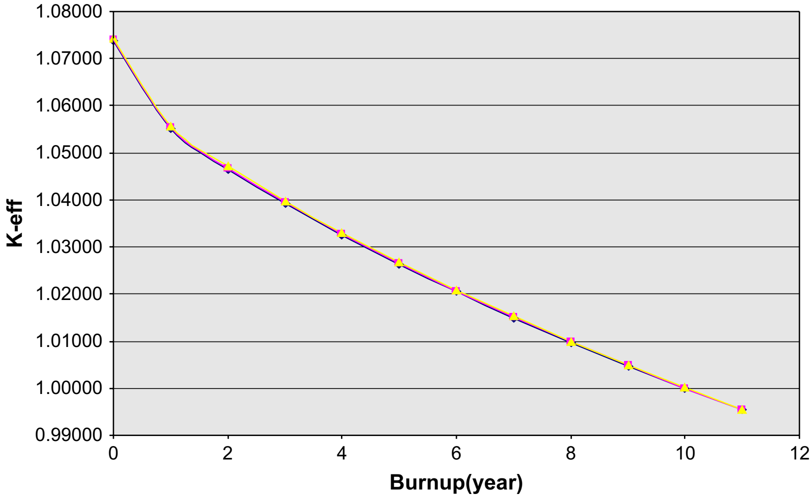

Fig. 5. Effective multiplication factor change during burn-up for the core configuration shown in Table 2.

Table 2
Design Specification of long-life PWR 100 MWth

Parameter	Specification
Power (thermal)	100 MWth
Refueling	10 years
Core type	Tall
Radial	90–100 cm
Axial	216–266 cm
Fuels	Thorium–uranium dioxide (Th,U)O_2
Structure	Zircalloy
Coolant	Light water (H_2O)
Cell type	Square cell
Smear density	90% T.D.
Enrichment	1.5–3% ^{233}U
Density (Th,U)O_2	9.64 g/cm^3
Fuel fraction	60%
Pin size	
Clad thickness	0.07 cm
Pitch	1.4 cm

shows a pattern of multiplication factor change for 100 MWth 10 years long-life PWR without on-site fueling. Detail parameters are shown in Table 2 as follows.

4.3. Small long-life boiling water reactors (BWR) without on-site refueling

Similar process to the long-life PWR was applied to the long-life BWR and some results are shown as follows. Fig. 6 shows infinite multiplication pattern change during burn-up for thorium cycle for various enrichment of ^{233}U.

It is shown that high enrichment fuel (around 6%) gives higher initial infinite multiplication factor but the value decreases much faster than that of lower enrichments. On the other hand, very low enrichment gives low initial infinite multiplication factor value but then increases. Using the above

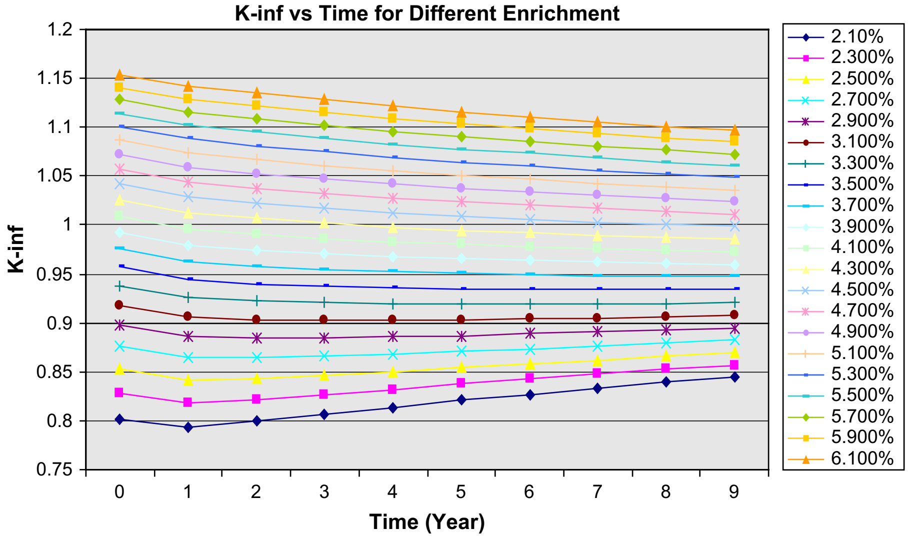

Fig. 6. Infinite multiplication factor change during burn-up for various enrichment of ^{233}U in thorium cycle tight lattice core.

parametric survey results and after some optimization processes we could get some designs which can be operated for 10 years of burn-up without on-site fueling with excess reactivity less than 5%.

5. Conclusion

The thorium cycle has been successfully applied to design long-life high temperature gas cooled reactor without on-site refueling, long-life pressurized water reactors without on-site refueling, and long-life boiling water reactors without on-site refueling. For small long-life high temperature gas reactors without on-site refueling. Calculation results show that 10 years lifetime without on-site refueling can be achieved with excess reactivity of about 10% dk/k.

For long-life PWR and BWR relatively high fuel volume fraction is applied to get relatively hard spectrum, small size, and high internal conversion ratio. For long-life small PWR without on-site fueling, 10 years lifetime without on-site refueling for 20–300 MWth PWR have been reached with maximum excess reactivity of a few %dk/k. Similarly for long-life BWR without on-site refueling, in the current study we have been able to reach more than 10 years lifetime without on-site refueling for 100–600 MWth BWR with maximum excess reactivity of a few %dk/k.