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Benefits of Thorium Fuel Utilization in Small PWR Core

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1. Introduction

A conceptual nuclear design of a small PWR core with 10 MWt rated power has been carried out. [1] Thorium oxide is used with uranium oxide for fuel conversion based on once-through cycle in order to accomplish ultra long fuel cycle length with higher proliferation resistance. Compared with commercial power plant, this core has a few unique design goals for remote power station with independent grid.

Initially loaded fuel should burn more than 20 years without refueling. Reactor system should be simple and passively safe for operator-free plant. Reactor fuel should be proliferation resistant against terror at remote location. For these design goals, thorium base thermal breeding core is designed to be cooled by natural circulation coolant at normal operation condition. Reactivity control is done by control rod without soluble boron resulting in removal of CVCS. However, nuclear design of ultra-long cycle core in soluble boron free option is a challenging goal with available material choices.

In this work, feasibility of reactor power control with burnable poisons and control banks were tested for 20 year once-through cycle. Benefits of thorium compared with uranium-only-core were also measured in cycle length and proliferation resistance. Reactor core design was done only for the nuclear design concept with HELIOS and MASTER code system which was already verified in previous study.[2]

CORE DESIGN

System analysis was done for 10 MWt PWR core for the natural circulation cooling without RCP. It was calculated that inlet/outlet coolant temperature should be 160℃/195℃ with 65.92 Kg/sec flow rate under 2 MPa. Core height and diameter are small as 1m and 1.1m resulting in very small linear power density of 1.71 kW/m. Table 1 shows basic design parameters for heterogeneous thorium fuel assemblies(FA) as shown in Fig.1.

In order to have a ultra-long cycle length, enrichment of uranium in a thorium fuel pin should be high upto 19.5 w/o. Initial excess reactivity of core at the beginning of cycle(BOC) is very high upto 1.25 even though large amount of fast neutrons are leaked from the core boundary. Fig.2 showed the core loading pattern of two kinds of fuel assemblies. Fig.3 shows the difference in excess reactivity of between core without burnable poison(BP) and core with BP.

High excess reactivity was controlled by Erbia integral BP pins. Gadolinia integral BP and Integral Fuel Burnable Absorber(IFBA) were also tested with Erbia. [3]

Table 1. Fuel Assembly Specifications

Parameter	Values
Fuel Composition	UO_2 4.5w/o U
	$(U+Th)O_2$ UO_2, 19.5w/o 25v/o
Pellet Radius [cm]	0.4096
Gas Gap [cm]	0.0082
Cladding Thickness [cm]	0.0572
Fuel Rod Radius [cm]	0.4750
Unit Cell pitch [cm]	1.26
Water Gap Width [cm]	0.08
Assembly Width [cm]	13.94

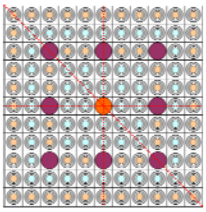

Figure 1. Fuel Pin Arrangement in FA

		A1	A1	A1	A1		
	A1	A1	A1	A1	A1	A1	
A1	A1	A2	A2	A2	A2	A1	A1
A1	A1	A2	A2	A2	A2	A1	A1
A1	A1	A2	A2	A2	A2	A1	A1
A1	A1	A2	A2	A2	A2	A1	A1
	A1	A1	A1	A1	A1	A1	
		A1	A1	A1	A1		

Figure 1. Core Loading Pattern

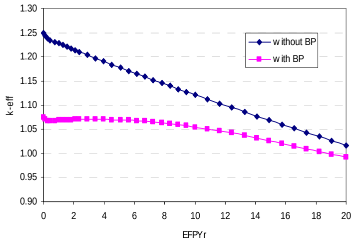

Figure 2. Excess Reactivity with Erbia BP

There are two kinds of FA, one is A1 which has 28 BP pins containing 4.0% Er_2O_3 in UO_2 and the other is A2 which has 40 BP pins containing 6% Er_2O_3.

Basic nuclear design parameters of core were measured throughout the core cycle length. Fuel temperature coefficient and moderator temperature coefficient are negative within a safe band. Maximum pin peaking is a little higher in the middle of cycle. Relative assembly peaking was upto 1.3216 without concerning local pin peaking. Even though pin peaking may be much higher than conventional core, the average linear power density was small enough to guarantee a large thermal margin against urania fuel pin limitations.

REACTIVITY CONTROL

In this soluble boron free core, excess reactivity and power level change should be done only by control rods. Reactor core is small enough not to cause an axial offset change and xenon oscillation. However, assurance of enough shutdown margin is an issue of nuclear design. As shown in Fig.4, every assembly should have control rods. There are two shutdown banks of B_4C control rods. One control bank, R1 is dedicated to power level control and is pulled out of core at full power condition. Two control banks, R2 and R3 are used for compensating core excess reactivity during burnup. All control rods for R1, R2 and R3 are made of strong Hafnium pins. Fig.5 shows the critical control rod positions of R2 and R3 searched by code MASTER.

Figure 3. Layout of Control Rod Banks

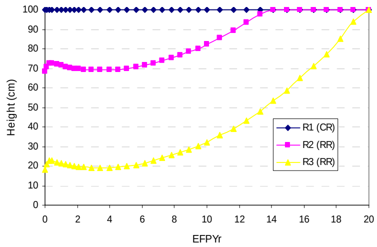

Figure 4. Critical Control Bank Positions

Benefits of thorium breeding were tested by comparison of core design performances with those of uranium-only-core(UOC). In order to have the same cycle length, UOC should have higher fissile loading and cause higher initial excess reactivity at the BOC. It was shown that production amounts of plutonium fissile isotopes are much less in this design compared with UOC. Fig. 6 shows difference in production rate of Pu-239 in the core.

Benefits of thorium core were also tested by comparison of nuclear safety parameters and proliferation resistance indices with those of UOC. Thorium core showed much larger FTC and MTC effect as shown in table 2. However, proliferation resistance is not better than UOC different from expectation. Except thermal generation rate(TG), bare critical mass(BCM) and spontaneous neutron source rate(SNS) are very comparable with UOC.

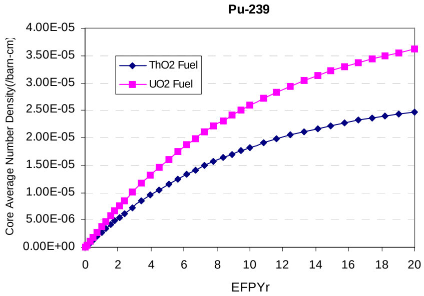

Figure 5. Production Rate of Pu-239 in the core

Table 2. Comparison of MTC and FTC at HFP between Proposed Core and Ulchin

	MTC (pcm/°C)		FTC (pcm/°C)	
	BOC	EOC	BOC	EOC
Proposed Core	-32.05	-27.88	-5.29	-5.49
Ulchin 3&4	-3.11	-12.77	-0.83	-0.83

Table 3. Measured Proliferation Resistance Indices

	BCM (kg)	SNS (#/kg-sec)	TG (Watts/kg)
Proposed Core	16.6403	2.5866×10^5	12.5241
UOC	16.3757	2.3074×10^5	7.7494

5. Conclusion

It was found that the use of thorium for thermal conversion is effective in achieving longer cycle length especially in small core which has high neutron leakage. Benefits in safety is not clear, but results in FTC and MTC is good enough. However, proliferation resistance was not improved by using thorium fuel because of limitation in small power reactor.

REFERENCES

[1] Mon Mon Kyaw and Myung-Hyun Kim, “A New Conceptual Core Design of REX-10 with Thorium Fuel,” Transactions of the Korean Nuclear Society **Spring** Meeting, Korea, **May**, 200**8**.

[2] Kang-Mok Bae and Myung-Hyun Kim, "Core Design for Heterogeneous Thorium Fuel Assemblies for PWR (I)-Nuclear Design and Fuel Cycle Economy," Nuclear Engineering and Technology, Vol.37, No.1, pp.91-100, February, 2005.

[3] J.C.Wagner and C.V. Parks, “Parametric Study of the Effect of Burnable Poison Rods for PWR Burnup Credit”, NUREG/CR-6761, ORNL/TM-2000/373, Oak Ridge National Laboratory.