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A Small Modular Reactor Core Design with Annular UO_2 and FCM Fuel Rods

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1. Introduction

Recently, the use of renewable energy is on the rise, and the safety or economics of nuclear power generation is becoming important factor in securing comparative advantages with other sources. Maintaining fuel integrity has a significant impact on the economics and safety of nuclear power plants. After the accident at Fukushima Dai-ichi, many researches are underway on the development of accident tolerant fuels to reduce the oxidation and hydrogen generation, to improve the thermal conductivity for reducing the fuel temperature, and to enhance retention of fissile products [1].

The objective of this work is to design and analyze an advanced SMR (Small Modular Reactor) core having improved safety and economics of reactor by combining the ATF (Accident Tolerant Fuel) concepts and power uprating. The employed ATF concepts include the annular fuel having an additional central coolant flow, the FCM (Fully Ceramic Micro-encapsulated) fuel, and FeCrAl cladding. Another core design goal is to extract the TRUs from the PWR spent fuels and use them in the kernel of the FCM fuel to reduce radiotoxicity and heat load of the spent fuels.

2. Methods and Results

2.1. Fuel Assembly Designs

In this work, a SMR core is considered to have the same active fuel length and the number of fuel assemblies as the SMART core. However, the fuel assemblies have quite different features such as 13x13 lattice structure, annular fuel and FeCrAl cladding. Also, the thermal power output is uprated by 15% in comparison with the SMART core. KAERI previously designed OPR core using annular fuel rods with power uprating core using annular fuel [2]. They suggested a 12x12 lattice fuel assembly with a 120% power rating. The fuel rods used in the Westinghouse type 17x17 assemblies have ~570μm thick Zircaloy-4 cladding. In this work, we suggested 13x13 annular fuel assemblies in which two different type annular fuels are used to enhance the thermal hydraulic performances by adding a central coolant flow channel. In particular, in contrast to the 570μm thick Zircaloy-4 cladding, we considered 400μm thick inner and outer FeCrAl claddings to increase fuel loading and to reduce the oxidation and hydrogen generation. This thinner FeCrAl cladding was considered due to the superior mechanical strength to the Zircaloy-4 cladding [3]. It is considered that DNBR and LPD margins would increase due to high strength of FeCrAl cladding and reduction of fuel centerline temperature by using annular fuel. The accompanying paper [4] shows the thermal hydraulic performances of the core described in this work. As shown in Fig. 1, the fuel assembly is comprised of the annular fuel rods in which UO_2 and FCM fuels are loaded in the annular regions between inner and outer claddings. The FCM fuels are considered to consume TRU nuclides from the existing PWR spent fuels. The 13x13 fuel assembly consists of 160 annular fuel rods and 9 guide tubes. Of 160 annular fuel rods, 36 UO_2 fuel rods are loaded in the central region while 112 $TRUO_2$ FCM fuel rods are in the outer region. The $TRUO_2$ FCM fuel rods are divided into two different types according to the packing fraction (PF) to flatten the power distribution; 32 FCM fuel rods having low packing fraction (PF) are located in the inner region while 80 FCM fuel rods are in the outer region. We considered Gd_2O_3 as the burnable poison in 12 UO_2 fuels. Table 1 summarizes the design parameters of the fuel assembly.

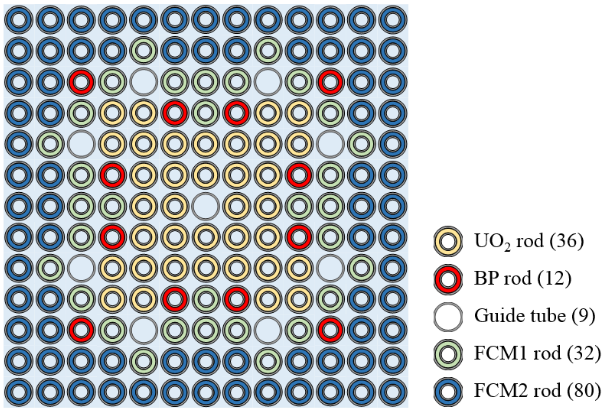


Fig. 1. Configuration of 13x13 annular fuel assembly

Table 1. Fuel and assembly design parameters

Design parameters	Values
Fuel pin pitch (cm)	1.642
Assembly pitch (cm)	21.504
Fuel pellet inner/outer diameters (cm)	0.901/1.436
UO_2 pellet density (g/cm^3)	10.412
TRUO2 density in FCM kernel (g/cm^3)	10.412
Matrix material of FCM fuel	SiC
Inner/outer diameters for inside cladding (cm)	0.82/0.90
Inner/outer diameters for outside cladding (cm)	1.447/1.527
Burnable poison material	Gd_2O_3
UO_2 enrichment in burnable poison rod	0.711
Cladding and guide tube material	FeCrAl
Guide tube inner and outer diameters (cm)	1.447/1.527

In the annular FCM fuel rods, the spherical TRISO fuel particles are randomly distributed in SiC matrix. The kernel of $TRUO_2$ having 800µm diameter is subsequently surrounded by buffer, IPyC, SiC, and OPyC layers. The thicknesses of the buffer layers and density of the kernel were determined through the discussion on the fabrication aspects with ORNL [5]. The composition of TRU in the TRISO fuel particle kernel is the same as that of PWR spent fuel having 40MWD/kg burnup and 10 years cooling time. The height of length of the fuel rod is 200cm, which is the same as SMART core fuel [6]. We considered 20 cm long bottom and top cutbacks having no burnable poison for BP rods in order to reduce the axial power peaking.

2.2. Fuel Assembly Calculation Results

In this work, eight fuel assemblies were designed and they are denoted as B0, B2, B3, E2, I2, K3, M3, N3 depending on the numbers of BP rods, Gd_2O_3 contents in BP rods, PFs of FCM fuels, and uranium enrichments. The uranium enrichment and PF are constrained within 4.95wt% and 40%, respectively. Table 2 summarizes the specifications of these fuel assemblies. The B type assemblies have the highest uranium enrichment (i.e., 4.95wt%) and highest PF values of 40% and 35% for high and low PF FCM annular fuel rods, respectively. The B0 type one has no BP rods while the B2 and B3 type ones have 5 wt% and 7 wt% Gd_2O_3 contents, respectively. The E2 type one has 3.5 wt% uranium enrichment and the same PF values with the B type ones. The I2 and K3 type ones have 3.0 wt% uranium enrichment in UO2 annular fuel rods and, 35 and 30 % PF values. The M3 and N3 type ones also have the same PF values but low uranium enrichments of 2.5 and 2.0 wt%, respectively. It is noted that K3, M3, and N3 type ones have high Gd_2O_3 content of 8 wt%.

Table 2. Specification of FA design parameters

FA Type	Uranium Enrich. (wt%)	No. of BP rod	TRISO P/F	Gd_2O_3 (wt%)
B0	4.95	NA	40 / 35	NA
B2	4.95	12	40 / 35	5
B3	4.95	12	40 / 35	7
E2	3.50	12	40 / 35	5
I2	3.00	12	35 / 30	5
K3	3.00	12	35 / 30	8
M3	2.50	12	35 / 30	8
N3	2.00	12	35 / 30	8

Fig. 2 shows the evolutions of infinite multiplication factors (k_{inf}) for the fuel assemblies used in the core design. The depletion calculations for FAs were performed using the DeCART-2D code and 47 group cross section library [7]. The B0 type assembly shows the highest k_{inf} because it has no BP and use the highest enrichment of 4.95 wt%. The other fuel assemblies have relatively flat change of the excess reactivity due to the use of BP rods. Even if the MTC and FTC values are shown here, they are estimated to be all negative over the considered time span.

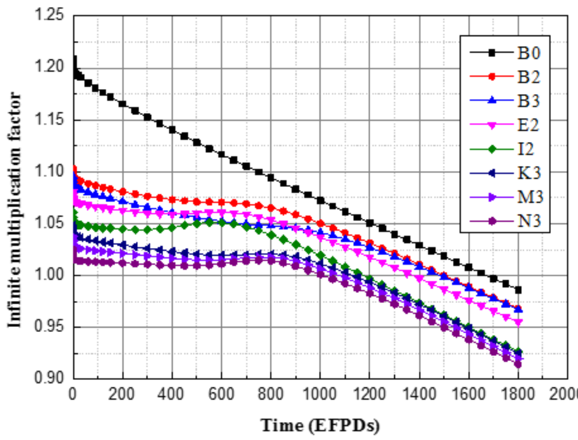


Fig. 2. Evolutions of k_{inf} for the different FAs

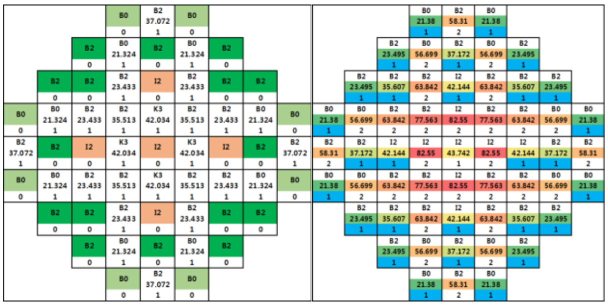
2.3. Core Designs and Results

The core power rates 379.5MWt which is higher by 15% than its original thermal output. The core is comprised of 57 fuel assemblies. The active core is 200 cm tall and the average linear heat generation rate is 203 W/cm which is much higher than the one of the SMART cores. We analyzed the neutronic characteristics of the core using the MASTER code [8]. Table 3 summarizes the core design parameters and the main design limits. For example, the target cycle length is 540 EFPDs which corresponds to ~ 22month cycle with 80% capacity factor.

Table 3. Core design parameters and design limits

Design parameter	Values
Core power (MWt)	379.5 (115%)
Number of assemblies	57
Active core height (cm)	200
Average Linear power density (W/cm)	203
Target cycle length (EFPD)	540
Maximum CBC (ppm)	< 2000
Axial Offset	± 0.15
3D peaking factor (F_q)	2.5
2D peaking factor (F_r)	1.6
Shutdown margin (pcm)	> 5000

Fig. 3 shows the loading patterns of the equilibrium cycle. The loading pattern is fixed to a single pattern after 4 cycle. We adopted a two-batch scheme which discharges 29 FAs having high burnup at the end of cycle (EOC) for all the cycles. The fresh fuel assemblies denoted with dark (B2 type FA) and light green (B0 type FA) colors are loaded in outer core region but some of fresh assemblies denoted with orange color (I2 type FA) are also in the inner core. The once burnt fuel assemblies at BOC are denoted with white color. The numbers given below fuel assembly ID means the accumulated burnup. The discharge burnup of the fuel assemblies ranges from 57 to 82.6 MWD/kg.



(a) BOC (b) EOC

Fig. 3. Loading patterns of equilibrium cycle

Table 4 summarizes the results of the reload cores from 1st cycle to 5th cycle. The evolutions of CBC (Critical Boron Concentration) are compared in Fig. 4. The cycle length as the cycle proceeds converges to ~554 EFPDs and all the cycles have similar cycle length of 550~554 EFPDs. The first cycle has the smallest CBC value of 737 ppm and the other cycles have similar values of 1665~1794 ppm. It is noted in Fig. 4 that CBC almost linearly decreases as time for all the cycles except the first cycle.

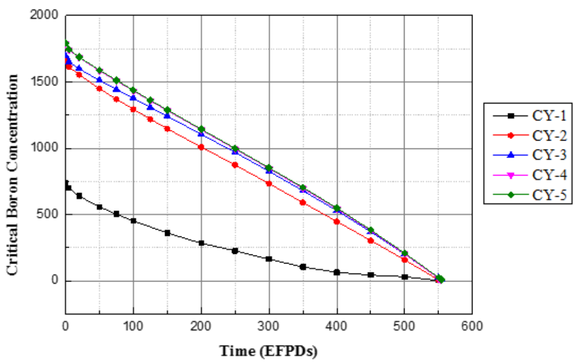


Fig. 4. Comparison of the CBC evolutions

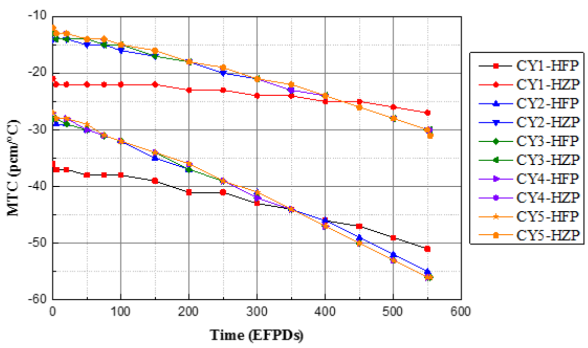


Fig. 5. Comparison of the MTC evolution

All the reload cycle cores have very narrow ranges of AO (Axial Offset) and those are negative except for the first cycle. The 3D power peaking factor (F_q) and radial peaking factor (F_r) are within the design limit. Fig. 5 shows the evolutions of moderator temperature coefficient (MTC) both at HFP and HZP. The MTC are negative over all the cycles both under HFP and HZP. As shown in Fig. 6, A detailed analysis of the fuel assembly at 5th cycle showed that the highest pin burnup for UO_2 and FCM annular fuel rods are 31MWD/kg and 327 MWD/kg, respectively. The typical burnup limit of the UO_2 pin is 60 MWD/kg and so the UO_2 annular fuel burnup is sufficiently lower than the typical burnup limit. Also, high burnup of FCM pin is not a problem due to the superb irradiation performance of the FCM fuel.

0	30.4969	27.3644	327.2705	287.5758	253.9721	249.6839	Burn up
0	1.0165	0.9879	0.9718	0.9569	1.0278	1.0121	Pin power
	28.7699	27.1949	16.8262	323.2401	266.5015	253.0294	
	0.9755	0.9704	0.8391	1.0037	1.0584	1.0225	
		27.2841	28.0815	0	301.1174	256.4032	
		0.9765	1.0583	0	0.9755	1.0333	
			26.9961	327.6947	266.5832	252.496	
			1.0678	1.0002	1.0587	1.0209	
				14.6124	248.9298	247.7786	
				0.8536	1.0188	1.0055	
					240.999	247.5041	
					0.9882	1.0035	
						256.1023	
						1.0276	

UO2 annular fuel FCM1 annular fuel
Burnable poison rod FCM2 annular fuel

Fig. 6. Pin burnup and power of I2 FA at EOC

Next, we analyzed the TRU mass change of discharge fuel assemblies. As shown in Table 5, The B0 type assemblies have its average discharge burnup of 56.7MWD/kg, its net TRU consumption rate of 12.8% (3.86kg). The B2 type fuel assemblies consists of three different types. The first group of B2 type fuel assemblies is comprised of 4 assemblies and they have 14.08 % (2.05kg) net TRU consumption rate while the second and third groups of B2 type ones have net TRU consumption rates of 15.45% (4.51kg) and 18.87 % (2.75kg), respectively. The I2 type fuel assemblies consists of two different types and they have net TRU consumption rates of 11.99% (0.38kg) and 22.93% (2.91kg), respectively. It is noted that the FCM annular fuel rods have very high TRU consumption rate ranging from 15.26% to 27.99% while the UO_2 annular fuel rods produces TRU but the TRU consumption by FCM annular fuel rods are significantly higher than the TRU production by UO_2 annular fuel rods. The net TRU consumption rate over all the discharge fuel assemblies is 15.79% which corresponds to 16.48kg.

Table 4. Comparison of the performances of the reload cores (add the AO range/MTC range)

	Cycle 1	**Cycle 2**	**Cycle 3**	**Cycle 4**	**Cycle 5**
Cycle length (EFPDs)	550.0	550.0	553.7	552.5	554.0
Maximum CBC (ppm)	737	1665	1697	1790	1794
Maximum Fq	2.01	1.86	1.90	1.96	1.96
Maximum Fr	1.56	1.56	1.54	1.59	1.59
Average discharge burnup (MWD/kg)	39.15	63.42	64.60	64.94	64.89
Shutdown margin (%Δρ) BOC/EOC	5392 / 6594	5716 / 6594	5625 / 6113	5706 / 6116	5701 / 6142

Table 5. Comparison of TRU consumption of discharged fuel assemblies

FA Type	Average Burnup (MWD/kg)	Pin Type	Charge (kg)	Discharge (kg)	Consume (kg)	Pin Average BU (MWD/kg)	Consumption Rate (%)
B0	56.70 (*8)	UO_2	0.00	0.86	- 0.86	20.5	-
		FCM	30.12	25.40	+ 4.71	153.2	15.65
		Total	30.12	26.26	+3.86	56.7	12.80
B2	58.31 (*4)	UO_2	0.00	0.52	- 0.52	23.1	-
		FCM	14.59	12.01	+ 2.57	172.6	17.64
		Total	14.59	12.53	+2.05	58.31	14.08
	63.84 (*8)	UO_2	0.00	1.01	-1.01	25.3	-
		FCM	29.17	23.56	+5.62	188.5	19.26
		Total	29.17	24.66	+4.51	63.84	15.45
	77.56 (*4)	UO_2	0.00	0.64	- 0.64	30.8	-
		FCM	14.59	11.20	+ 3.39	227.9	23.23
		Total	14.59	11.8.	+2.75	77.56	18.87
I2	43.74 (*1)	UO_2	0.00	0.10	- 0.10	14.7	-
		FCM	3.17	2.69	+ 0.48	149.5	15.26
		Total	3.17	2.79	+0.38	43.74	11.99
	82.55 (*4)	UO_2	0.00	0.64	-0.64	28.0	-
		FCM	12.70	9.14	+ 3.55	279.0	27.99
		Total	12.70	9.79	+2.91	82.55	22.93

* Number of discharge fuel assemblies

4. Conclusions

In this work, we designed and analyzed a SMR core with 115% power uprating core using UO_2 and FCM annular fuel rods. In particular, The FeCrAl cladding was considered to reduce hydrogen production under accident and oxidation, and the FCM annular fuel rods were considered to achieve a considerably high net TRU consumption rate. The results of the design and analysis showed it was possible to design a SMR core with 115% uprating and a high net TRU consumption rate of 15.79% over a long cycle length of 550 EFPDs. The TRU mass analysis showed that for the discharged fuel assemblies, the UO_2 annular fuel rods produce 3.87kg TRU, while the FCM annular fuel rods consume 20.33kg TRU.

Acknowledgement

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