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Boron-Free Small Modular Reactor Design by McCARD Burnup Calculation with T/H Feedback

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Contents

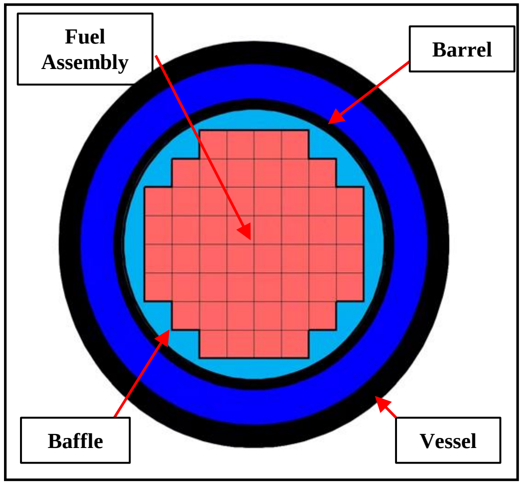
1. Introduction

- There are many studies of small modular reactor (SMR) for several advantages of power supply to remote locations, seawater desalination, etc.
- Many of SMRs are designed for a soluble boron-free operation which can reduce the size of the nuclear power plant and the corrosion issues caused by boric acid.
- In this study, SMR is designed for 4 to 5 years of cycle length at 200MW thermal power considering design parameters.
- Monte Carlo (MC) burnup calculation with or without thermal-hydraulic(T/H) feedback of SMR is performed by Monte Carlo code for advanced reactor design and analysis (McCARD).
- Based on the calculation result, analysis of the effective multiplication factor ($k_{eff.}$), radial and axial power distribution, and temperature distribution is conducted.

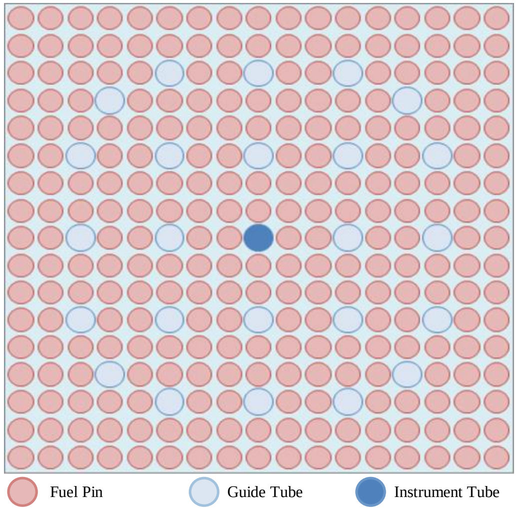
2.1. Core Design Parameters

- The design parameters of boron-free SMR

Parameters	Value
Reactor type	PWR
Thermal power	200 MW
System pressure	15 MPa
Linear power density	7.28 kW/m
Coolant & Moderator	Light water
Coolant Inlet Temp.	563.15 K
Coolant Outlet Temp.	598.15 K
Core Mass Flow	997.5 kg/s
Boron concentration	0 ppm
Number of FAs	52
Active core height	200 cm
FA type	Westinghouse 17×17
FA pitch	21.50 cm
Fuel rod pitch	1.26 cm
Fuel material	UO_2
Fuel enrichment	4.95 w/o
BA material	Solid Pyrex
Target cycle length	4 ~ 5 year
Max. excess reactivity	< 5000 pcm



[Core configuration]



[Fuel assembly configuration]

2.1. Core Design Parameters

- Core design consideration factor
  - Axial Offset(AO) : ± 0.4 [1] * The factor for the axial power distribution

    * $AO = (P_B - P_T)/(P_B + P_T)$

    * P_B = POWER OF THE BOTTOM HALF OF CORE

    * P_T = POWER OF THE TOP HALF OF CORE

  - Power Peaking factor (Fq) : 5.68 [2]

    * $MDNBR = (q''_{crit})/(q''_{max} \times f)$

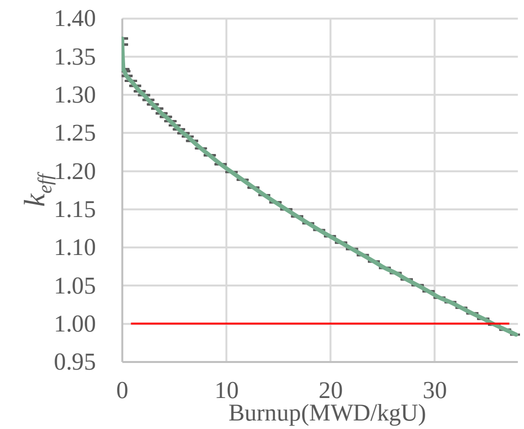
    * $Fq = q''_{max} / q''_{avg.} = (q''_{crit}) / (f \times MDNBR) / (q''_{avg.}) = 2579.0\ \mathrm{kW/m^2} / (1.05 \times 1.15 \times MDNBR) / (q''_{avg.})$

    $= 2135.8\ \mathrm{kW/m^2} / (MDNBR \times q''_{avg.})$

[1]	[2]	[3]	[4]	[5]	[6]
MDNBR	Themal Power (kWt)	Maximum Heat Flux	Heat transfer area (17×17, 9.5mm rod)	Average Heat Flux	Power peaking factor (Fq)
		q''_{max} = 2135.8 / [1]	$\pi \times D \times H \times 240 \times 52$	q''_{avg} = [2] / [4]	Fq = [3] / [5]
1.4	200000	1525.56	774.93	268.48	5.68
* D(Fuel pin diameter) : 9.5 mm / H(Active core height) : 2 m / 240 : Number of Fuel pins / 52 : Number of FAs					

[1] Justin RM, Feasibility study on a soluble boron-free small modular reactor, Master thesis, Oregon State University, 2013.
[2] KEPCO E&F, Development of Boron Free Operational Reactor System Design and Material Selection Technology, 2018.

2.1. Core Design Parameters

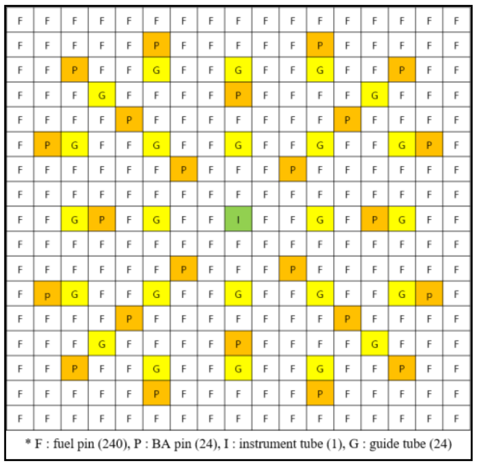


[$k_{eff.}$ changes according to burnup]

- Reactivity Control
  - Maximum burnup : 35.62MWD/kgU
  - Effective Full Power Day (EFPD) : More than 5 years
  - $k_{eff.}$ at the beginning of cycle (BOC) : 1.36695 ± 0.00038
  - Maximum excess reactivity : 26,844 ± 20pcm

  ➔ Need a lot of burnable absorber (BA) for reactivity control

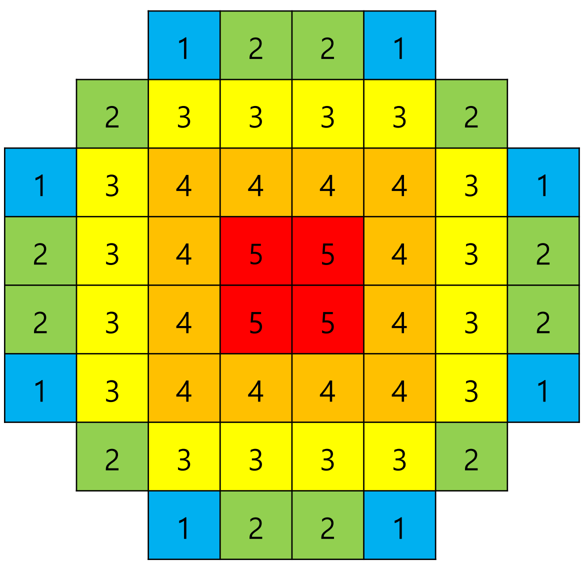
- Fuel pin arrangement in FA
  - SMR is designed using FA loaded with Solid Pyrex
  - 24 BAs are loaded instead of fuel pins
  - The arrangement is decided according to the previous study
  - The neutron absorption capacity of BA is proportional to the weight percent (w/o) of B_2O_3 contained in Pyrex



[Fuel assembly configuration]

2.2. Loading Pattern of SMR

- The core is composed of a combination of 5 types of FA with different concentrations of B_2O_3 in Pyrex.
- FAs using a high concentration of B_2O_3 are placed at the center of the core and FAs using a low concentration of B_2O_3 are placed on the periphery to make radial power distribution smooth.



* B_2O_3 (w/o) in Pyrex : 5 / 10 / 25 / 35 / 40

[Loading pattern of SMR]

FA Type	B_2O_3 w/o in Pyrex	Number of fuel pins	Number of BA pins	Number of FA
1	5	240	24	8
2	10	240	24	12
3	25	240	24	16
4	35	240	24	12
5	40	240	24	4
Total		12480	1248	52

[The information of FA types by the concentration of BA]

2.2. Loading Pattern of SMR

- In boron-free SMR, the reactivity change is controlled by using the control rods.
- There are forty Control Element Assemblies (CEAs) in the core [3] .
- The location of CEA is determined to control reactivity change caused by change in core state.

			SB	RB			
	SB	SB	RB	SB	RB	SB	
	RB		SB	RB	SB	SB	
RB	SB	RB	RB	SB		RB	SB
SB	RB		SB	RB	RB	SB	RB
	SB	SB	RB	SB		RB	
	SB	RB	SB	RB	SB	SB	
			RB	SB			

* RB: Regulating Bank (18), SB: Shutdown Bank (22)

[Location of the CEAs]

[3] Il Hwan Kim et al., Development of BANDI-60S for a Floating Nuclear Power Plant, KNS Meeting, Goyang, Korea, October 24-25, 2019

3. McCARD Burnup Calculation with T/H feedback

- McCARD has a pin-by-pin T/H feedback capability which considers only simple problems including coolant, gap, cladding, and fuel pellet.
- A radial temperature profile and an axial temperature profile in a fuel pin cell can be calculated by heat transfer equation and energy conservation equation with the 1-D T/H model.
- Average Temperature Calculation equation :

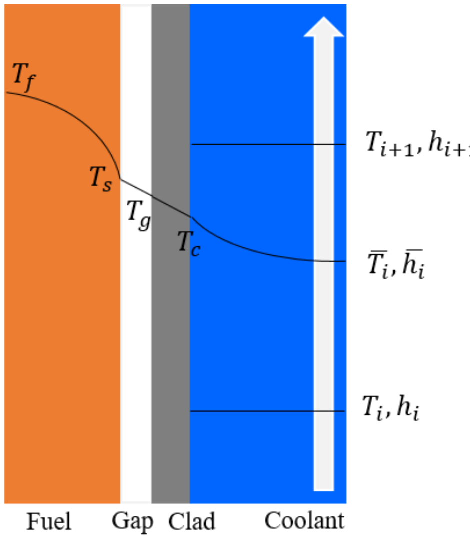
$$\overline{T_i} = f(\overline{h_i}),\quad \overline{h_i} = \frac{h_i + h_{i+1}}{2},\quad \overline{T_c} = \frac{T_c + T_g}{2},\quad \overline{T_g} = \frac{T_g + T_s}{2},$$

$$\overline{T_f} = 0.5T_f + 0.5T_s$$

- The heat transfer coefficient and thermal conductivity [5] :

$$h_g\left[\frac{W}{m^2K}\right] = 1000,\quad h_w\left[\frac{W}{m^2K}\right] = \sum_{n=0}^{3} a_n T^n$$

$$k_{f(UO_2)}\left[\frac{W}{mK}\right] = 1.05 + \frac{2150}{T - 73.15}\quad k_{c(Zr_4)}\left[\frac{W}{mK}\right] = 7.51 + 2.09 \times 10^{-2}T - 1.45 \times 10^{-5}T^2 + 7.67 \times 10^{-9}T^3$$



[1D T/H model in McCARD]

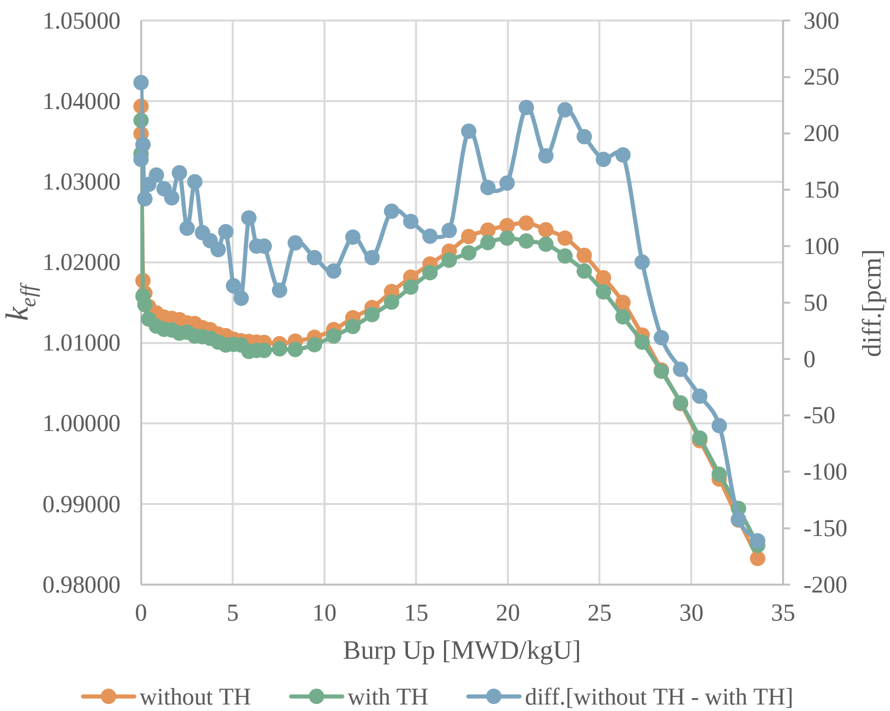
[5] Finnemann, H. and Galati, A.: "NEACRP 3-D LWR Core Transient Benchmark. Final Specifications", 1992.

4.1. The effective multiplication factor

- Calculation option

구분	Nuclear Data	Histories / Active cycles / Inactive cycles	Coolant Temperature	Fuel Temperature
without T/H	ENDF/ B-VII.1	100,000/300/150	580.65K (Average)	700K
with T/H		100,000/300/150	563.15 (Inlet) / 598.15K (Outlet)	-

- Results



[$k_{eff.}$ vs. burnup behavior with or without T/H feedback]

Division		Without T/H	With T/H	Diff. [pcm]
Burnup [MWD/kgU]	EFPD [day]	$k_{eff.}$ (SD)	$k_{eff.}$ (SD)	
0	0 (BOC)	1.03939 (0.00015)	1.03762 (0.00013)	177
16.82	1000 (MOC1)	1.02140 (0.00013)	1.02026 (0.00012)	114
23.12	1375 (MOC2)	1.02301 (0.00012)	1.02080 (0.00012)	221
29.43	1750 (EOC)	1.00248 (0.00012)	1.00257 (0.00012)	-9

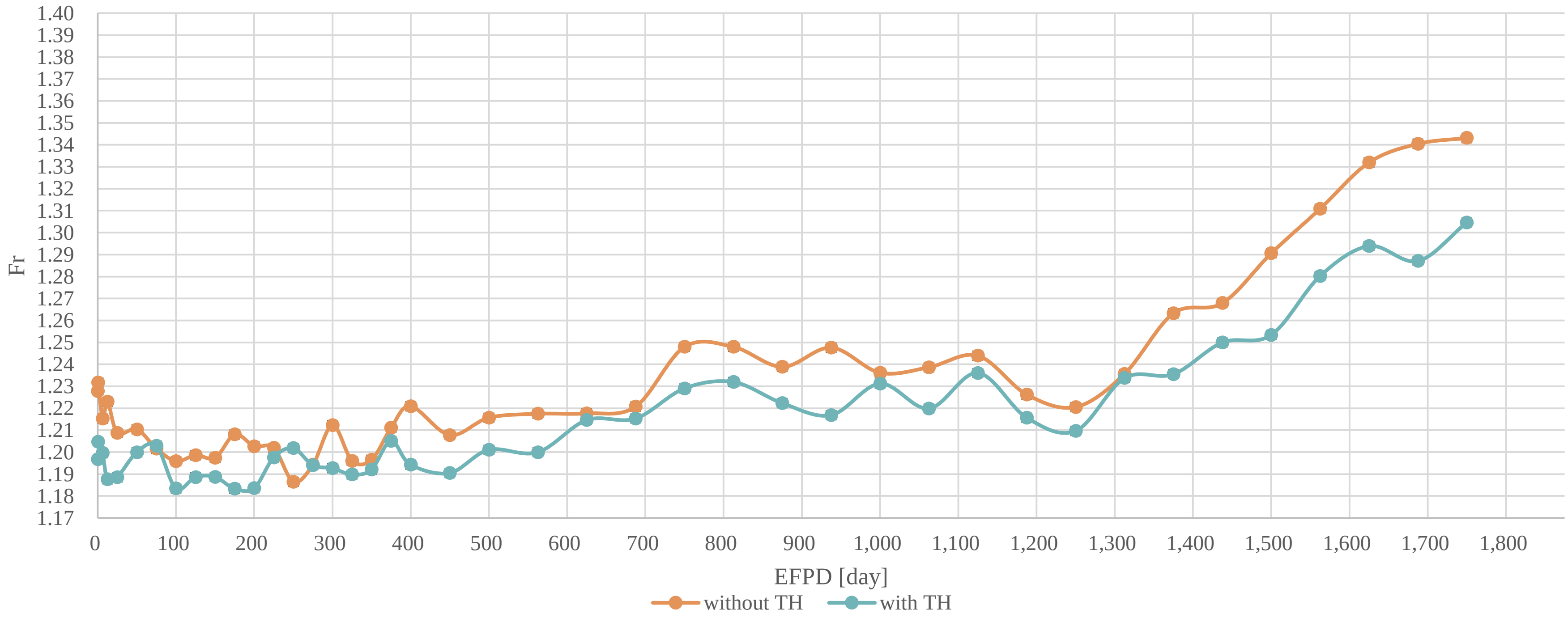
[The difference of $k_{eff.}$ at BOC, MOC, and EOC]

✓ Cycle length
- without T/H : 4.8864 ± 0.0003
- with T/H : 4.8978 ± 0.0002

✓ Maximum excess reactivity : less than 5,000pcm

4.2. Power distribution

- Radial Power Peaking Factor (Fr)



- The Fr value increases and decreases repeatedly and increases rapidly from around 1300 EFPD.
- At 1300 EFPD, where the burnup of BAs decreases the rapid burn of uranium causes the increase in Fr values.

4.2. Power distribution

- Radial Power Distribution

Division		EFPD [day]			
		0(BOC)	1000(MOC1)	1375(MOC2)	1750 (EOC)
Fr	without T/H(SD)	1.222(0.001)	1.229(0.001)	1.249(0.001)	1.334(0.001)
	with T/H(SD)	1.201(0.001)	1.211(0.001)	1.218(0.001)	1.297(0.001)
RMS difference		1.84%	0.94%	2.24%	1.84%
Maximum Relative difference		2.81%	1.74%	3.35%	2.86%

Without T/H(0 day)			
1.205	**1.222**	1.192	0.876
1.210	1.147	1.015	0.693
1.182	1.010	0.686	
0.871	0.692		
Max SD 0.0010		Fr 1.222	

With T/H(0 day)			
1.183	1.188	1.173	0.885
1.201	1.134	1.019	0.712
1.180	1.021	0.702	
0.892	0.712		
Max SD 0.0010		Fr 1.201	

Without T/H(1000 day)			
1.018	**1.122**	1.229	0.948
1.118	1.096	1.055	0.732
1.219	1.049	0.750	
0.939	0.726		
Max SD 0.0010		Fr 1.229	

With T/H(1000 day)			
1.023	1.114	1.211	0.944
1.113	1.095	1.055	0.736
1.208	1.058	0.763	
0.941	0.739		
Max SD 0.0010		Fr 1.211	

Without T/H(1375 day)			
1.221	**1.246**	1.179	0.824
1.249	1.187	1.042	0.653
1.175	1.037	0.724	
0.817	0.646		
Max SD 0.0010		Fr 1.249	

With T/H(1375 day)			
1.185	1.216	1.176	0.845
1.218	1.168	1.051	0.674
1.171	1.047	0.743	
0.838	0.668		
Max SD 0.0010		Fr 1.218	

Without T/H(1750 day)			
1.334	1.282	1.138	0.784
1.282	1.213	1.028	0.630
1.140	1.031	0.720	
0.786	0.632		
Max SD 0.0010		Fr 1.334	

With T/H(1750 day)			
1.297	1.260	1.143	0.806
1.258	1.197	1.035	0.649
1.141	1.035	0.731	
0.802	0.646		
Max SD 0.0010		Fr 1.297	

1.205	1.222	1.192	0.876
1.183	1.188	1.173	0.885
1.93%	2.81%	1.60%	-1.06%
1.210	1.147	1.015	0.693
1.201	1.134	1.019	0.712
0.76%	1.16%	-0.42%	-2.60%
1.182	1.010	0.686	
1.180	1.021	0.702	
0.19%	-1.00%	-2.30%	
0.871	0.692		
0.892	0.712		
-2.43%	-2.73%		

		Fr
	Without TH	1.222
	With TH	1.201
Without TH	Max. SD = 0.001	
With TH	RMS diff.	MAX diff.
Rel. Diff.	1.84%	2.81%

[0day]

1.018	1.122	1.229	0.948
1.023	1.114	1.211	0.944
-0.47%	0.76%	1.56%	0.45%
1.118	1.096	1.055	0.732
1.113	1.095	1.055	0.736
0.38%	0.04%	-0.05%	-0.64%
1.219	1.049	0.750	
1.208	1.058	0.763	
0.87%	-0.87%	-1.74%	
0.939	0.726		
0.941	0.739		
-0.17%	-1.72%		

		Fr
	Without TH	1.229
	With TH	1.211
Without TH	Max. SD = 0.001	
With TH	RMS diff.	MAX diff.
Rel. Diff.	0.94%	1.74%

[1000day]

1.221	1.246	1.179	0.824
1.185	1.216	1.176	0.845
3.05%	2.49%	0.25%	-2.46%
1.249	1.187	1.042	0.653
1.218	1.168	1.051	0.674
2.51%	1.57%	-0.88%	-3.06%
1.175	1.037	0.724	
1.171	1.047	0.743	
0.39%	-0.96%	-2.56%	
0.817	0.646		
0.838	0.668		
-2.47%	-3.35%		

		Fr
	Without TH	1.249
	With TH	1.218
Without TH	Max. SD = 0.001	
With TH	RMS diff.	MAX diff.
Rel. Diff.	2.24%	3.35%

[1375day]

1.334	1.282	1.138	0.784
1.297	1.260	1.143	0.806
2.86%	1.72%	-0.44%	-2.65%
1.282	1.213	1.028	0.630
1.258	1.197	1.035	0.649
1.94%	1.32%	-0.68%	-2.85%
1.140	1.031	0.720	
1.141	1.035	0.731	
-0.09%	-0.43%	-1.50%	
0.786	0.632		
0.802	0.646		
-2.07%	-2.17%		

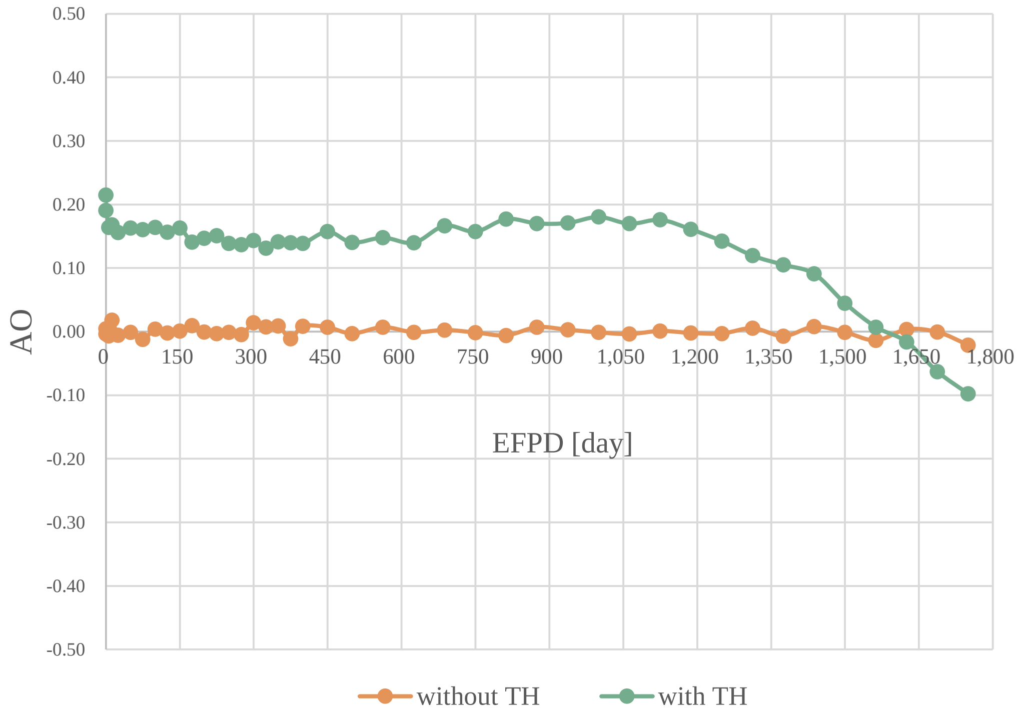
		Fr
	Without TH	1.334
	With TH	1.297
Without TH	Max. SD = 0.001	
With TH	RMS diff.	MAX diff.
Rel. Diff.	1.84%	2.86%

[1750day]

- There is a shit in power peak from the inner core region to the outer core region from BOC to MOC, and after MOC, a power peak moves vice versa.

4.2. Power distribution

- Axial Offset (AO)

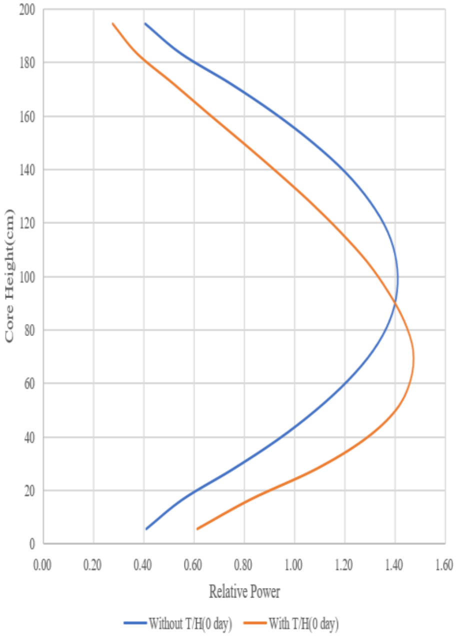


Division		without T/H	with T/H
Burnup [MWD/kgU]	EFPD [day]	AO (SD)	AO (SD)
0	0 (BOC)	0.0044 (0.0011)	0.2149 (0.0011)
16.82	1000 (MOC1)	-0.0013 (0.0011)	0.1806 (0.0011)
23.12	1375 (MOC2)	-0.0071 (0.0011)	0.1052 (0.0011)
29.43	1750 (EOC)	-0.0210 (0.0011)	-0.0979 (0.0011)

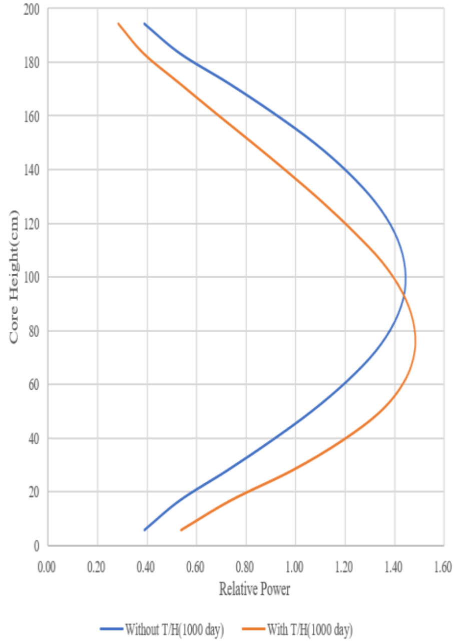
- In the case of using T/H feedback, it can be seen that the axial power distribution is biased toward the lower part of the core.
- The axial power peak moves to the upper part of the core toward at EOC.

4.2. Power distribution

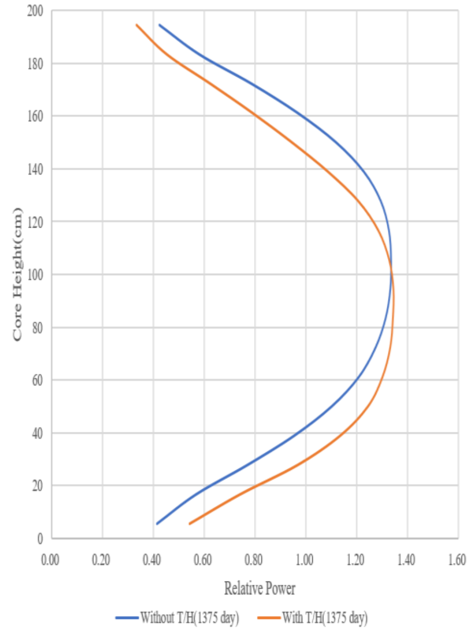
- Axial Power Distribution



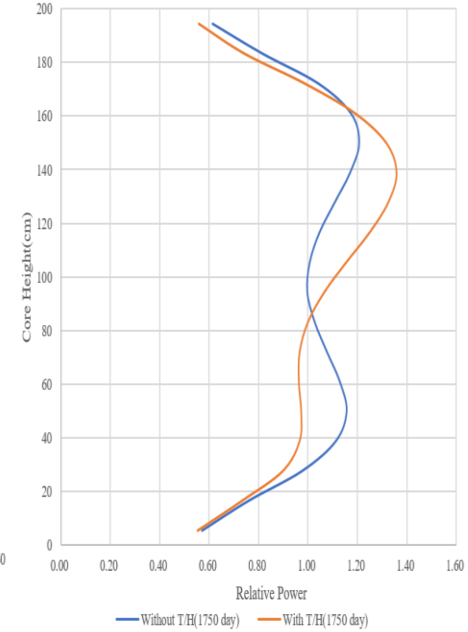
[0day]



[1000day]



[1375day]

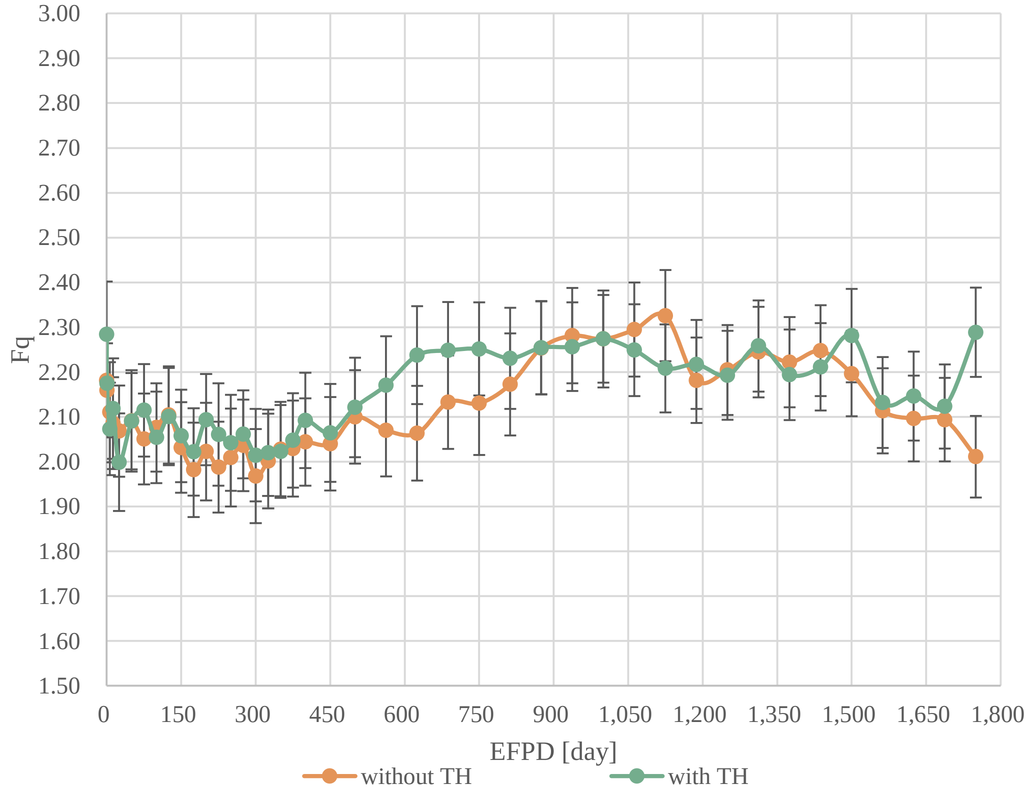


[1750day]

- The graphs maintain the cosine shape of axial power distribution for a longer time than the conventional PWR.
- It shows the axial power distribution in the center of the core are flattened at 1375 days, when the burnup of boron in BAs decreases.

4.2. Power distribution

- Power Peaking Factor (Fq)



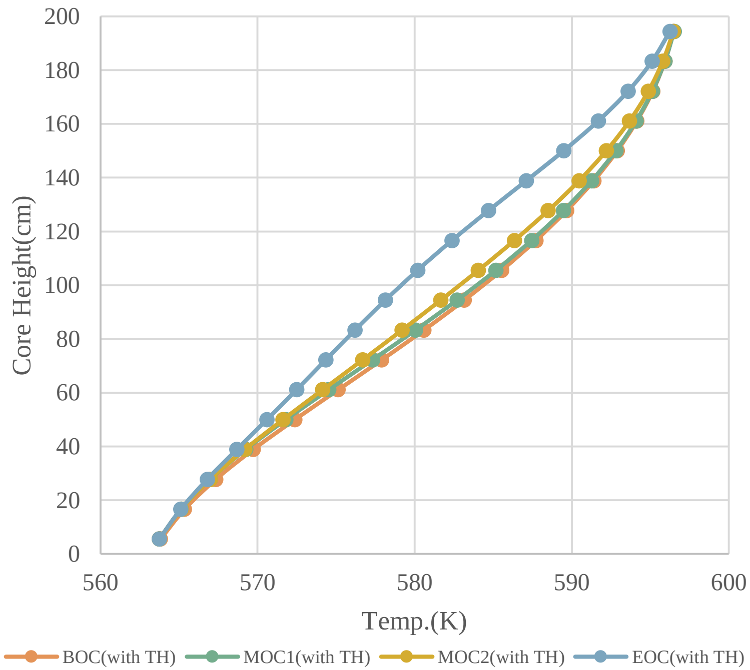
Division		without T/H	with T/H
Burnup [MWD/kgU]	EFPD [day]	AO (SD)	AO (SD)
0	0 (BOC)	2.1817 (0.1031)	2.2843 (0.1178)
16.82	1000 (MOC1)	2.2738 (0.1082)	2.2743 (0.0978)
23.12	1375 (MOC2)	2.2223 (0.1007)	2.1941 (0.1010)
29.43	1750 (EOC)	2.0113 (0.0910)	2.2886 (0.0997)

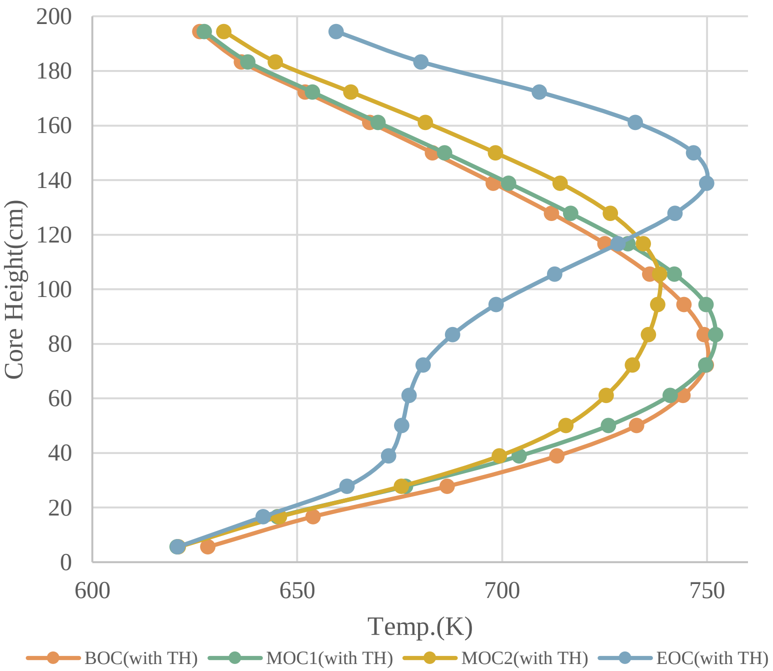
- Maximum of the Fq value : without TH 2.3259 ± 0.1153 / with TH 2.2886 ± 0.1178
- Maximum linear power density : 16.67 ± 0.73 kW/m (Average linear power density : 7.28 kW/m)

  * Limit of linear power density [kW/m] : 41.38 (MDNBR = 1.4, Fq = 5.68)

4.3. Temperature profile

- The axial coolant temperature profile and fuel temperature profile





- The average fuel temperature and the axial fuel temperature profile

EFPD [day]	0 (BOC)		1000 (MOC1)		1375 (MOC2)		1750 (EOC)	
	Temp.[K]	SD	Temp.[K]	SD	Temp.[K]	SD	Temp.[K]	SD
Avg. Coolant Temp.	582.50	0.25	582.13	0.25	581.75	0.24	580.02	0.25
Avg. Fuel Temp.	696.61	1.21	696.17	1.25	695.62	1.22	693.25	1.30

  - The average fuel temperature of SMR is about 150 K lower than that of conventional PWR.

4.3. Temperature profile

- The radial coolant temperature profile and fuel temperature profile

EFPD [day]

0 (BOC)

Radial Power distribution

1.183	1.188	1.173	0.885
1.201	1.134	1.019	0.712
1.180	1.021	0.702	
0.892	0.712	Max SD = 0.001	

Avg. Coolant Temp.

585.8	585.9	585.6	580.4
586.1	585.0	582.8	577.2
585.8	583.0	577.2	
580.5	577.3	Max SD = 0.12	

Fuel Avg. Temp.

721.9	724.1	721.8	679.7
724.6	716.0	699.1	655.4
722.6	699.6	654.7	
680.5	656.0	Max SD = 0.45	

1000 (MOC1)

Radial Power distribution

1.023	1.114	**1.211**	0.944
1.113	1.095	1.055	0.736
1.208	1.058	0.763	
0.941	0.739	Max SD = 0.001	

Avg. Coolant Temp.

582.6	584.3	**586.0**	581.2
584.3	584.0	583.3	577.5
585.9	583.3	578.0	
581.1	577.5	Max SD = 0.12	

Fuel Avg. Temp.

698.5	711.9	726.8	687.0
713.1	709.6	704.4	658.5
727.1	704.7	662.8	
687.3	658.7	Max SD = 0.45	

1375 (MOC2)

Radial Power distribution

1.185	1.216	1.176	0.845
1.218	1.168	1.051	0.674
1.171	1.047	0.743	
0.838	0.668	Max SD = 0.001	

Avg. Coolant Temp.

585.2	585.7	584.7	578.8
585.7	584.8	582.6	575.9
584.6	582.5	577.2	
578.6	578.0	Max SD = 0.12	

Fuel Avg. Temp.

724.5	727.6	719.3	671.1
728.8	720.7	701.1	647.8
720.9	701.6	658.1	
672.6	648.7	Max SD = 0.45	

1750 (EOC)

Radial Power distribution

1.297	1.260	1.143	0.806
1.258	1.197	1.035	0.649
1.141	1.035	0.731	
0.802	0.646	Max SD = 0.001	

Avg. Coolant Temp.

585.1	584.3	582.1	576.8
584.2	583.3	580.6	574.4
582.0	580.5	575.8	
576.7	574.3	Max SD = 0.12	

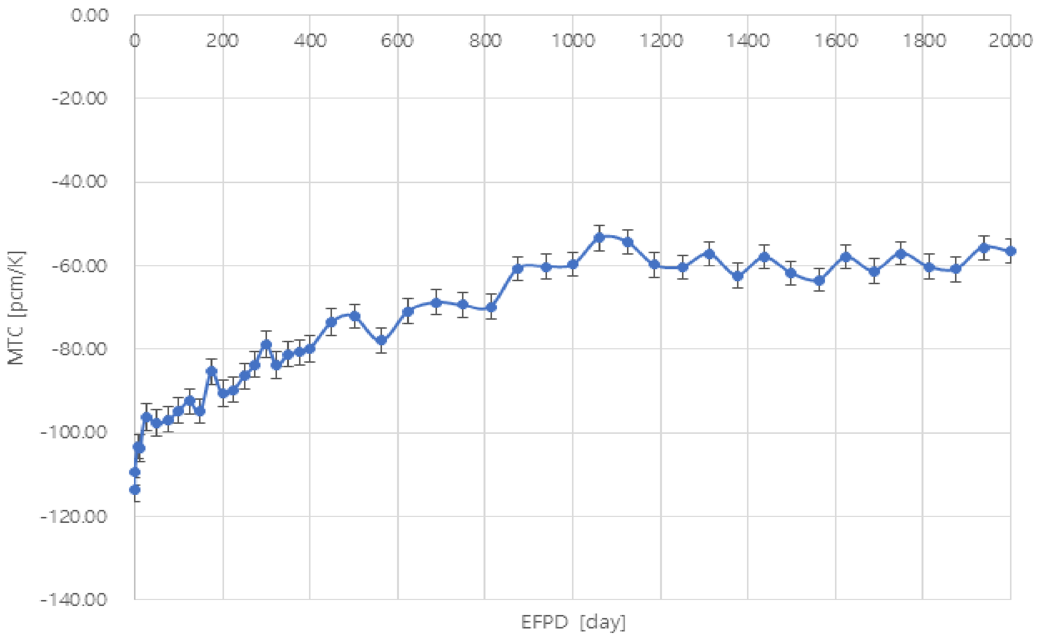
Fuel Avg. Temp.

736.5	730.1	712.5	665.0
730.7	720.5	697.5	644.3
712.4	697.4	656.0	
664.9	644.5	Max SD = 0.45	

4.4. Temperature Coefficient

- The moderator temperature coefficient (MTC)

* Average temperature of moderator used in calculation : 580.65K, 573.15K (ΔT : 7.5K)



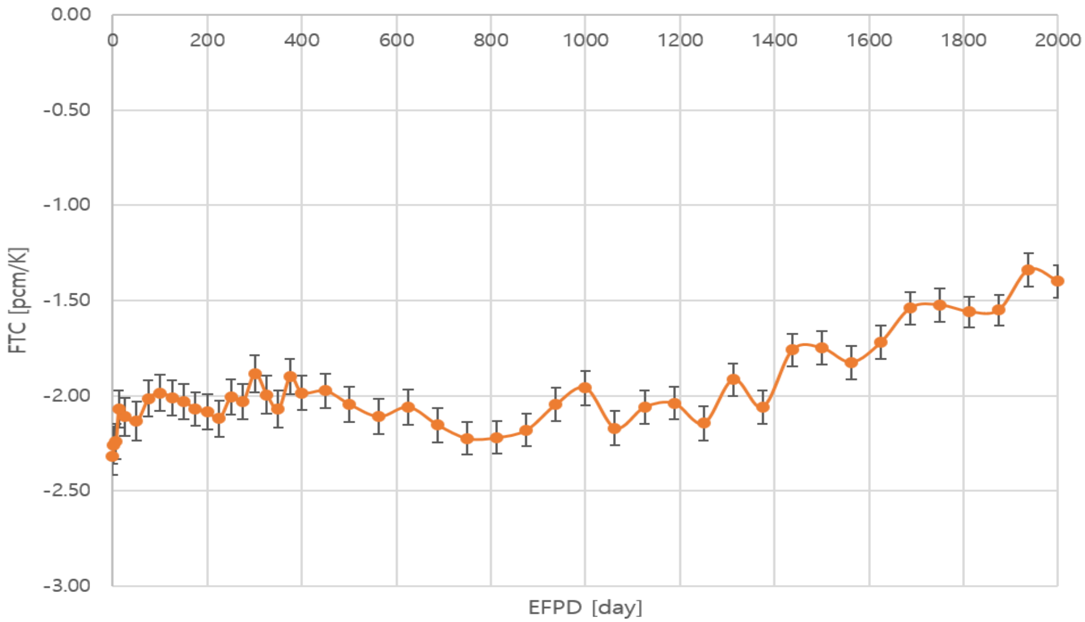
Burnup [MWD/kgU]	EFPD [day]	MTC [pcm/K]	SD [pcm/K]
0.0000	0.00	-113.60	2.88
16.8157	1000.00	-59.73	2.85
23.1216	1375.00	-62.27	2.85
29.4275	1750.00	-56.93	2.75

- MTC of boron-free SMR has a larger negative value than that of a commercial PWR.
- It shows the largest negative value at -113.60 ± 2.88 pcm/K at BOC

4.4. Temperature Coefficient

- The fuel temperature coefficient (FTC)

* Average temperature of moderator used in calculation : 900K, 700K (ΔT : 200K)



Burnup [MWD/kgU]	EFPD [day]	MTC	SD
		[pcm/K]	
0.0000	0.00	-2.32	0.10
16.8157	1000.00	-1.96	0.09
23.1216	1375.00	-2.06	0.09
29.4275	1750.00	-1.53	0.09

- FTC of boron-free SMR has a value similar to that of a commercial PWR.
- It shows the largest negative value at -2.32 ± 0.10 pcm/K at BOC

5. Conclusion & Future work

- This study presents the design of boron-free SMR by McCARD burnup calculation with T/H feedback.
- The core is designed using 5 types of FAs with different concentrations of Pyrex BA satisfying the design parameters with 200MWt.

구 분	Without TH	With TH	Limit Value
Cycle length [year]	4.8864±0.0003	4.8978±0.0002	4~5 years
Maximum excess reactivity [pcm]	3790±14	3626±12	< 5,000pcm
Maximum Fr	1.3431±0.0020	1.3046±0.0019	-
Maximum Fq	2.3259±0.1153	2.3129±0.1185	< 5.68
Maximum linear power density [kW/m]	16.9429±0.8402	16.8482±0.8633	< 41.38kW/m
Maximum Axial Offset (AO)	-	0.2149 ±0.0011	-0.4<AO<+0.4
Average coolant temperature [K]	580.65	580.02±0.25 ~ 582.50±0.25	-
Average Fuel temperature [K]	700	693.25±1.30 ~ 696.61±1.21	-
MTC [pcm/K]	-113.60±2.88 ~ -53.33±3.07		-
FTC [pcm/K]	–2.32±0.10 ~ -1.13±0.08		-

- The average fuel temperature is about 150 K lower than that of conventional PWR.
- The cosine shape of the axial power distribution is maintained longer than that of PWR.

5. Conclusion & Future work

- The burnup calculation of the SMR will be performed under critical-state conditions using a control rod.
- The core characteristics will be calculated by the results of the burn-up calculation under critical-state conditions.

Thank you

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