A Monte Carlo-Diffusion Two-step Analysis of a Soluble-Boron-Free SMR Using Centrally-Shielded Burnable Absorber

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1. Introduction

Small modular reactors (SMRs), which are considered as ones of the Gen-VI reactor concepts, have gained significant international attention after Fukushima-Daiichi accident [1]. SMRs are required to be compact, simple, and less dependent of the active control components to improve reactor safety and performance [2]. To achieve these requirements, a soluble boron free (SBF) coolant system is favorable since the use of soluble boron (SB) for reactivity control complicates plant operation and maintenance. Moreover, a high boron concentration can result in positive moderator temperature coefficient at the beginning of cycle (BOC), which is unfavorable in term of reactor safety requirements [3]. Furthermore, due to boron-neutron absorption radioactive wastes are accumulated in the coolant system.

In light water reactors, there are three types of reactivity control methods: SB, burnable absorber (BA), and control rods (CRs). Without SB, the excess reactivity is mostly compensated by BA since the CR insertion can cause a massive axial power distortion and increase possibility of rod ejection accident. Therefore, an SBF system is only achievable with an effective BA design. To eliminate SB, a new BA concept, centrally-shielded burnable absorber (CSBA), was introduced and optimized in the center for autonomous small modular reactor research (CASMRR) [4, 5].

In this paper, an SBF SMR loaded with the CSBA has been designed and analyzed with both the Monte Carlo (MC) Serpent code and a two-step Serpent-diffusion nodal procedure [6-8]. In the two-step nodal analysis, the Monte Carlo Serpent code was used for the FA spatial homogenization and the COREDAX nodal diffusion code was used for 3D nodal calculation. In addition, thermal hydraulic (TH)-coupled neutronic calculation is also investigated using the 2-step Serpent-COREDAX procedure. Lastly, the local peaking factor, safety parameters, CR pattern and rod worth are investigated to ensure the reactor safety and performance.

2. The CSBA Concept and SBF SMR Core Design

2.1 Conceptual CSBA Design

In CSBA design, gadolinia (Gd_2O_3) is selected as the BA candidate for reactivity control due to its favorable neutronic and thermomechanical performances [8, 9]. Since gadolinia, a highly absorbing BA, is used in a thermal reactor, its depletion rate needs to be reduced to match the fuel depletion rate by enhancing self-shielding effect. Therefore, Gd_2O_3 is loaded into the central region of fuel pellet as shown in Fig. 1, which utilizes spatial self-shielding of fuel. In addition, to offer the highest self-shielding effect the single ball is used, since the spherical shape minimizes the exposed area per unit volume. Moreover, the neutronic flexibility can be obtained by varying the number of BAs from one ball to three balls. By this, the power peaking factor can be lowered with an optimal CSBA position-dependent loading scheme. Nevertheless, by loading gadolinia into the fuel region the fuel inventory in CSBA design will be slightly smaller than that in typical PWR one, a clear disadvantage of the CSBA design.

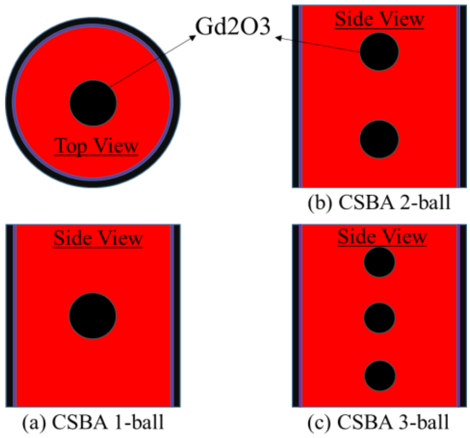

Fig. 1. Various design configurations of CSBA pellet

2.2 CSBA-loaded SMR Core Design

In CASMRR, a 450MWth SBF SMR, namely autonomous transportable on-demand reactor module (ATOM), has been investigated. The CSBA is loaded into the ATOM core with a single-batch fuel management. Table I shows the major design parameters of the ATOM core while its radial and axial layouts are presented in Figs. 2 and 3, respectively. The ATOM core consists of 69 17x17 PWR fuel assemblies and each fuel assembly (FA) is loaded with 264 CSBA fuel rods, 24 guide tubes and a central instrumentation tube. The enrichment of the U-235 is 4.95 w/o with 95.5% theoretical density of the fuel. The core-average power density is quite low, 25.99 W/gU, to enhance the reactor safety and thermal margin. An optimum height-to-diameter ratio, 0.993, is a result of 202 cm core equivalent diameter and 200 cm active height.

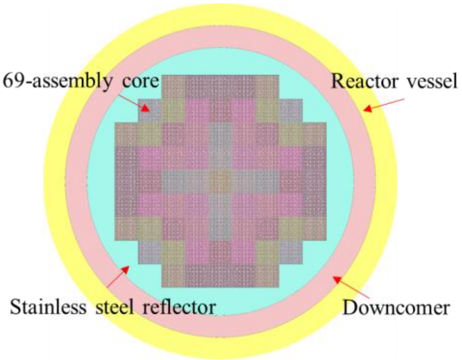

Fig. 2. SBF core radial layout

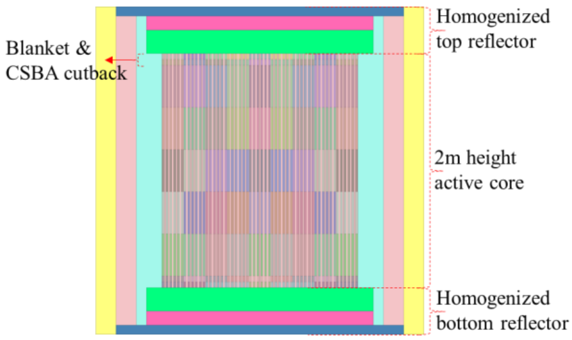

Fig. 3. SBF core axial layout

To improve the neutron economy, stainless steel reflectors are used instead of water-baffle ones. At the top and bottom active core 5cm axial fuel blankets are placed with 2.0 w/o UO_2 fuels to reduce axial neutron leakage. In addition, the core axial peaking factor can be lowered by applying 5 cm CSBA cutbacks. The axial core is divided into 5 axial layers for more accurate 3-D Serpent simulation. In the whole-core calculation, the uniform effective fuel temperature is 840K. In addition, the typical uniform coolant temperature, 575k, is used.

Table I: ATOM core major design parameter

Parameters	Target Value
Thermal power	450 MWth
Active height, eq. diameter	200 cm, 201.6 cm
Cycle length, fuel loading	> 3 years, single-batch
FA type, number of FA	17 x 17, 69
Fuel materials, enrichment	UO_2, 4.95 w/o

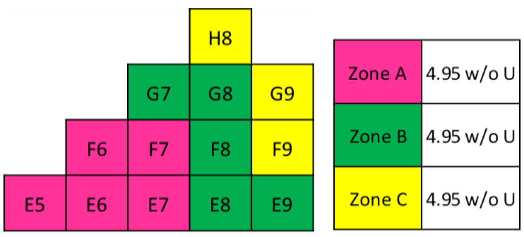

Fig. 4. CSBA loading scheme of one-eighth ATOM core

The single enrichment value of fuel, 4.95 w/o, is used uniformly. The core is radially divided into 3 zones, in which various quantities and sizes of CSBA balls are loaded to optimize the reactivity pattern, as shown in Fig. 4 and Table II. The big single CSBA ball is loaded into zone A to slow down fuel depletion rates here, consequently this reduce the power peaking factor. Less self-shielded designs, 2- and 3-ball CSBAs, are placed to zones B and C, respectively, as their powers are lower than that at zone A in general.

Table II: CSBA loading scheme in ATOM core

Parameters	Optimal CSBA loading		
	Zone A	Zone B	Zone C
CSBA design	1-ball	2-ball	3-ball
Ball radius	r = 1.69 mm	r = 1.26 mm	r = 0.70 mm
m_{Gd2O3}/m_{UO2}	0.0268	0.221	0.0055

3. Numerical Results and Discussion

3.1 Serpent Results.

The pin-wise burnup-dependent power distribution for a representative CSBA-loaded FA is shown in Fig. 5. In this analysis, the 1-ball FA is considered since this design is loaded into high power regions. It can be seen that the pin peaking factor is quite small, about 1.08, at different burnup conditions even though there is no fuel zoning near water holes. This demonstrates the promising feasibility of CSBA design in term of minimizing local peaking factor. The associated uncertainty of pin power is around 0.25%.

9	10	11	12	13	14	15	16	17	
								0.937 0.932 0.932	1
							0.913 0.915 0.913	0.926 0.925 0.921	2
						0.963 0.962 0.965	0.928 0.924 0.928	0.928 0.931 0.926	3
		0 GWd/tU 15 GWd/tU 30 GWd/tU			Water Hole	1.030 1.031 1.027	0.952 0.948 0.950	0.938 0.936 0.935	4
				1.043 1.047 1.047	1.078 1.082 1.077	1.056 1.057 1.057	0.980 0.979 0.978	0.949 0.949 0.952	5
			Water Hole	1.060 1.066 1.064	1.064 1.066 1.063	Water Hole	1.022 1.020 1.019	0.962 0.961 0.961	6
		1.010 1.008 1.013	1.055 1.052 1.053	1.014 1.012 1.014	1.011 1.011 1.012	1.040 1.041 1.039	0.986 0.984 0.986	0.960 0.960 0.960	7
	1.007 1.010 1.014	1.010 1.009 1.008	1.048 1.049 1.051	1.009 1.010 1.007	1.004 1.003 1.006	1.038 1.036 1.037	0.980 0.984 0.985	0.956 0.960 0.957	8
Water Hole	1.051 1.051 1.048	1.050 1.052 1.053	Water Hole	1.044 1.046 1.048	1.044 1.046 1.046	Water Hole	1.021 1.017 1.017	0.967 0.964 0.963	9

Fig. 5. Local peaking factor for 1-ball FA design

In Fig. 6 and Table III, the performance of the non-poisonous reference core is compared to the CSBA-loaded one. The cycle length of CSBA-loaded core is 30.10 GWd/tU (38.41 months), which is slightly shorter than that of non-poisonous SBF core, which is about 33.5 GWd/tU. It is indicated that cycle length of CSBA-loaded core is quite comparable to that of the single-batch PWR. The slightly shorter cycle length with CSBA-loaded core is mainly due to less fuel inventory and partially due to of the residual CSBA at end of cycle (EOC). Note that the uncertainty of k-eff is about

11 pcm as a results of 50,000 histories, 1000 active and 500 inactive cycles. The minimal reactivity, 545 pcm, shows that the reactor can survive through a power drop transient [8].

Table III: Neutronic property of ATOM cores

Case	Rho Swing (pcm)	Minimal Rho (pcm)	Discharged Burnup (GWd/tU)
Without BA	24318	-	33.85
CSBA-loaded	1155	545	30.10

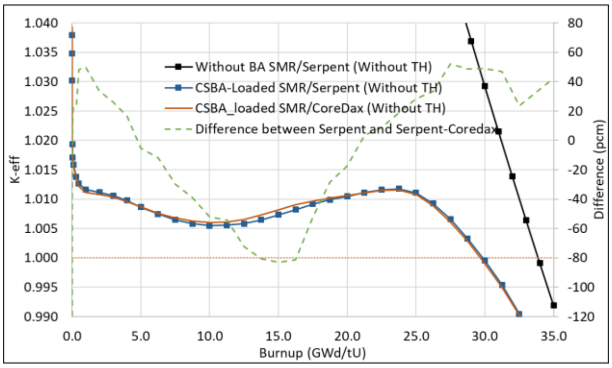

Fig. 6. Burnup-dependent k-eff (without TH coupling)

The ATOM core also has inherent safety properties similar to typical PWR. It can be seen from Table IV that the fuel temperature coefficient (FTC) and coolant temperature coefficient (CTC) are clearly negative. In the evaluation of CTC and FTC, it is assumed that both FTC and CTC are the linear functions of temperature. As the burnup increases, both FTC and CTC become more negative due to plutonium and fission product buildup leading to neutron spectrum hardening. Deviation (STDV) of CTC and FTC are also presented.

Table IV: Safety parameters at different conditions

Condition	FTC (pcm/K)	FTC STDV (pcm)	CTC (pcm/K)	CTC STDV (pcm)
BOC	-2.365	0.145	-48.114	1.47
MOC	-2.650	0.141	-51.429	1.46
EOC	-3.038	0.113	-62.853	1.37

3.2 Serpent-COREDAX Results

The continuous-energy Monte Carlo Serpent code is capable of handling complicated geometry, physical interaction, and branch calculations without critical approximations, which is highly advantageous for assembly spatial homogenization. A 3-D coupled neutronic and thermal-hydraulic calculation can be offered by the diffusion-based COREDAX code utilizing homogenized group constants from the Monte Carlo lattice analysis. The 3-D COREDAX code is well validated against other commercial codes [7]. Therefore, the 2-step Serpent-COREDAX is expected to provide reliable solutions for the SBF SMR core analysis.

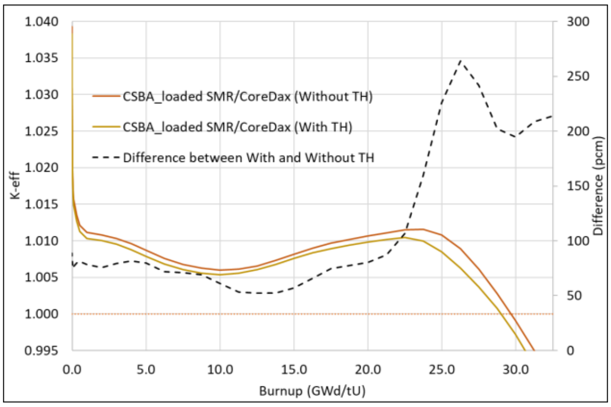

Fig. 7. With- and without-TH multiplication factor behaviors

To feed 3-D COREDAX core calculation, three Serpent CSBA-loaded branch calculations, radial and axial baffle-reflector branch calculations are needed. As can be seen from Fig. 6, Serpent and Serpent-COREDAX show a good agreement in term of k-eff. The maximum difference is only 120 pcm during long operation of the core. The k-eff comparison between with and without TH coupling is shown in Fig. 7. The difference, ranging from 50 pcm to 250 pcm, is because of the power redistribution due to TH condition. Fig. 8 illustrates normalized radial power profiles at three conditions. The radial power distribution is rather flat with TH coupling. This shows a clear advantage of the CSBA design in view of flattening power.

BOC MOC EOC			0.978 0.941 0.747	
		1.012 1.076 1.139	1.005 1.045 0.983	0.939 0.881 0.676
	1.019 0.99 1.239	1.018 1.027 1.183	1.032 1.084 1.081	1.074 1.018 0.798
1.021 0.964 1.277	1.02 0.976 1.258	1.017 1.013 1.201	0.999 1.059 1.107	0.815 1.059 0.799

a) Without TH

BOC MOC EOC			0.979 0.944 0.776	
		1.013 1.071 1.128	1.005 1.043 0.997	0.940 0.887 0.709
	1.02 0.992 1.193	1.018 1.025 1.156	1.030 1.079 1.082	1.067 1.016 0.829
1.022 0.97 1.218	1.021 0.98 1.205	1.017 1.012 1.168	1.000 1.056 1.102	0.823 1.056 0.826

b) With TH

Fig. 8. Radial assembly-wise power profiles

Fig. 9 shows the burnup-dependent axial power and temperature profiles with TH analysis. At BOC, the power distribution is bottom-skewed as expected due to higher coolant density at the bottom of the core. At middle of cycle (MOC), BA is largely burned out and the axial power profile returns to a cosine-shape curve. It becomes top-skewed as usual power shifting at EOC. Throughout the cycle, the maximum axial peaking factor is quite small, about 1.3, and we can observe small peaks at top and bottom due to CSBA cutbacks. Note that the axial temperature closely follows the pattern of the axial power profile as expected. The discharged burnup, as depicted in Fig. 10, is quite flat as a result of very flat power profile during the cycle.

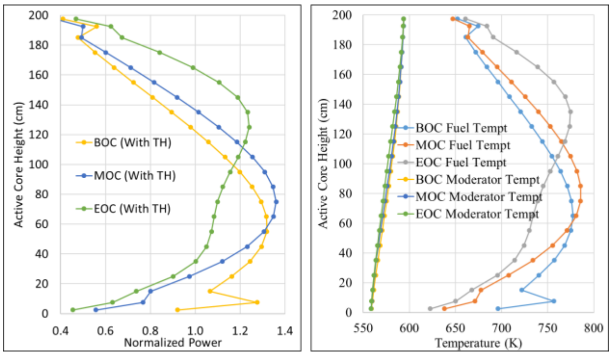

Fig. 9. Axial power and temperature profiles

			26.830	
		32.718	31.094	25.032
	31.465	32.028	32.549	28.863
31.054	31.243	31.787	32.044	24.907

Fig. 10. Discharged burnup (GWd/tU) of the one-eight core

3.3 Control Rod Pattern and Rod Worth Evaluation

In ATOM core, mechanical shims (MS) are used to attain critical condition. The MS rods should be loaded symmetrically in bulk throughout the core so that the resulting radial power perturbation can be practically minimized. Therefore, stainless steel doped with 2.5% hafnium, less absorbing, is selected as material for MS rod instead of typical Ag-In-Cd rod. Shutdown and regulating rods uses B_4C with 95% enriched B-10 and natural boron, respectively, to enhance the shutdown margin. Fig. 11 shows the rodded configuration of MS, regulating and shutdown rods.

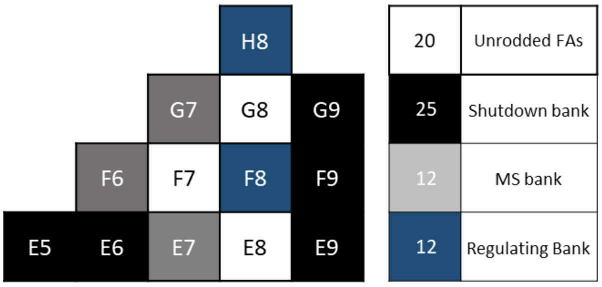

Fig. 11. CR pattern for one-eighth ATOM core

Table V: CR worth comparison

Case	Serpent-Coredax		Serpent		Rho Dif. (pcm)
	K-eff	Total Worth	K-eff	Total Worth	
All rod out	1.10796	NA	1.10701	NA	77
ARI (Except F9)	0.97718	-12079	0.97942	-11768	-234
ARI (Except G9)	0.97890	-11899	0.98063	-11643	-180
ARI (Except E9)	0.97607	-12196	0.97900	-11812	-307
ARI (Except E6)	0.98679	-11083	0.98997	-10680	-326
ARI (Except E5)	0.97765	-12030	0.97986	-11722	-231
All rods in (ARI)	0.97526	-12281	0.97838	-11876	-328

Table V illustrates the rod worth comparison between Serpent and Serpent-COREDAX calculations at cold zero power and BOC conditions. It indicates that the reactor has enough shutdown margin even during the rod-stuck scenario. A good agreement between two approaches is observed even in rodded condition with only around 300 pcm difference.

4. Conclusions

This paper presents a preliminary investigation on the neutronic feasibility of an SBF ATOM core loaded with CSBA by using the MC-diffusion hybrid two-step procedure. The numerical results show a good agreement between Serpent and Serpent-COREDAX in terms of core depletion reactivity, power profiles, and the control rod worth. We conclude that the MC-diffusion hybrid two-step analysis can be reliably used for an SBF SMR design and analysis.

On the other hand, three unique CSBA designs are loaded region-wise in the core, resulting in an optimal reactivity swing, between 500 pcm and 1200 pcm. Moreover, safe cold shutdown operation can also be assured with the proposed CR arrangement. Thus, it can be concluded that the SBF operation in the ATOM core is potentially attainable with the strategic loading of the CSBA absorber, MS, and shutdown bank rods.

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