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Original Article

Reactivity balance for a soluble boron-free small modular reactor

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ABSTRACT

Elimination of soluble boron from reactor design eliminates boron-induced reactivity accidents and leads to a more negative moderator temperature coefficient. However, a large negative moderator temperature coefficient can lead to large reactivity feedback that could allow the reactor to return to power when it cools down from hot full power to cold zero power. In soluble boron-free small modular reactor (SMR) design, only control rods are available to control such rapid core transient.

The purpose of this study is to investigate whether an SMR would have enough control rod worth to compensate for large reactivity feedback. The investigation begins with classification of reactivity and completes an analysis of the reactivity balance in each reactor state for the SMR model.

The control rod worth requirement obtained from the reactivity balance is a minimum control rod worth to maintain the reactor critical during the whole cycle. The minimum available rod worth must be larger than the control rod worth requirement to manipulate the reactor safely in each reactor state. It is found that the SMR does have enough control rod worth available during rapid transient to maintain the SMR at subcritical below k-effectives of 0.99 for both hot zero power and cold zero power.

1. Introduction

Small modular reactor (SMR) designs are an interesting topic of research because of the applicability of such reactors in rural areas and developing countries, where large-size reactors are impractical due to lack of infrastructure and grid capacity. SMRs are reactors with electric power of less than 300 MWe, extended core lifetimes, and reduced core power density. For integral type SMRs, the steam generators and control rod drive mechanisms are located inside the vessel. Some SMR designs also aim to eliminate the use of soluble boron [1].

Elimination of soluble boron from the reactor design has many benefits, the most important being the elimination of boron-related reactivity accidents. A boron-free reactor would also have a more negative moderator temperature coefficient (MTC), which is advantageous when considering Criterion 11 of Appendix A to Part 50 of 10 CFR, which states that the reactor core and coolant systems should be designed such that the net effect of prompt inherent nuclear feedback characteristics will compensate for any rapid increase in reactivity. This implies that the temperature coefficients should be negative whenever the reactor is at significant power levels [2,3].

The large negative MTC of a soluble boron-free design could pose a challenge for reactor start-up and shutdown. The temperature difference between cold conditions and operating conditions would cause a large amount of reactivity feedback (due to the large negative MTC). In the case of a soluble boron-free design, the reactivity changes must be controlled through use of control rods.

In the current study, a soluble boron-free SMR is modeled to minimize the excess reactivity for depletion, and a reactivity balance analysis is performed to determine the control rod worth required to compensate for the reactivity changes during reactor shutdown and cooling from hot full power (HFP) condition. The same reactivity components would cause negative feedback during reactor start-up from cold zero power (CZP) condition.

The reactivity balance analysis result provides the control rod worth requirement and shows whether the available control rod worth in the soluble boron-free SMR is large enough to enable reactor shutdown and cooling, as well as reactor start-up and operation. The analysis is first completed for a model in which the

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Abbreviations: BA, Burnable Absorber; BOC, Beginning of Cycle; CEA, Control Element Assembly; CZP, Cold Zero Power; EOC, End of Cycle; FA, Fuel Assembly; FTC, Fuel Temperature Coefficient; HFP, Hot Full Power; HZP, Hot Zero Power; ITC, Isothermal Temperature Coefficient; LP, Loading Pattern; MOC, Middle of Cycle; MTC, Moderator Temperature Coefficient; PWR, Pressurized Water Reactor; SLOBA, Slow Burnable Absorber; SMR, Small Modular Reactor.

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maximum number of control element assemblies (CEAs) is used. The results of the analysis are then used to determine if some CEAs can be eliminated, while meeting the subcriticality condition for both hot zero power (HZP) and CZP.

2. SMR nuclear design characteristics

2.1. SMR model

The soluble boron-free SMR model used in this study is based on a model that was used in several previous studies. In 2015, Park et al [4] investigated a new conceptual burnable absorber (BA) design to determine an optimized BA for application in a soluble boron-free SMR. It was reported that a BA with a double-layer B_4C design had the most desirable reactivity flattening effect. This BA has recently been patented and is now known as slow burnable absorber (SLOBA).

In 2016, Muth [5,6] continued the work of Park by performing a comparative study of the different BA types for use in soluble boron-free SMRs. In that article, the performance of the SLOBA design is compared with the three most commonly used BA types for pressurized water reactors, which are gadolinia, boron, and erbium. Muth's study [5,6] indicated that gadolinia had the highest absorption cross section, thus leading to the steepest burnout curve. SLOBA showed the slowest burnout time and flattest burnout curve of the BAs that were investigated, making it desirable for use in the soluble boron-free SMR application to minimize the control rod movement.

The SMR model in this study is an integral pressurized water reactor that produces 180 MW_{th} power. This SMR model uses the Westinghouse 17 × 17 type fuel assembly (FA). The design requirements for the SMR model used in this study are given in Table 1. The core has an active height of 200 cm and consists of 37 FAs. Each FA has 264 fuel rods, 24 guide tubes, and a single in-core instrumentation tube.

Since no soluble boron will be present in the reactor coolant, the excess reactivity will be controlled by use of BAs and control rods. In this model, a combination of gadolinia (15 w/o) and SLOBA (8 w/o) is used as BA in the core design. SLOBA rods are of discrete type and thus displace fuel rods, whereas gadolinia rods are of integral type with a uniform mixture of BA material and 2% enriched uranium fuel. The FA specifications are presented in Table 2. The fuel enrichment for all FAs is 4.95 w/o. FA cross section calculations are performed using CASMO-4 [7].

Fig. 1 shows the loading pattern (LP) design for the SMR model used in this study. The desired cycle length is 22 GWD/MTU. The labels in the blocks of the LP figure represent the FA types specified in Table 2. The core depletion and other nuclear design data generation are completed using SIMULATE-3 [8].

2.2. Nuclear characteristics of the SMR

The LP in Fig. 1 is designed to have negative MTC, negative fuel temperature coefficient, and pin peaking factor lower than 1.7 and to minimize the excess reactivity so that the control rod worth available to compensate for rapid transient can be maximized.

Table 1
SMR design requirements.

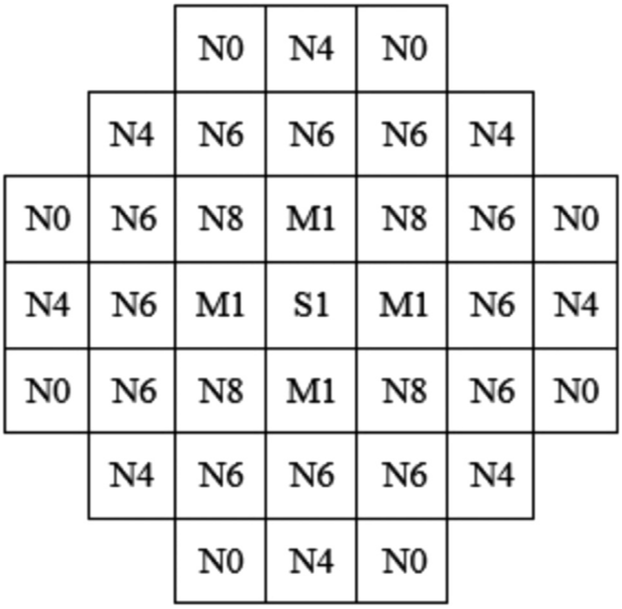
Reactor type	PWR
Thermal power	180 MWth
Cycle length	< 4 years
UO_2 enrichment	< 5 w/o
Inlet temperature	285°C
Outlet temperature	315°C
Operating pressure	15.5 MPa

PWR, pressurized water reactor; SMR, small modular reactor.

Table 2
Fuel assembly specifications.

FA type	No. of FA	W/o of fuel	No. of BA	W/o of BA	Type of BA
N0	8	4.95	0	8	
N4	8	4.95	16	8	SLOBA
N6	12	4.95	24	8	SLOBA
N8	4	4.95	32	8	SLOBA
S1	1	4.95	40	8	SLOBA
M1	4	4.95	20/20	8/15	SLOBA/Gd_2O_3

BA, burnable absorber; FA, fuel assembly; SLOBA, slow burnable absorber.



		N0	N4	N0		
	N4	N6	N6	N6	N4	
N0	N6	N8	M1	N8	N6	N0
N4	N6	M1	S1	M1	N6	N4
N0	N6	N8	M1	N8	N6	N0
	N4	N6	N6	N6	N4	
		N0	N4	N0		

Fig. 1. Core loading pattern.

Fig. 2 shows the excess reactivity curve for the SMR with LP shown in Fig. 1, with an obtained cycle length of 21.904 GWD/MTU. The SMR core depletion calculation shows maximum excess reactivity of 1910 pcm at the beginning of cycle (BOC), and a secondary peak value of excess reactivity observed to be around 15 GWD/MTU

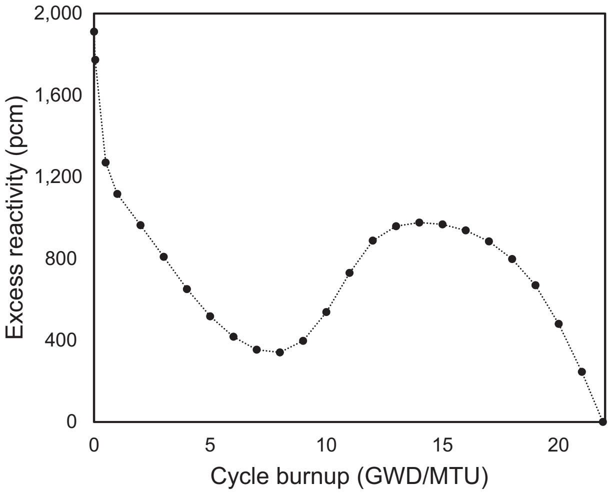


Fig. 2. Core depletion characteristics.

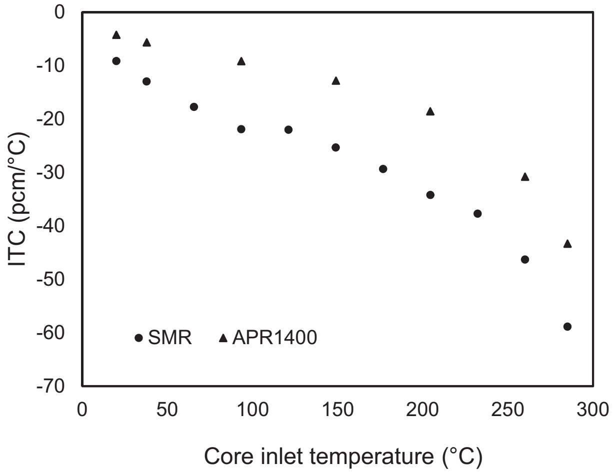


Fig. 3. Isothermal temperature coefficient (ITC).
SMR, small modular reactor.

due to burnout of BAs. This excess reactivity needs to be suppressed by control rod insertion to achieve boron-free SMR.

Fig. 3 shows the isothermal temperature coefficient (ITC) from the CZP condition to HFP condition at the BOC for the soluble boron-free SMR model and the APR1400 [9]. ITC shows the combined effects of fuel temperature coefficient and MTC. In Fig. 3, the ITC values for the SMR are around 50% more negative than for the APR1400, therefore the ITC reactivity feedback of the SMR is expected to be much more than that for APR1400.

3. Reactivity balance calculation

The purpose of the reactivity balance calculation is to determine whether it would be possible to decrease the reactor power from HFP to HZP by insertion of the control rods without return to power and then cool the reactor down to CZP, ensuring sufficient subcriticality. Conversely, this will indicate whether it will be possible for the reactor to reach criticality after overcoming the negative reactivity feedback caused by reactor state change from CZP, through HZP, to HFP.

The reactivity balance calculation needs to identify the reactivity components at each reactor state and evaluates the worth of each reactivity component to determine the minimum required control rod worth to overcome the total reactivity change. The net rod worth requirement is then compared to the available control rod worth. Table 3 shows the reactor state points that will have to be analyzed with SIMULATE-3 to calculate the worth of each reactivity component in the reactivity balance.

The largest of the reactivity components is the available control rod worth, dependent on the total number of CEAs, which has not yet been determined in the SMR design. The reactivity balance calculation first assumes CEAs placed above each of the FAs in the model to maximize the amount of control rod worth, thus a total of 37 CEAs. Fig. 4 shows the CEA configuration for the model using 37 CEAs made of Ag-In-Cd. The numbers in the blocks of Fig. 1 represent control rod groups. The results of this initial reactivity balance analysis are used to determine whether some of the CEAs can be eliminated while meeting subcriticality under k-eff of 0.99 at both HZP and CZP with N-1 control rod insertion condition.

Table 3
Reactor states for reactivity balance calculation.

State	Abbreviation	Inlet temp. (°C)	Press. (MPa)	Power (%)	Xenon
Hot full power (equilibrium xenon)	HFP (Eq.Xe)	285	15.5	100	Eq.
Hot full power (no xenon)	HFP (No.Xe)	285	15.5	100	0
Hot zero power (no xenon)	HZP	285	15.5	0	0
Cold zero power (no xenon)	CZP	20	0.1	0	0

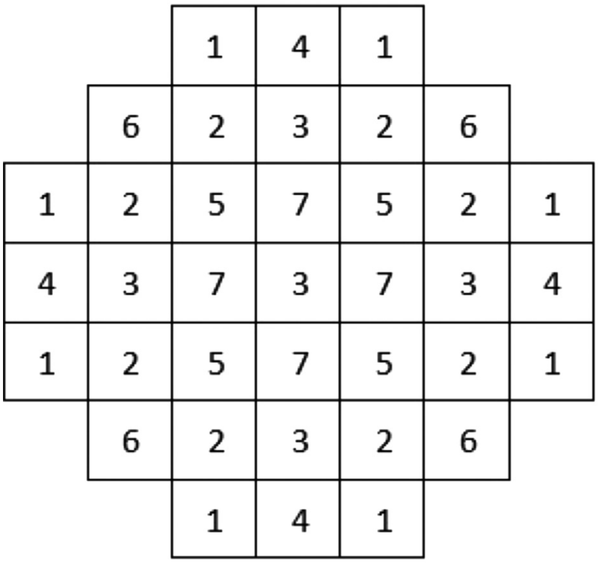


Fig. 4. 37 CEA model.
CEA, control element assembly.

The reactivity balance is divided into four main sections. Section 1 will analyze the reactivity components at HFP. Section 2 will analyze the reactivity components when reducing reactor power from HFP to HZP. Section 3 will analyze the components when the reactor is cooled from HZP to CZP. In section 4, the total control rod requirement at CZP is determined using the control rod worths in sections 1, 2, and 3, and then compared with the available control rod worth at CZP. For the explanation of the reactivity balance analyses, only the BOC components will be discussed in detail, since this is the limiting case. The same logic can be followed for the reactivity components of the middle of cycle and end of cycle cases.

3.1. Section 1—HFP reactivity components

Table 4 shows the reactivity balance at HFP. The reactivity components at HFP consist of excess reactivity for depletion, reactivity suppressed by Bas, and the reactivity worth of control rods to eliminate soluble boron. In this state, the reactor is operating at 285°C and 15.5 MPa, while producing 100% power. To ensure the reactor can produce 100% power over the entire cycle length, the excess positive reactivity is provided by enriched fuel. This excess reactivity is mostly suppressed by the BA rods in the core, and the remaining excess reactivity is suppressed by control rods. The total of the reactivity components must equal zero to ensure the reactor remains critical over the entire cycle.

The BA hold-down component of 25040 pcm is estimated from a core average calculation. The amount of negative reactivity that will be suppressed by use of control rods is found, from the depletion curve in Fig. 2, to be 1910 pcm. The total amount of excess reactivity required for cycle length operation is the positive reactivity component, which is balanced by the negative reactivity components, and therefore should be 26950 pcm.

Table 4
Reactivity balance section 1—HFP.

Section 1—HFP reactivity components		Reactivity (pcm)		
		0 GWD/MTU	15 GWD/MTU	22 GWD/MTU
a.	Excess reactivity for depletion	26950	12157	0
b.	Burnable absorbers	−25040	−11190	0
c.	Control rods	−1910	−967	0
d.	Subtotal	0	0	0

HFP, hot full power.

3.2. Section 2—HFP to HZP reactivity components

Table 5 shows the reactivity balance during the core transient from HFP to HZP. This means that the reactor power is decreased from 100% to 0%, while the coolant inlet temperature and pressure are maintained at operating levels. The reactivity components in this transient are power defects resulting from moderator and fuel temperature feedback, the reactivity worth due to xenon decay, and the reactivity worth of the control rods.

In this section, the positive reactivity components are divided into two parts. First is the power defect, which indicates that 1949 pcm of positive reactivity feedback would occur when the reactor power is changed from 100% to 0%. The second positive reactivity component is caused by the xenon decay and was found to be 1745 pcm. These positive reactivity components must be balanced by the control rods, and therefore, the control rod reactivity requirement for this transient is 3694 pcm.

3.3. Section 3—HZP to CZP reactivity components

Table 6 shows the reactivity balance during the core transient from HZP to CZP. This means the temperature is decreased to room temperature and the pressure is decreased to atmospheric pressure. The reactivity components in this transient are a positive reactivity feedback called isothermal defect. This positive reactivity must again be balanced by use of the control rods. Furthermore, when the reactor is at HZP, it is required that the core k-eff value be at least 0.99, and therefore, an additional 1000 pcm of reactivity suppression is required [10].

During this change of state, the changes in moderator and fuel temperatures are equal and only the isothermal defect causes positive reactivity feedback, which is found to be 7337 pcm. The control rods are required to cancel this positive reactivity and must also ensure that the core k-eff value be 0.99 at HZP. Therefore, the control rods must account for an additional 1000 pcm. The total control rod requirement for this transient is thus 8337 pcm.

Table 5
Reactivity balance section 2—HFP to HZP.

Section 2—HFP to HZP reactivity components		Reactivity (pcm)		
		0 GWD/MTU	15 GWD/MTU	22 GWD/MTU
a.	Power defect	1949	2265	2453
b.	Xenon decay	1745	1737	1940
c.	Control rods	−3694	−4002	−4393
d.	Subtotal	0	0	0

HFP, hot full power; HZP, hot zero power.

Table 6
Reactivity balance section 3—HZP to CZP.

Section 3—HZP to CZP reactivity components		Reactivity (pcm)		
		0 GWD/MTU	15 GWD/MTU	22 GWD/MTU
a.	Isothermal defect	7337	5596	5425
b.	Control rods	−8337	−6596	−6425
c.	Subtotal	−1000	−1000	−1000

CZP, cold zero power; HZP, hot zero power.

3.4. Section 4—total requirements

In section 4 of the reactivity balance, the control rod requirements at each reactor state are combined. The worths of the control rods at the different core states have to be converted to equivalent CZP worths. The equivalent CZP worths are calculated by multiplying these values by conversion ratios, which are determined by comparing the available N-1 control rod worth at the given state with the available N-1 control rod worth at CZP.

The control rod requirements at different core states can then be added together to produce the net rod worth requirement. As a final step, the minimum available control rod worth with highest worth rod stuck (N-1 control rod worth) at CZP is computed. The control rod worth margin would then be the remaining available control rod worth when the net rod worth requirement value is subtracted from the value of the minimum available rod worth at CZP.

The 37 CEA model results for section 4 of the reactivity balance are shown in Table 7. This section combines the control rod requirements from the first three sections of the reactivity balance. The HFP control rod requirement is converted to the equivalent CZP value, which is 1130 pcm. The HZP control rod requirement is also converted to the equivalent CZP value, which is 2703 pcm. These can now be added to the 8337 pcm CZP control rod requirement. The net control rod worth requirement is thus 12170 pcm. The total available control rod worth (with the highest worth rod assumed to be stuck in the fully withdrawn position) is found from calculation to be 20570 pcm.

There is thus the additional control rod worth of 8400 pcm available after the control rods have canceled out all the positive reactivity components that occurred from reducing reactor power from 100% to 0% and then cooling the reactor to CZP. This additional control rod worth will make the reactor core more subcritical.

3.5. CEA reduction

To maximize the available control rod worth, the first reactivity balance calculation is done for a model that uses 37 CEAs. Based on the results from the 37 CEA model, a reduction model for CEAs is proposed to minimize the number of CEAs while meeting the subcriticality condition for both HZP and CZP. The results of the first three sections of the reactivity balance for a reduction model are the same as for the 37 CEAs model. Table 7 results are different because of the difference in the control rod worth based on the number of CEA and the CEA configuration.

3.5.1. Reduction model: 29 CEA model

From the reactivity balance results for the model with 37 CEA, it was found that there was 8400 pcm control rod worth

Table 7
Reactivity balance section 4—total requirements (37 CEA).

Section 4—total requirements reactivity components		Reactivity (pcm)		
		0 GWD/MTU	15 GWD/MTU	22 GWD/MTU
a.	HFP control rod requirement, converted to CZP value	−1130	−2641	0
b.	HZP control rod requirement, converted to CZP value	−2703	−5018	−3321
c.	CZP control rod requirement	−8337	−6596	−6425
d.	Net rod worth requirement	−12170	−14255	−9746
e.	Minimum available rod worth at CZP	20570	24015	25205
	Control rod worth margin	8400	9760	15459

CEA, control element assembly; CZP, cold zero power; HFP, hot full power; HZP, hot zero power.

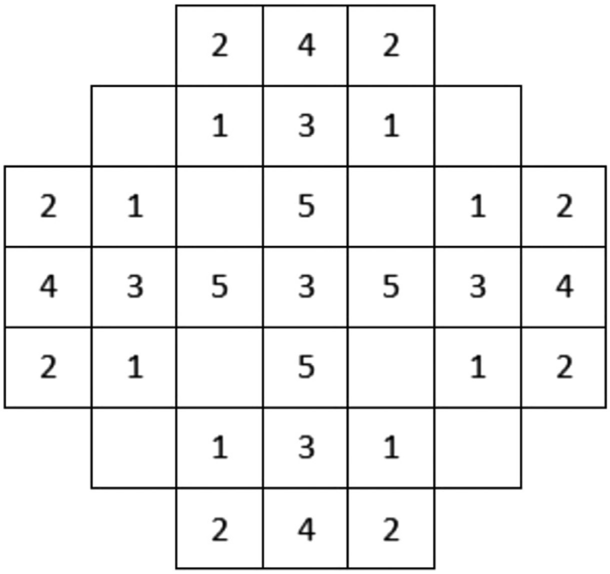


Fig. 5. 29 CEA model.
CEA, control element assembly.

remaining at BOC after all the reactivity insertion of power change and cool down had been balanced. If there are 37 CEA in the core model, the in-core instrumentation cannot be inserted from above the FAs, as is the standard practice. With the amount of remaining control rod worth, it can be seen that it should be possible to remove some CEAs. Fig. 5 shows a model for which the number of CEAs is reduced to 29.

The 29 CEA model results for section 4 of the reactivity balance are shown in Table 8. The HFP control rod requirement is converted to the equivalent CZP value, which is 1210 pcm. The HZP control rod requirement is also converted to the equivalent CZP value, which is 2807 pcm. These can now be added to the 8337 pcm CZP control rod requirement. The net control rod worth requirement is thus 12354 pcm. The total available control rod worth (with the highest worth rod assumed to be stuck in the fully withdrawn position) was found from calculation to be 14906 pcm.

There is thus 2552 pcm of additional control rod worth available after the control rods have overcome all the positive reactivity components that occurred from reducing reactor power from 100% to 0% and then cooling the reactor to CZP. This result shows that it is possible to remove 8 CEAs from the soluble boron-free SMR; nonetheless this model cannot provide enough space for the in-core instrumentation.

4. Conclusion

This study focused on investigating the reactivity components of a soluble boron-free SMR through a reactivity balance to determine whether the minimum available control rod worth would be enough to overcome the reactivity feedback caused by core state change.

The reactivity components for operation at HFP are found to be only the excess reactivity required to operate to end of cycle, and this reactivity would be mostly balanced by the use of BA rods, and the remaining amount by control rods. The reactivity components considered between the HFP and HZP states are caused by the power defect (change of power between 100% and 0%) and the decay of xenon concentration in the core. These reactivity components have to be balanced by the use of control rods. The reactivity components for cooling the reactor from HZP to CZP are caused by the ITC and have to be balanced by the use of control rods.

Finally, the sum of the equivalent CZP control rod worths for the different core states indicated the total minimum control rod worth requirement that would be necessary to shutdown the reactor power from 100% to 0% and then cool the reactor to the CZP state. The available control rod worth at CZP (with highest worth rod stuck at fully withdrawn) is also calculated and compared to the control rod requirements.

The reactivity balance analysis is first performed on a model using 37 CEAs and other CEA reduction models to see if CEA reduction is possible with the satisfaction of subcriticality condition. From these results it is seen that the SMR design investigated in this study has enough available control rod worth to meet the minimum required control rod worth. Therefore, this reactor can be shutdown and cooled by insertion of the control rods. Conversely, this means that, using only control rod manipulation,

Table 8
Reactivity balance section 4—total requirements (29 CEA).

Section 4—HFP to HZP reactivity components		Reactivity (pcm)		
		0 GWD/MTU	15 GWD/MTU	22 GWD/MTU
a.	HFP control rod requirement, converted to CZP value	−1210	−660	0
b.	HZP control rod requirement, converted to CZP value	−2807	−3143	−3385
c.	CZP control rod requirement	−8337	−6596	−6425
d.	Net rod worth requirement	−12354	−10396	−9810
e.	Minimum available rod worth at CZP	14906	15834	16166
	Control rod worth margin	2552	5436	6356

CEA, control element assembly; CZP, cold zero power; HFP, hot full power; HZP, hot zero power.

it is possible to heat up the reactor from CZP to HZP and then increase reactor power to HFP and operate till the end of cycle at critical state.

The results of the 37 CEA models also showed that there is a relatively large amount of excess control rod worth still available after meeting the control rod worth requirements. A model with 29 CEAs is therefore also investigated. For this model, it is found that the soluble boron-free SMR with a reduced number of CEAs still has enough available control rod worth to maintain the SMR at subcritical at any reactor state.

Conflicts of interest

The authors have no conflicts of interest to declare.

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