Control Rod Worth Requirement Based on Reactivity Balance for a Soluble Boron Free Small Modular Reactor

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1. Introduction

All reactor cores are designed with enough excess reactivity to enable long-term operation. During operation, the reactor has to be kept critical. This excess reactivity can be controlled by three methods: soluble boron in the reactor coolant, burnable absorber (BA) rods in the core, and insertion of control rods.

One of the Small Modular Reactor (SMR) conceptual designs which has been developed in Korea aims to eliminate soluble boron. A soluble boron free reactor design would eliminate the inherent problems associated with boron-induced reactivity accidents and corrosion of piping, bolting, and other critical components of the reactor coolant system. Plant operation and maintenance would be simplified, and the radioactive waste volumes and water requirements would decrease, by elimination of deboration operations. A large negative Moderator Temperature Coefficient (MTC) would be maintained at all times (as required by the regulatory board). [1]

During startup of the reactor, the large negative MTC would cause a large amount of negative reactivity insertion as the temperature of the moderator increases from cold zero power (CZP) to hot zero power (HZP). Increasing the power level from hot zero power to hot full power (HFP) will lead to further negative reactivity insertion due to the MTC, power defect, and Xenon buildup. This paper aims to investigate how much control rod worth would be required to overcome the collective negative reactivity insertion thus enabling startup of the reactor, as well as ensure the reactor can operate for the full cycle. This control rod worth will be calculated by completing a shutdown margin calculation and reactivity balance for this reactor model.

2. Characterization of SMR Nuclear Design

2.1 SMR Model

The SMR design for this study is based on the Westinghouse 17 x 17 fuel assembly (FA) type. Table 1 shows the SMR design requirements used in this study. The core consists of a total of 37 FAs and has an active height of 200 cm. The FAs each consists of 264 fuel rods, 24 guide tubes, and an in-core instrumentation tube. Control element assemblies (CEAs) are located above each of the 37 FAs.

Table 1: SMR Design Requirements

Reactor Type	PWR
Thermal Power	180 MWth
Cycle Length	< 4 years
UO_2 Enrichment	4.95 w/o
Inlet Temperature	292 °C
Outlet Temperature	322 °C
Fuel Temperature	960.95 K
Operating Pressure	2250 psi

BA rods and control rod assemblies would be required to control the excess reactivity in the absence of soluble boron. A previous study investigated different possible BA types which could be used in a soluble boron free SMR design. The results indicated that gadolinia had the highest reactivity hold-down power, but also had a very steep burnout slope (thus burning out very quickly). A new burnable absorber type, SLOBA (Slow Burnable Absorber with B_4C), was designed that has a flatter burnout curve, which is desirable for the soluble boron free SMR design to minimize the movement of control rods. [2,3]

For this study, a combination of SLOBA (15 w/o) and gadolinia (8 w/o) will be used as BA. SLOBA rods are discrete type and thus displace the fuel, while gadolinia rods are integral type (uniform mixture of fuel and BA material). Figure 1 shows the loading pattern for this study and Table 2 shows the FA characteristics.

Assembly cross section calculations were done by CASMO-4 [4] and the core depletion and other calculations were performed using SIMULATE-3 [5].

		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		

Figure 1: Core Loading Pattern

Table 2: Fuel Assembly Specification

FA Type	# of FA	# of BA	Type of BA
N0	8	0	
N4	8	16	SLOBA
N6	12	24	SLOBA
N8	4	32	SLOBA
S1	1	40	SLOBA
M1	4	20/20	SLOBA/Gd_2O_3

Figure 2 shows the depletion characteristics of the loading pattern. The maximum reactivity value is 1910 pcm. It would be desirable to further reduce this value, and will thus be a topic for future investigation.

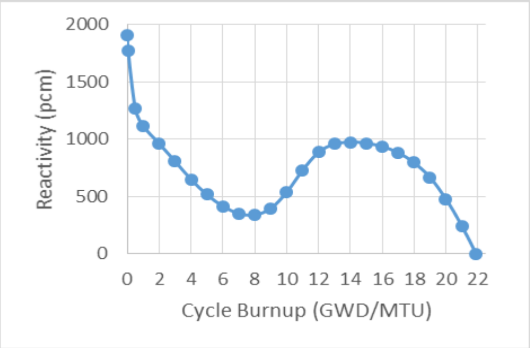

Figure 2: Core Depletion Characteristics

2.2 Shutdown Margin

The shutdown margin indicates whether the reactor power can be decreased from 100% to 0% by insertion of the control rods. Table 3 shows the calculated shutdown margin for this loading pattern. From this calculation it can be seen that there is enough control rod worth available to safely shut down the reactor power.

Table 3: Shutdown Margin

A. Control Rod Requirement	**Reactivity (pcm)**
Power Defect	3692
• Doppler	
• Moderator Temperature	
• Redistribution	
B. Control Rod Worth	
SCRAM (N-1) worth	26621
Uncertainty (4.6%)	-1225
Remaining worth	25397
Shutdown Margin (B-A)	**21704**

2.3 Reactivity Balance

The reactivity balance shows the control rod requirements to shut down the reactor, as well as maintain the reactor subcritical when cooled to CZP. Reversely, it also indicates whether the reactor can be started up from CZP, through HZP, to HFP by withdrawing the control rods.

At HFP the positive reactivity component is only the excess reactivity required for depletion. This positive reactivity must be balanced by a combination of burnable poisons and control rods.

From HFP to HZP there are two components causing positive reactivity insertion, which are power defect and xenon redistribution. From HZP to CZP all the positive reactivity insertion is due to the isothermal temperature defect (which is a combination of the fuel temperature and moderator temperature defects). These effects must be balanced by the control rods alone.

Table 4 shows the reactivity balance that was completed for the soluble boron free SMR model with the loading pattern in Figure 1. From the balance it can be seen that the available control rod worth meets the control rod requirements. The k-eff value at CZP (with worst rod stuck) is 0.929, which indicates that the core is subcritical at this condition.

Table 4: Reactivity Balance

	Reactivity Component	**Reactivity (pcm)**
	1. HFP	
a.	Excess reactivity for depletion	26950
b.	Burnable poisons	-25040
c.	Control rods	-1911
d.	Subtotal	0
	2. HFP to HZP	
a.	Power defect	1745
b.	Xenon burnout	1947
c.	Control rods	-3692
d.	Subtotal	0
	3. HZP to CZP	
a.	Isothermal defect	14887
b.	Control rods	-15887
c.	Subtotal	-1000
	4. Control Rod Requirements	
a.	HFP control rod requirement, converted to CZP value	-1127
b.	HZP control rod requirement, converted to CZP value	-2701
c.	CZP	-15887
d.	Net rod worth requirement	-19715
e.	Minimum available rod worth at CZP	20570

3. Conclusion

The current loading pattern (using a combination of gadolinia and SLOBA as BA) results in excess reactivity of 26950 pcm required for 22 GWD/MTU cycle length, of which 1910 pcm must be controlled by use of the control rods.

For the soluble boron free SMR model that was investigated in this study, it was demonstrated through the shutdown margin calculation that the reactor power can be safely reduced from 100% to 0%. The reactivity balance calculation also demonstrated that with the available control rod worth, the reactor can be maintained subcritical when cooled to CZP. Reversely, this implies that it is possible to startup the reactor from CZP, through HZP, to HFP, and then operate to the desired cycle length.

Future work should focus on reducing the control rod requirements. This might be achieved by changing the core loading pattern, BA type, and BA arrangement in the core. The largest control rod requirement comes from the isothermal defect which occurs due to the large negative MTC value. Therefore, research should be done to determine whether the MTC value could be made less negative, which would lead to lower control rod worth requirements for suppression of the temperature defect.

Ultimately the aim is to decrease the control rod requirements, which would allow for a reduction in the number of CEAs for this soluble boron free SMR design. Reducing the number of CEAs will allow for the accommodation of in-core instrumentation and will also have some cost benefits.

REFERENCES

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