Nuclear Engineering and Technology xxx (2018) 1–6

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Reactivity balance for a soluble boron-free small modular reactor

Lezani van der Merwe, Chang Joo Hah*

Department of Nuclear Power Plant Engineering, KEPCO International Nuclear Graduate School, 1456-1 Shinam-ri Seosaeng-myeon, Ulju-gun, Ulsan, Republic of Korea

ARTICLE INFO

Article history:
Received 25 December 2017
Accepted 29 January 2018
Available online xxx

Keywords:
Control Rod Worth
Reactivity Balance
Reactivity Feedback
Small Modular Reactor
Soluble Boron Free

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

---

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.

* *Corresponding author.*
E-mail address: changhah@kings.ac.kr (C.J. Hah).

https://doi.org/10.1016/j.net.2018.01.019

Please cite this article in press as: L. van der Merwe, C.J. Hah, Reactivity balance for a soluble boron-free small modular reactor, Nuclear Engineering and Technology (2018), https://doi.org/10.1016/j.net.2018.01.019

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.

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

Table 1
SMR design requirements.

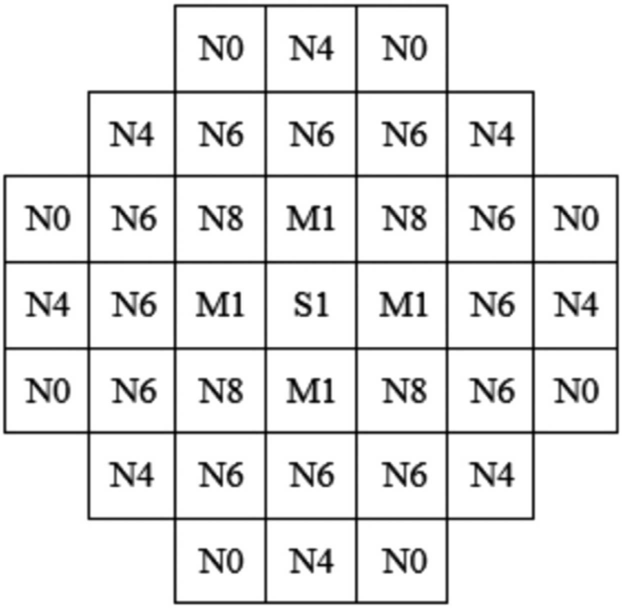
Reactor type	PWR
Thermal power	180 MWth
Cycle length	< 4 years
UO_2 enrichment	< 5 w/o
Inlet temperature	285°C
Outlet temperature	315°C
Operating pressure	15.5 MPa

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.

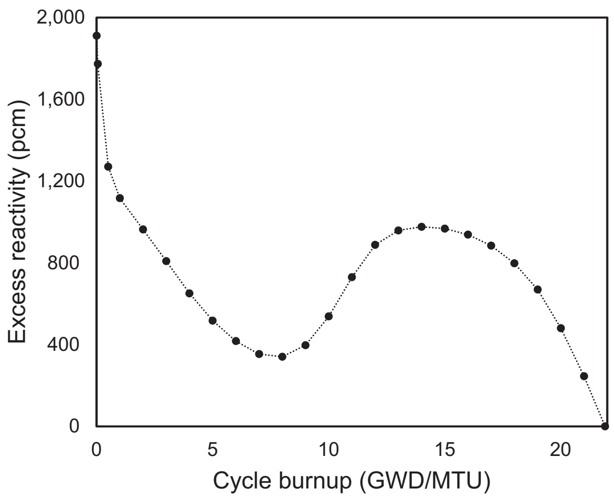


Fig. 2. Core depletion characteristics.

Please cite this article in press as: L. van der Merwe, C.J. Hah, Reactivity balance for a soluble boron-free small modular reactor, Nuclear Engineering and Technology (2018), https://doi.org/10.1016/j.net.2018.01.019