Proceedings of the Reactor Physics Asia 2015 (RPHA15) Conference
Jeju, Korea, Sept. 16-18, 2015

Preliminary Analysis of New Secondary Shutdown System of Small Modular Pressurized Water Reactor

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1. Introduction

A boron-free Pressurized Water Reactor (PWR) design is difficult to achieve due to the large size of the reactors, whereas it is one of the viable options for small modular PWRs (SMPWRs). The boron-free operation can reduce a large amount of liquid radioactive waste and also remove the corrosion problem caused by boric acid [1]. According to the licensing requirements [2], there must be at minimum two independent shutdown systems. The two shutdown systems of commercial PWRs are control rod insertion and boron injection. A boron-free SMPWR requires an additional shutdown system other than boron injection.

This paper suggests two kinds of new shutdown systems for SMPWRs at the beginning of cycle (BOC). The first one is a gadolinium nitrite ($Gd(NO_3)_3$) injection in the coolant of the reflector region. The second one is core separation into two or three parts. The performances of the proposed secondary shutdown systems are evaluated using the CASMO-4E/SIMULATE-3 code system with the ENDF/B-VI library [3-5].

2. Primary Shutdown System

2.1 Specification of SMPWR

The specification of SMPWR is summarized in Table I. The electrical power is 50 MWe and the efficiency is assumed to be 25 %, such that the thermal power is 200 MWt. The fuel assembly (FA) is based on the Westinghouse 17x17 fuel assembly and a total of 37 FAs are loaded in the core. The fuel enrichment of fresh fuel is 4.95 %. Gadolinia rods are used as burnable absorbers. The core diameter is about 1.5 m and the height is 2.0 m. The initial excessive reactivity is less than 5000 pcm. There is no boron in the moderator.

Table I. SMPWR Core Specification

Parameters	Target value	Unit
Thermal power	200	MWt
Electrical power	50	MWe
FA type	17x17	Westinghouse
Fuel enrichment	4.95	%
Number of FAs	37	
Active core height	2.0	m
Excessive reactivity	< 5,000	pcm
Shutdown margin	> 4,500	pcm
Boron concentration	0	ppm

The loading pattern of the core is shown in Fig. 1. The 33 FAs are loaded with 16 gadolinia pins and the other 4 FAs are loaded with 12 gadolinia pins. The layout of the control element assembly (CEA) is shown in Fig. 2. There are five groups of CEAs. The CEA material is Ag-In-Cd which is used in commercial Westinghouse PWRs [6].

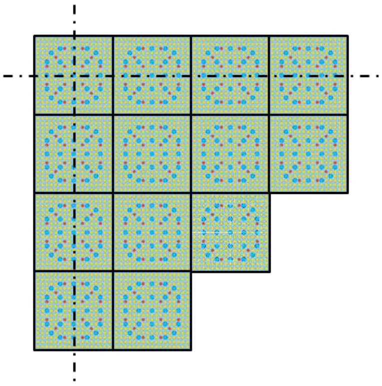

Fig. 1. SMPWR Quarter Core Loading Pattern.

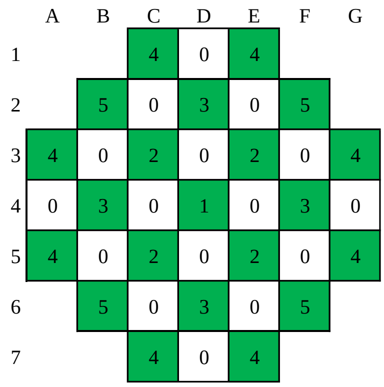

Fig. 2. CEA Layout of SMPWR. There are five groups of CEA.

2.2 Primary shutdown system – CEA

The primary shutdown system is the CEAs. Fig. 3 shows the rod worth of each group of CEAs. The initial excessive reactivity is within 5,000 pcm, so for CEA 1, and 3-5 is enough to control the reactivity during operation. CEA 2 can be the shutdown bank due to its having the largest rod worth.

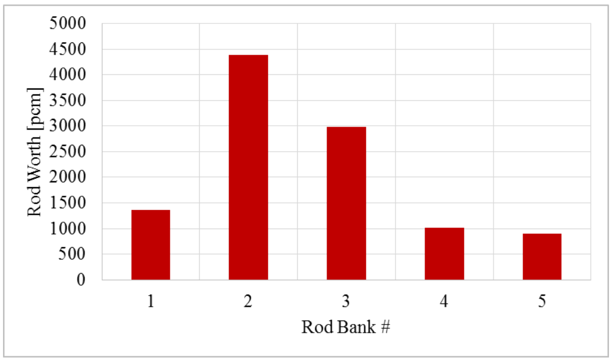

Fig. 3. Control Rod Worth of each group of CEA.

3. Secondary Shutdown Systems

In this section, two types of secondary shutdown systems are proposed: 1) $Gd(NO_3)_3$ injection in the reflector region and 2) Reactor separation.

3.1 $Gd(NO_3)_3$ injection in the reflector region

The first proposal of the new secondary shutdown system is a gadolinium nitrate ($Gd(NO_3)_3$) injection in the coolant in the reflector region. $Gd(NO_3)_3$ solution has been used as a burnable absorber in pressurized heavy water reactors (PHWRs) [7].

The radial reflector worth as a function of $Gd(NO_3)_3$ concentration is shown in Fig. 4. The worth of 10,000 ppm of $Gd(NO_3)_3$ solution is less than 100 pcm compared with that of 0 ppm of $Gd(NO_3)_3$. The PWR core is a thermal spectrum system such that the mean free path of neutrons is as short as several centimeters. The reactivity effect of neutron absorption in the reflector region is very small and not sufficient to meet the required shutdown margin.

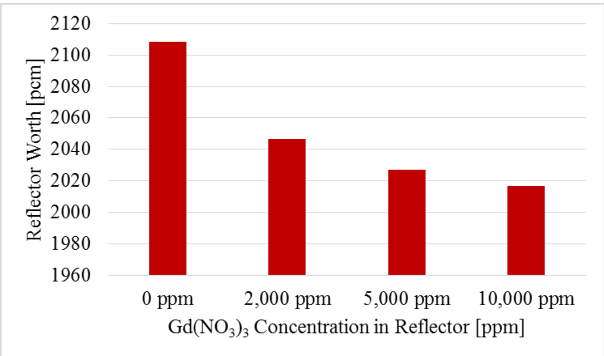

Fig. 4. Radial reflector worth vs. $Gd(NO_3)_3$ concentration.

3.2 Core separation

The second proposal for a secondary shutdown system is a core separation. It is feasibility calculation in point of neutronics. The core geometry of this idea is as shown in Fig. 5. A concept of core separation drive mechanism is similar to a control rod drive mechanism (CRDM) [8]. The top core is fixed. Other cores are supported by plates and axial holders through guide tubes. They can move between latches inside a reactor vessel. The core will be separated in the axial direction for shutdown. The k_{eff} difference as a function of gap distances between the separated cores is shown in Fig. 6. The first core separation option is separation in two parts as shown in Fig. 5 (a). The reactivity effect is smaller than 1000 pcm, which is insufficient for shutdown. The second separation option is separation in three parts, the reactivity effect of which is bigger than 6000 pcm for a gap distance of 40 cm.

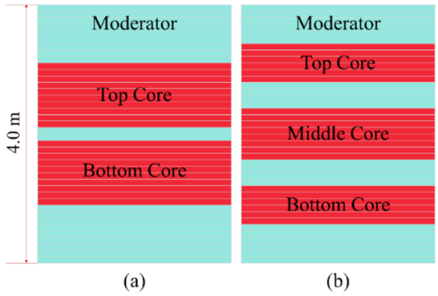

Fig. 5. Core separations: (a) Two parts. (b) Three parts.

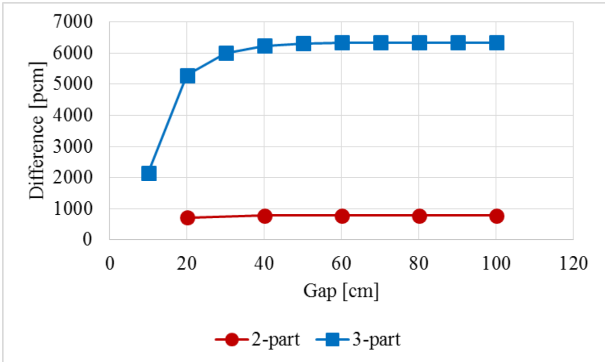

Fig. 6. Reactivity vs. gap distance.

6. Conclusions

This paper suggests new secondary shutdown systems for SMPWR, which requires a new secondary shutdown system in place of the boron injection of the commercial PWR due to boron-free operation. Two new shutdown mechanisms are suggested: 1) $Gd(NO_3)_3$ injection and 2) core separation. It is demonstrated that the $Gd(NO_3)_3$ injection in the reflector region provides insufficient reactivity effect for shutdown due to the characteristics of the thermal core, and the core separation into three parts with a gap distance of 40 cm provides sufficient reactivity effect for a safe SMPWR shutdown.

References

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