Estimation of Shutdown Margin for the Long-term Sustainable Small Modular Reactor, SALUS

Jong-Hyuck Won and Jae-Yong Lim
Gen-IV Reactor Technology Development Division, Korea Atomic Energy Research Institute
111 Daedeok-daero 989 beon-gil, Yuseong-gu, Daejeon 34057, KOREA
jhwon@kaeri.re.kr

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1. Introduction

Recently, interest in small modular reactors (SMRs) has increased worldwide. In fast reactor systems, a long-term sustainable SMR that maximizes uranium utilization can be easily achieved due to the breeding capability of fast neutrons. Based on the PGSFR [1] design experience, KAERI has carried out a conceptual design of SALUS (Small, Advanced, Long-cycled and Ultimate Safe SFR). [2]

In this paper, the shutdown margins for the primary and secondary control systems of the SALUS are estimated. The excess reactivity during long-term operation considering the irradiation expansion of metallic fuels and its impact on the shutdown margin, will be discussed.

2. Overview of the SALUS core

The SALUS core was designed to have a cycle length of 20 years with a power output of 100 MWe. To achieve such a long cycle length, the radial and axial fuel enrichment zoning concept has been used. Figure 1 and 2 show the radial layout of the SALUS core and the axial geometry of the fuel rods, respectively.

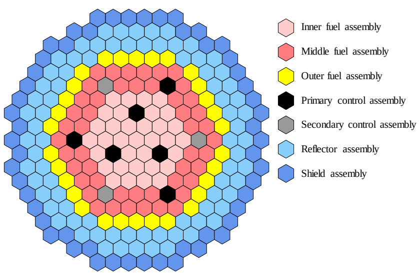

Fig. 1. Radial core layout of the SALUS

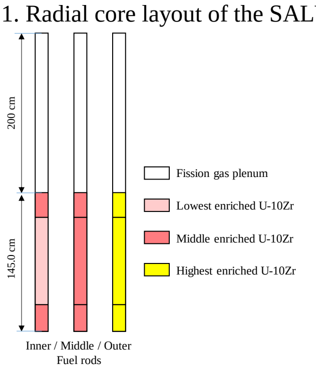

Fig. 2. Axial geometry of fuel rods of the SALUS

The table I summarizes the design parameters and core performances of the SALUS core.

Table I: Design parameters and core performances of the SALUS core

Thermal power	267 MWth
Coolant Inlet/Outlet Temperature	360 / 510 ℃
EFPDs	6580 ~ 6840 days
Fuel type	U-10%Zr
# of fuel pins per assembly	169
Assembly pitch	17.995 cm
Active core height	145 cm
Fission gas plenum height	200 cm
CDF design limit	> 0.05
Cladding mid-wall temperature limit	> 645 ℃
Average discharge burnup	72.8 GWd/MT
Peak fast neutron fluence	3.78E+23 n/cm^2
Average/Peak power density	52.3 / 88.7 W/cm^3

In Table I, the effective full power days range from 6,580 to 6,840. Over a 20-year cycle length, five planned reactor shutdowns and eight unplanned reactor shutdowns are assumed for the SALUS operation plan. Four of the five planned reactor shutdowns are intended for control assembly (CRA) exchange.

If the SALUS core can operate for 20 years without CRA exchanges, the capacity factor increases to 93.7%. The detailed types and periods of reactor shutdowns, along with their corresponding capacity factors, are summarized in Table II.

Table II: Shutdown periods and capacity factor of the SALUS core

	Number of shutdowns	Shutdown period (days/#)
Refueling	1	365
Exchange of CRA	4	65
Unplanned shutdown	8	12
	Capacity factor	
with CRA exchange	90.1 % (~6580 EFPDs)	
w/o CRA exchange	93.7 % (~6840 EFPDs)	

A detailed evaluation of control assembly performance is required to ensure the integrity of the control rod cladding and to assess the control assembly's worth with boron-10 (B-10) depletion, especially for a

20-year operation without CRA exchange. These evaluations will need to be conducted in the future.

3. Shutdown margin estimation

3.1. Large excess reactivity at BOC

In general, soluble boron for reactivity control is not used in sodium-cooled fast reactor designs. Therefore, control assemblies must control excess reactivity and it affects the required control assembly worth for reactor shutdown.

In the SALUS design, U-10%Zr metallic fuel is used for the fuel elements. The metallic fuel has very high thermal conductivity, providing a large thermal margin for reactor safety. However, irradiation expansion of the metallic fuel is significant compared to ceramic fuels. Consequently, the excess reactivity at the beginning of the core (BOC) would be high. According to Ref. [3], an axial irradiation growth of 8% occurs within a burnup of 1.0 atomic percent in U-10%Zr fuel. In radial direction, fuel slug-cladding gap exists because the 75 % smeared density of the fuel is assumed. This gap is filled with sodium bond at BOC, and fuel slug expanded radially as burnup increases.

The figure 3 shows the k_{eff} curve of the SALUS.

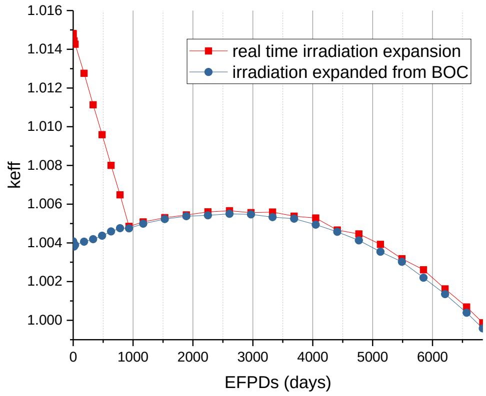

Fig. 3. keff curve of the SALUS

The McCARD [4] Monte Carlo code was used for the SALUS depletion calculation. For "real time irradiation expansion" depicted in Fig. 3, the number densities and geometry of the fuel element were modified using an in-house Python script at each burnup step up to a 1.0 atomic percent average burnup. As shown in Fig. 3, the excess reactivity at BOC is relatively high.

3.2. Shutdown margin of the SALUS core

To ensure the sufficient negative reactivity insertion capability for the reactor shutdown system, the shutdown margins for the primary/secondary control system were evaluated as follows:

Temperature defect: In case of a reactor shutdown, the power rate decreases and the core temperature drops. As a result of this core temperature drops, positive reactivity is introduced into the system. This positive reactivity insertion is called a temperature defect.

Overpower: To ensure a conservative reactor core design, the shutdown margin must cover a temperature defect when 15 % overpower compared to normal operation is assumed. This additional positive reactivity insertion during reactor shutdown is evaluated to be 15 % of the temperature defect from hot full power to hot shutdown condition.

Excess reactivity: The primary control assembly is not only used for reactor shutdown but also for excess reactivity control. Hence, the primary control assembly should achieve a reactor shutdown even when the primary control assembly is positioned at the critical rod position to control excess reactivity.

Reactivity fault: It is assumed that one control rod assembly with the highest control rod worth among the primary control rod assemblies is withdrawn from the core when the reactor is shut down at the beginning of cycle. For conservative design, the shutdown margin should compensate this reactivity fault.

Fuel fissile loading uncertainty: The primary control system should cover the reactivity from the fuel fissile loading tolerance. The fissile loading tolerance 1$ is considered.

As shown in Fig.1, there are two kinds of reactivity control systems in the SALUS core, and each of them has a different role. The primary control system should compensate temperature defect from the hot full power condition (HFP) to the refuelling condition (RC) while the secondary control system should compensate temperature defect from the hot full power condition to the hot shutdown (HS) condition.

For the temperature defect, overpower, and the reactivity fault, the 97.5/97.5 uncertainties are considered. For the excess reactivity, the 97.5/97.5 k-eff prediction uncertainty is considered. Those uncertainties were quantified by analysis of the BFS-84-1 experiment using McCARD code.[5]

The combined uncertainty of the required control system worth is obtained by root square sum of each uncertainty components. Table III and IV shows the shutdown margin for the primary/secondary control system of the SALUS.

Table III: Shutdown margin for the primary control system of the SALUS ($)

	BOC	EOC
Temperature defect (HFP to RC)	0.502 ± 0.184	0.501 ± 0.206
15% overpower capability	0.038 ± 0.014	0.037 ± 0.015
Excess reactivity	1.994 ± 0.842	0.114 ± 3.085
Reactivity fault	0.265 ± 0.047	-
Fuel fissile loading tolerance	0.000 ± 1.000	0.000 ± 1.000
Required control system worth	2.799 ± 1.321	0.652 ± 3.250
(N-1) primary control assembly worth	6.380 ± 1.110	11.068 ± 2.025
Shutdown margin	1.150	5.141

Table IV: Shutdown margin for the secondary control system of the SALUS ($)

	BOC	EOC
Temperature defect (HFP to HS)	0.256 ± 0.094	0.247 ± 0.100
15% overpower capability	0.038 ± 0.014	0.037 ± 0.015
Reactivity fault	0.265 ± 0.047	-
Required control system worth	0.559 ± 0.106	0.284 ± 0.101
(N-1) secondary control assembly worth	2.118 ± 0.369	2.953 ± 0.540
Shutdown margin	1.085	2.028

As shown in table III and IV, the shutdown margins of the primary/secondary control system is greater than 1$. However, in the primary control system, shutdown margin is around 1$ at BOC while it is over than 5$ at EOC. The major factor of this phenomena is large excess reactivity due to metallic fuel's irradiation expansion behaviour as discussed in Section 3.1.

If core design improvement to reduce large excess reactivity at BOC is achieved, more efficient primary control system design would be possible.

4. Conclusion

The shutdown margins of the primary and secondary control system for the SALUS are estimated in this study. For the metallic fueled SFR, a large excess reactivity at BOC has impact on the minimum required control assembly worth. Despite of large excess reactivity at BOC, the shutdown margins of the primary/secondary control system are greater than 1$. However, due to the large excess reactivity at BOC, the shutdown margin of primary control system at EOC is over than 5$.

For efficient and improved control system design for the SALUS, the core design would be changed to reduce the excess reactivity at BOC. The usage of B4C burnable poison is one candidate of core design improvement and this research topic will be studied as a further study.

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