*Transactions of the Korean Nuclear Society Spring Meeting*
*Jeju, Korea, May 18-19, 2023*

# The Preliminary Analysis of the Reactivity Parameters and Fuel Performance Evaluation on a Long-term Sustainable Small Modular Reactor, SALUS

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## 1. Introduction

Korea Atomic Energy Research Institute (KAERI) has studied pool-type sodium cooled fast reactors (SFRs), and the specific design of Proto-type Gen-IV SFR (PGSFR) has been done in 2017 [1]. Recently, there has been a growing interest in small modular reactors (SMRs) worldwide. In a fast reactor system, a long-term sustainable SMR that maximizes uranium utilization can be easily achieved due to the breeding capability of fast neutrons. Using their experience with the PGSFR design, KAERI has developed a conceptual design for SALUS (Small, Advanced, Long-cycled and Ultimate Safe SFR).

In a long-term operation of the reactor core without refueling, the neutron flux distribution and the number density of fuel element will be changed a lot. So, the reactivity parameters of the SALUS core would be changed also during operation. In this study, various reactivity parameters are calculated and compared at the beginning, middle, end of the SALUS core to investigate whether safe long-term operation of the reactor is possible.

Additionally, this study examines fuel rod integrity in the SALUS core. The fuel rods are exposed to high temperatures and fast neutron flux for a long period of time. To determine the fuel rod's integrity after long-term operation, the Cumulative Damage Fraction (CDF) of the cladding is calculated in this study.

## 2. SALUS Core Description

The SALUS core was designed with a cycle length of 20 years with 100 MWe power. Fig.1 and Fig.2 show radial and axial view of the SALUS core and fuel rods.

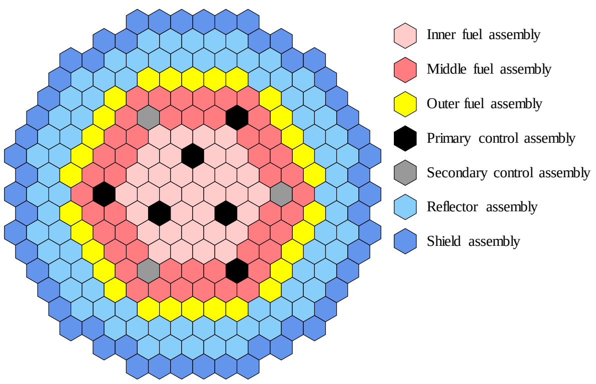


Fig. 1. Radial core layout of the SALUS

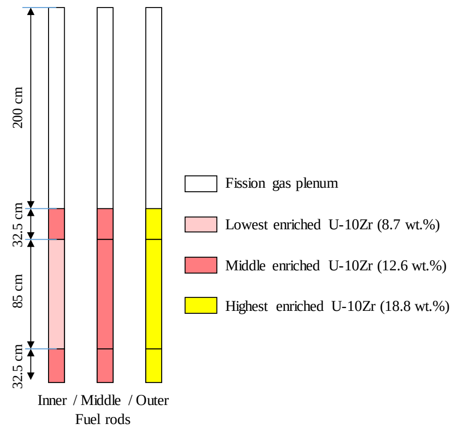


Fig. 2. Axial geometry of fuel rods of the SALUS

The SALUS core is charged with U-10Zr metallic fuel. As shown in Fig. 1 and 2, the U-235 enrichment in the inner core region is relatively lower than in other regions. To achieve a 20-year long-term operation with a small reactivity swing, effective breeding of fertile isotopes to fissile isotopes is required. Therefore, the lowest enriched fuel is placed in the inner region of the core. In the radially peripheral region of the active core, the highest enriched fuel assemblies are placed to provide enough criticality at the beginning of the core. The table below summarizes the main design parameters and core characteristics of the SALUS core.

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

| | |
|---|---|
| Thermal power | 268 MWth |
| Coolant Inlet/Outlet Temperature | 360 / 510 ℃ |
| EFPDs | 7300 days |
| Fuel type | U-10Zr |
| # of fuel pins per assembly | 169 |
| Assembly pitch | 17.995 cm |
| Active core height | 150 cm |
| Fission gas plenum height | 200 cm |
| CDF design limit | < 0.05 |
| Cladding mid-wall temperature limit | < 645 ℃ |
| Burnup reactivity swing | 507.9 pcm |
| Average discharge burnup | 75.019 GWd/MT |
| Peak fast neutron fluence | 3.94E+23 n/cm$^2$ |
| Average/Peak power density | 50.5 / 85.9 W/cm$^3$ |

The design limit of the fuel rod is determined by the CDF and the cladding mid-wall temperature values. The CDF should be less than 0.05, and the maximum cladding mid-wall temperature should be less than 645 ℃ to avoid eutectic melting. These design limits are the same as those for the PGSFR.

## 3. Numerical Results

### *3.1 Reactivity calculation results*

For neutronics calculations, the McCARD [2] Monte Carlo code was used. In the PGSFR design, the deterministic fast reactor analysis code package $MC^2$-3 [3], DIF3D [4], and REBUS-3 [5] were used. However, for long-term depletion calculations, it was observed that the $MC^2$-3/DIF3D/REBUS-3 codes show a large discrepancy in the depletion curve result [6]. Therefore, the McCARD code was mainly utilized for the SALUS core design, and the $MC^2$-3/DIF3D/REBUS-3 codes were used as an auxiliary code system.

The reactivity calculation results of the McCARD and $MC^2$-3/DIF3D codes are shown in Tables II and III.

Table II: McCARD reactivity calculation results of the SALUS core (pcm/K)

| Reactivity | BOC | MOC | EOC |
|---|---|---|---|
| Doppler | -0.606 | -0.529 | -0.483 |
| Sodium temperature | 0.038 | 0.130 | 0.172 |
| Axial expansion | -0.181 | -0.201 | -0.200 |
| Radial expansion | -0.658 | -0.796 | -0.853 |

Table III: $MC^2$-3/DIF3D reactivity calculation results of the SALUS core (pcm/K)

| Reactivity | BOC | MOC | EOC |
|---|---|---|---|
| Doppler | -0.589 | -0.527 | -0.491 |
| Sodium temperature | 0.052 | 0.132 | 0.171 |
| Axial expansion | -0.178 | -0.193 | -0.202 |
| Radial expansion | -0.686 | -0.823 | -0.886 |

As shown in Table II and III, both McCARD and $MC^2$-3/DIF3D calculation results agree well with each other except for the sodium temperature reactivity at BOC. At BOC, the metallic fuel is not smeared, so there is a sodium bond between the fuel element and cladding. Due to $MC^2$-3/DIF3D treating homogeneous assembly in the whole core calculation, this heterogeneous effect may not be fully resolved when the sodium coolant density changes.

The sodium temperature reactivity feedback shows positive in both calculations. The active core height is increased to 150 cm from 90 cm of the PGSFR, so the effective neutron leakage from the system will be decreased when the coolant temperature rises. Therefore, the neutron spectrum hardening effect plays a dominant role when the sodium temperature changes. However, the radial expansion reactivity parameter, which is also related to the sodium coolant temperature, shows very large negative values. So, the overall coolant temperature effect is negative.

The sodium temperature reactivity varies a lot compared to other reactivity parameters during operation. In the SALUS core, the radial power shape is changing due to breeding of Pu-239 isotope. The net neutron leakage will be decreased at EOC because the inner core region has more neutron population. This leads to a more positive sodium temperature reactivity effect. In addition to net leakage changing, increasing the inventory of Pu-239 also affects the positive sodium temperature reactivity.

### *3.2 CDF calculation results*

For the CDF calculation, the LIFE-METAL code [7] is used, which was co-developed by KAERI and Argonne National Laboratory (ANL). The LIFE-METAL calculation in this paper considers power density, cladding temperature, and model uncertainties.

To perform the LIFE-METAL calculation, a cladding temperature profile is required as input data. The cladding temperature profile during long-term operation was calculated using the SLTHEN thermal-hydraulic code [7]. In the SLTHEN calculation, uncertainties were taken into account through the hot channel factor (HCF). Currently, the HCF values for the SALUS core are employed from the PGSFR.

Since the CDF value is a strong function of the cladding temperature, the flow grouping and allocation methods are important. Fig.3 shows the conventional flow grouping scheme in which the maximum cladding mid-wall temperature for each flow group is the same during the operation period.

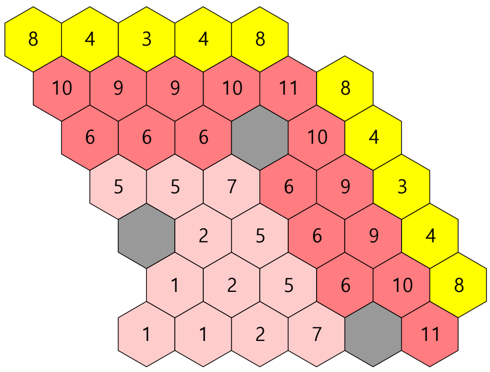

Fig. 3. Cladding temperature based flow allocation flow group numbering

In Fig.3, a lower flow group number means a larger flow rate is allocated. As shown in the figure, there is a large flow rate at the inner and outer fuel assemblies. At BOC, the outer fuel assembly has a high thermal power due to its high enriched fuel. After long-term operation, the inner fuel assembly has high thermal power due to the breeding of fissile isotopes. Hence, a large amount of flow should be allocated to those regions.

Unlike the inner and outer fuel assemblies, the middle fuel assembly does not show a peak power during long-term operation. The power in time at the middle fuel assembly does not vary much.

Fig.4 and Fig.5 show the CDF calculation results when the maximum cladding mid-wall temperature flattening flow grouping scheme is used. As shown in Fig.4, after 18.5 years of operation, some of the middle fuel assemblies do not satisfy the CDF design limit. Those fuel assemblies experience high cladding temperature for a long time because power in time does not change much, so the CDF exceeds the design limit.

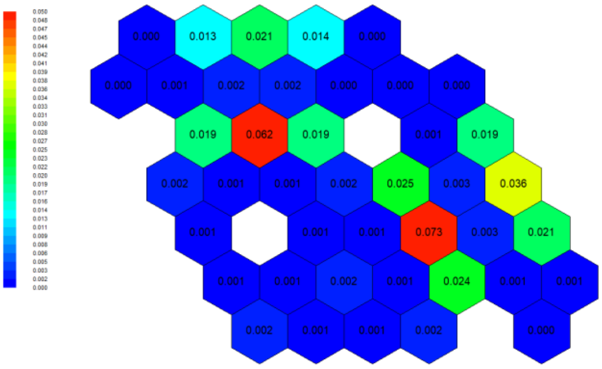


Fig. 4. CDF results after 18.5-year operation (cladding temperature based flow allocation)

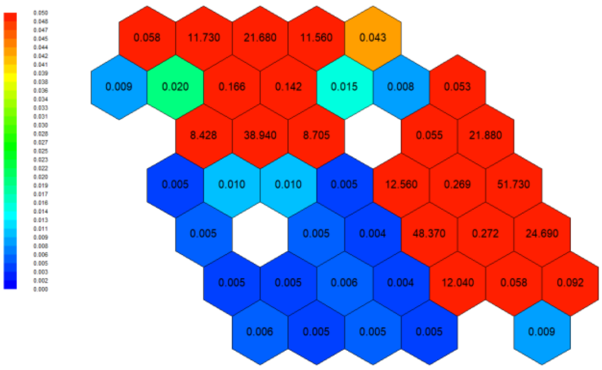


Fig. 5. CDF results after 20.0-year operation (cladding temperature based flow allocation)

The Fig.5 shows CDF values after 20.0-year operation. It is shown that inner fuel assemblies show very small CDF values compared to middle/outer fuel assemblies.

To lower CDF values at middle/outer fuel assembly, flow re-allocation was performed. The flow rate at inner fuel assemblies are moved to middle/outer fuel assemblies and minor adjustment was done with iterative work.

The Fig.6 shows re-allocated flow grouping scheme to reduce the maximum CDF values of the SALUS core. (the lower number means large flow rate like Fig. 3)

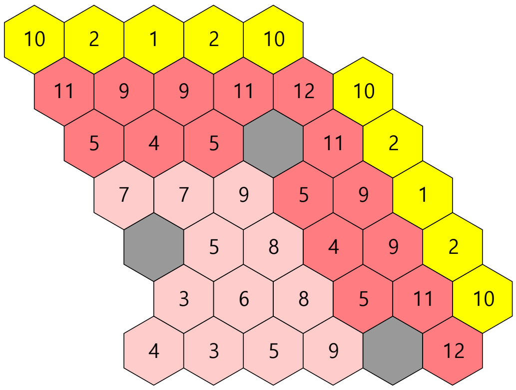


Fig. 6. CDF based flow allocation flow group numbering

The Fig.7 and Fig.8 show CDF calculation result when re-allocated flow group is used.

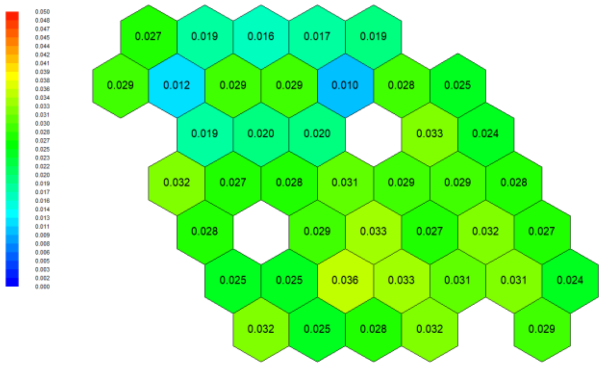


Fig. 7. CDF results after 19.5-year operation (CDF based flow allocation)

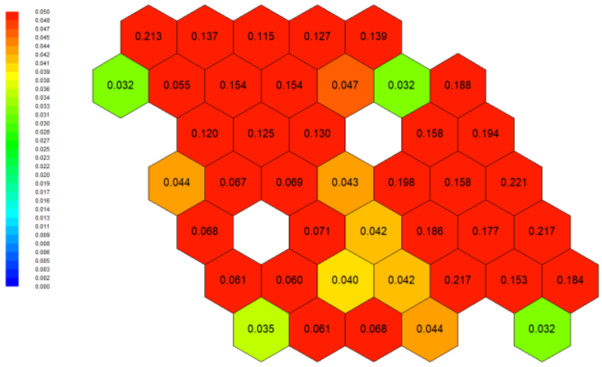


Fig. 8. CDF results after 20.0-year operation (CDF based flow allocation)

After 19.5-year operation, the CDF values satisfy design limit. Unfortunately, after 20.0-year operation which is target EFPDs, the CDF values does not satisfy design limit. As shown in Fig.8, almost all fuel assemblies show CDF values larger than design limit. Hence, there is not enough flow to re-allocate for lowering CDF. Even though flow is re-allocated, the maximum cladding mid-wall temperature during operation period is 631.9 ℃ which satisfy design limit.

The core design changes such as fuel enrichment adjustment should be considered to reduce peak burn-up and satisfy the design limit.

## 4. Conclusions

In this study, the preliminary analysis of the reactivity parameters and the CDF of the SALUS core were performed. The Doppler, radial and axial expansion reactivity parameters show negative values during long-term operation. However, sodium coolant temperature parameter shows positive value. In SFR, positive sodium void reactivity effect is well known problem. Fortunately, the amount of positive reactivity is much smaller than the negative radial expansion reactivity which is also related with sodium coolant temperature. Therefore, overall sodium coolant temperature reactivity feedback is shown as negative. As a further study, the transient analysis should be done to verify the SALUS core keep its safety in various accident scenarios.

The CDF values are preliminary estimated to check fuel rod integrity after long-term operation without refueling. In numerical results, it is shown that proper flow allocation to reduce the maximum CDF could extend cycle length effectively. In current conceptual design stage, only 19.5-year operation satisfy the CDF design limit. For the future works, core design modification such as fuel enrichment zone adjustment will be performed to achieve 20-year target operation period.

## ACKNOWLEDGEMENTS

This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. NRF-2021 M2E2A1037869).

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