# Comparison of REBUS-3 and McCARD Depletion Calculations on a Long-term Sustainable Small Modular Reactor, SALUS

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## 1. Introduction

Korea Atomic Energy Research Institute (KAERI) has been studied pool-type sodium cooled fast reactors (SFR), and issued Specific Design Safety Analysis Report (SDSAR) according to the specific design of Proto-type Gen-IV SFR (PGSFR) in 2017 [1]. Since then, the project has been stagnant for a long time due to the domestic energy policy change. Currently long-term sustainable small modular reactors are attracting attentions worldwide, which are designed for maximize the utilization of uranium resources by using fast neurons. KAERI is also carrying out a conceptual design of SALUS (Small, Advanced, Long-cycled and Ultimate Safe SFR) under the PGSFR design experience.

The reactor core design of PGSFR was conducted by MC$^2$-3 [2] / REBUS-3 [3], but there were concerns about SALUS core design with MC$^2$-3/REBUS-3 codes because of several reasons. REBUS-3 uses pre-calculated multi-group cross sections, but the multi-group cross sections for later depletion steps of SALUS cannot be prepared in advance. Also, the lumped fission product of PGSFR is uncertain to be adopted in SALUS analysis. Additionally, the code system was set-up based on ENDF/B-VII.0 library only, so other libraries can be hardly examined.

As an alternative approach, the parametric study was performed by deterministic code systems, MC$^2$-3/REBUS-3, while McCARD [4] Monte Carlo calculations were assigned for SALUS core design. In this paper, the conceptual design of SALUS is described, and the depletion calculation results of McCARD and REBUS-3 are discussed.

## 2. Conceptual Design of SALUS

The SALUS core was designed with a cycle length of 20 years with 100MWe power. The key design limit of the fuel rod is determined by the Cumulative Damage Fraction (CDF), which should be kept less than 0.05 as PGSFR. Since CDF is a function of cladding temperature, fuel rod internal pressure, and burn-up, in order to unsure the fuel rod integrity for extended cycle length, the coolant inlet/outlet temperatures were set lower than that of PSGFR, and the gas plenum length was also increased.

The long cycle length can be achieved by lowered power density, and the conversion of isotopes, fertile to fissile, through high neutron economy. Fuel volume fraction was increased to maintain the criticality during the long-term sustainable operation. It is essential to load more fuels in the core to compensate the reactivity loss during 20 years of operation. Also, affordable discharge burn-up could be achieved by increased heavy metal, and this secures CDF margin by reducing the fission gas pressure. Increased fuel loading results in increased assembly pitch, and the active core becomes greater than PGSFR. However, the whole core can be loaded inside the core shroud of PGSFR, because of the absence of In-Vessel Storage (IVS) and its shielding structures; SALUS does not re-load fresh fuels during 20 years of the fuel cycle length. The detailed design parameters and characteristics can be found in Table 1 and Table 2.

The core layout is given in Fig. 1 comparing with that of PGSFR. The distribution of non-fuel assemblies is the same as PGSFR, while core regions are sub-divided differently to keep the core critical over 20 years of operation.

Table 1 Design parameters of PGSFR and SALUS

| Design parameter | PGSFR | SALUS |
|---|---|---|
| Thermal power | 392.2 MWth (150 MWe) | 268 MWth (100 MWe) |
| Design limit | CDF < 0.05 | CDF < 0.05 |
| Coolant Inlet/Outlet Temperature | 390 / 545 ℃ | 360 / 510 ℃ |
| EFPDs | 290 days | 7300 days (target) |
| Fuel batch | Inner/Outer = 4/5 | No refueling |
| Fuel type | U-10Zr | U-10Zr |
| Assembly pitch | 13.636 cm | 17.995 cm |
| # of fuel pins / assembly | 217 | 169 |
| Fuel smear density | 75 % TD | 75 % TD |
| Heavy metal inventory | 7545.2 kg | 25520.9 kg |
| Fuel volume fraction (hot condition) | 0.433 | 0.504 |
| Active core height | 90 cm | 150 cm |
| Fission gas plenum height | 127.5 cm | 200 cm |

Table 2 Main characteristics of PGSFR and SALUS

| | PGSFR | SALUS |
|---|---|---|
| Avg. Discharge Burnup | 65.941 GWd/MT | 75.019 GWd/MT |
| Peak fast neutron fluence | $2.867 \times 10^{23}$ n/cm$^2$ | $3.935 \times 10^{23}$ n/cm$^2$ |
| Burnup reactivity swing | 2219.5 pcm | 507.9 pcm |
| Avg. power density (Active core region) | 211.503 W/cm$^3$ | 50.537 W/cm$^3$ |
| Peak power density (BOEC or BOC) | 386.264 W/cm$^3$ | 85.876 W/cm$^3$ |

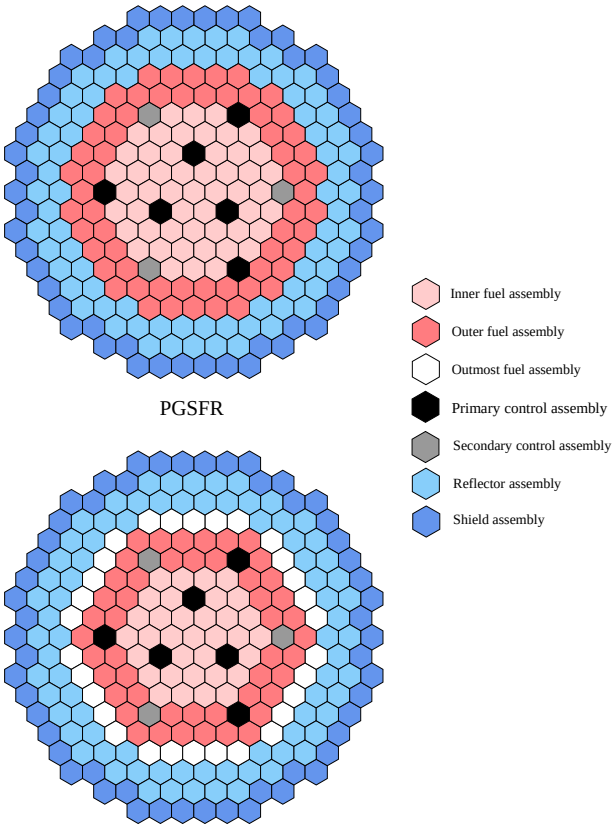


Fig. 1 Core layout of PGSFR and SALUS

The axially integrated fission power distributions for BOC, MOC and EOC are given in Fig. 2. At BOC, the fission power is lower at the center assemblies because low-enriched fuels are loaded in the inner core. However, the fission power at the center is increased at MOC and EOC after breeding, while the power of outer core becomes decreased.

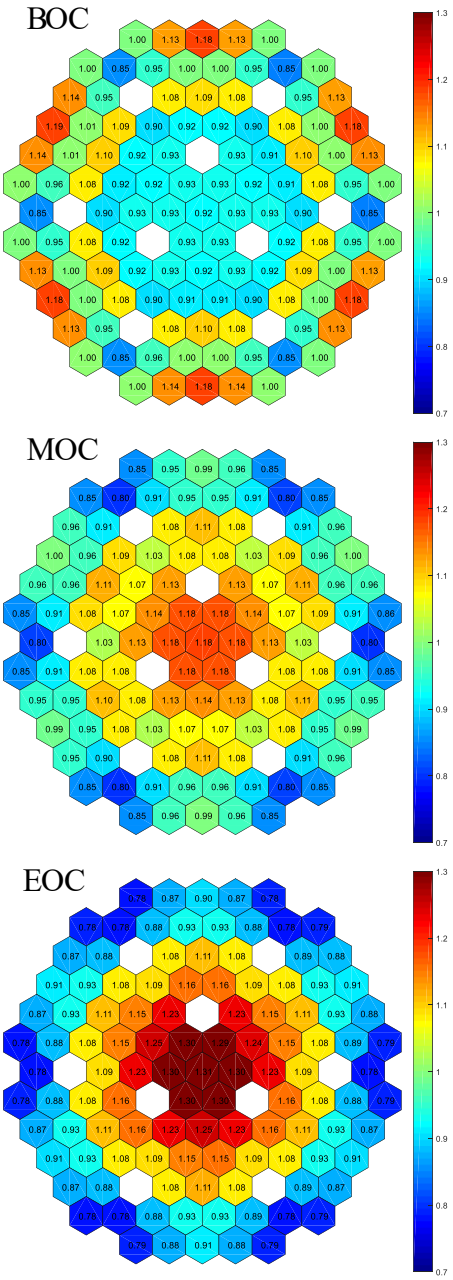


Fig. 2 Axially integrated fission power of SALUS

## 3. Depletion Calculations

### *3.1 McCARD with various models*

The McCARD model for SALUS depletion calculation has been developed with heterogeneous geometries. However, the lower and upper plug and axial reflector in the fuel pin are modeled as homogenized cells. Axially 14 sub-meshes are modeled for the depletion zones, while the 169 fuel pins are to be burned together. The built-in one-group cross section for depletion calculation in McCARD was not suitable for fast reactors, so very short time step (0.01 day) was calculated initially to obtain updated one-group cross sections. The depletion calculation was conducted with

500k particles for 250 active cycles (50 inactive cycles) based on ENDF/B-VII.0 library. Note that the uncertainty of k-eff at each burn-up step was estimated about 4 pcm.

In this work, two different homogenized models were compared to the heterogeneous model. The one is a typical homogenization model, and the other one has a homogenized cell inside the duct while duct and gap coolant are explicitly molded. This model reflects the spatial self-shielding effects by duct, which is occurred by the large resonance cross section of Fe-56. Axial meshes remained the same as the heterogeneous model in the two different homogeneous models.

The depletion calculation results of heterogeneous and homogeneous models are plotted together in Fig. 3. At BOC, the k-eff of typical homogeneous model (orange line in the figure) showed 250 pcm difference while the homogeneous model with explicit duct and gap (green line in the figure) showed 150 pcm difference. However, the difference seems getting smaller, and this leads to totally different depletion curves for both homogeneous models.

Fig. 4 shows the k-eff error of homogeneous model, which is the difference of k-eff between homogeneous and heterogeneous model. The error is not a constant value, but it is almost linearly decreased according to operation days. This does not mean the error is decreasing as fuel burns, but means the error of homogenization is accumulated in the depletion calculation. As the error appeared significantly reduced at EOC, the cycle length of SALUS obtained from homogeneous models will have large error compared to the heterogeneous model. The explicit duct model has less error compared to the typical assembly homogenization model, but the error trend is similar.

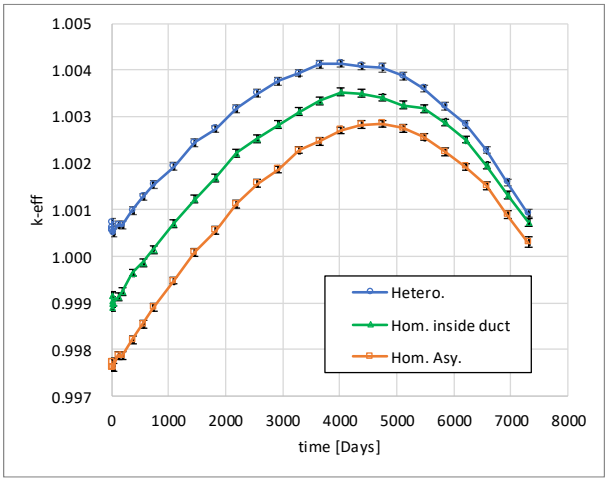


Fig. 3 McCARD depletion results with various models

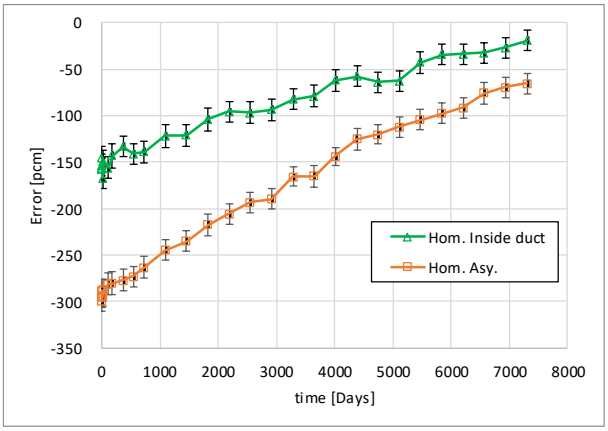


Fig. 4 k-eff error of homogeneous models compared to the heterogeneous mdel

### *3.2 REBUS-3 homogeneous calculation*

The cross section for each homogenized assembly in REBUS-3 calculation was prepared by MC$^2$-3/ TWODANT based on ENDF/B-VII.0 library. The ultra-fine group (1041G) cross section for fuel assembly and control assemblies were obtained 0D slowing down calculation. The neutron spectrum in the core was reflected into the multi-group cross section by TWODANT R-Z calculation. Note that the multi-group cross section was not updated; this was not issued previously since the spectrum transition is minor in PGSFR.

The depletion results of McCARD heterogeneous model and REBUS-3 were plotted in Fig. 5. Unlike McCARD homogeneous model, the depletion curves look similar to the McCARD heterogeneous model. The k-eff difference at BOC is about 350 pcm and it becomes about 270 pcm at EOC. The k-eff at BOC is similar to the assembly homogenization model of McCARD, but the EOC k-eff is significantly different even though the geometric modeling is essentially the same.

The error component in REBUS-3 calculation is plotted in Fig. 6. The green line indicates the k-eff difference between REBUS-3 and McCARD heterogeneous model. Note that the time step for REBUS-3 is different from McCARD, so the linearly interpolated REBUS-3 results are compared to McCARD. Since the geometry modeling is the same in REBUS-3 and McCARD homogeneous model, the homogenization error component would be similar and it is plotted as a blue dotted line in Fig. 4. The orange dotted line shows substitution of homogenization error from REBUS-3 error. The orange dotted line includes all other errors such as multi-group cross section, lumped fission product, and other methodology error. Before MOC, the homogenization error is dominant, so depletion curve seems similar to that of the McCARD homogeneous model. However, the homogenization error is canceled out by other error components, and REBUS-3 depletion curve shows steep decrease of k-eff until EOC. Fortunately, the overall depletion curve of REBUS-3 appeared similar to McCARD heterogeneous

model, and better depletion results can be obtained compared to the McCARD homogeneous model.

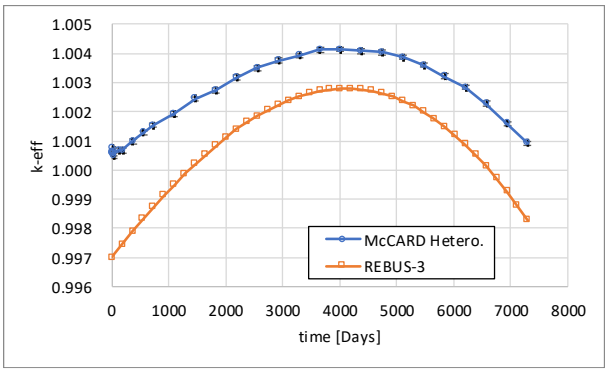


Fig. 5 Comparison of McCARD heterogeneous and REBUS-3 depletion calculation

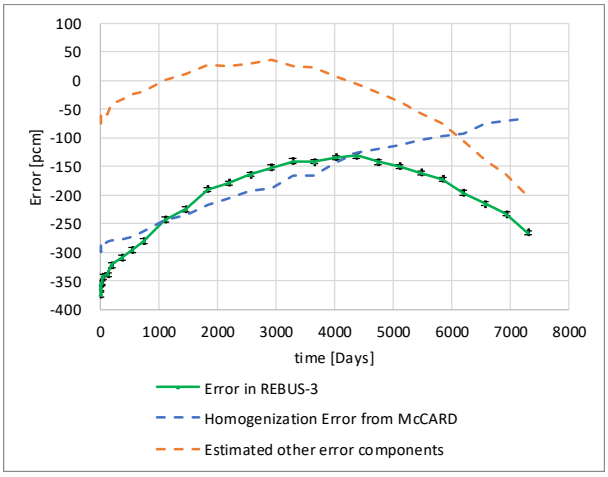


Fig. 6 k-eff error of REBUS-3 compared to the McCARD heterogeneous model

The other error components beside the homogenization error are not quantified yet, but the major one might be the error in multi-group cross section. Since the multi-group cross sections are unchanged, the accuracy becomes worse as fuel burns. As shown in Fig. 2, fission power distribution of SALUS changes dramatically from BOC to EOC, so the cross section would have greater error at EOC.

## 4. Conclusions

In this paper, the conceptual design of SALUS was described, and depletion calculation was performed for 20 years with two different neutronics codes, REBUS-3 and McCARD. For the fair comparison, McCARD models with homogeneous geometry was developed and the homogenization error was quantified first. Two different homogenization, assembly homogenization and the homogenization inside duct, were developed and the depletion calculation results were compared to the heterogenous model case. The homogeneous model with explicit duct showed reduced error, but the homogenization error behavior appeared similarly. The homogenization error is accumulated and results in greater k-eff at EOC. Therefore, large error in k-eff at BOC was reduced at EOC for both homogeneous models.

On the other hand, REBUS-3 shows better depletion results than McCARD homogeneous models. The error in k-eff was observed similarly at both BOC and EOC. Since the error of k-eff is smaller in MOC, slightly steeper depletion curve is obtained, but still reliable. In this manner, REBUS-3 can be considered suitable for parametric study on SALUS analysis.

The error of REBUS-3 was analyzed by dividing two components; homogenization error and all others. It turned out that other error components play important role after MOC, and errors are canceled out in REBUS-3 depletion calculation. The major error component is not cleared revealed yet, but the error related to fixed multi-group cross section might be the one because the error will be increased in the later depletion steps. The effects of fixed multi-group cross section on depletion calculation will be assessed in the further work.

## 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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