ESFR-LIKE PLUTONIUM BURNERS: DESIGN AND SAFETY STUDIES

Y. Tobita
Karlsruhe Institute of Technology
Karlsruhe, Germany
Email: Yoshiharu.tobita@kit.edu

X.-N. Cheng
Karlsruhe Institute of Technology
Karlsruhe, Germany

A. Rineiski
Karlsruhe Institute of Technology
Karlsruhe, Germany

INTRODUCTION: In the EU project PuMMA, several Pu burner cores based on the ESFR-SMART are proposed. They are analysed with respect to their burning performance and safety. Safety studies include ULOF (Unprotected Loss of Flow) transient simulations with the SIMMER-III code. In this study we present design and ULOF results for two cores: a Pu burner core with a conventional core configuration and a core, in which some fuel assemblies (SAs) are replaced with empty ones, with can-wall, but without fuel inside. Empty SAs are introduced in order to adjust the criticality in case of high Pu content. Oscillatory behaviours of reactivity and reactor power is observed, caused by the negative reactivity feedback due to coolant boiling above the fissile column, which lowers the reactor power and stops the boiling. In contrast to ESFR-SMART, this oscillation does not lead to prompt criticality even for conservative assumptions on reactivity feedback mechanisms. The empty SA locations can be also occupied by GEMs (Gas Expansion Modules), and the GEM effectiveness in ULOF is confirmed by SIMMER-III simulations.

1. OVERVIEW

In the context of the EU PuMMA [1] project on Pu management, the objective of this study is to elucidate the safety characteristics of SFRs used as reactors for the burning of Pu, and to provide insights that could contribute to the future licensing process of SFRs by analysing representative severe accident of SFRs, such as the Unprotected Loss of Flow (ULOF). The target cores are based on the ESFR-SMART [2] core developed in an earlier EU project. To ensure flexibility in responding to possible future societal demands for plutonium burning, this study assumes two types of plutonium burner core concepts with different plutonium contents. The first Pu burner core have been adapted to improve the Pu burning capability of ESFR-SMART core. Compared to ESFR-SMART core, the target core is of reduced axial dimensions and power, with increased Pu enrichment, while the Pu isotopic composition is assumed to be the same in the safety studies. It can be considered as a “mild” burner compared to the “strong” ones, with similar dimensions and power, but higher Pu enrichment, thinner fuel pins and introduced inert pins, which are investigated in PuMMA scenario studies. To maintain appropriate criticality with a "mild" Pu burner, an upper limit must be set on the Pu content, thereby limiting the Pu burning ability. To mitigate this, a core design was devised that increases the Pu content while replacing some of the fuel assemblies with empty ones to compensate for the excessive reactivity. This results in the second Pu burner core concept, i.e., "moderate" Pu burner.

One of the safety-oriented design features of ESFR-SMART and the Pu burners is the sodium plenum, which is placed just above the fissile top. The analysis of ULOF in ESFR-SMART using the SIMMER-III code [3] shows that reactivity and reactor power decrease due to sodium boiling in the sodium plenum, which increases neutron leakage, during the accident, followed by a subsequent reactor power increase when boiling subsides, indicating oscillatory behaviour reactivity and reactor power. This oscillatory behaviour is influenced by feedback effects, such as reactivity feedback due to core thermal expansion, and has been shown to drive to prompt criticality under certain conditions. The purpose of this study is to elucidate the effect of increased Pu enrichment and reduced core height in the Pu burner cores on this oscillatory behaviour. ULOF event is analysed with SIMMER-III, a safety code developed and applied by JAEA, KIT and other partners.

2. SPECIFICATION OF PU BURNER CORES

The radial and axial layout of the "mild" Pu burner core is almost similar to ESFR-SMART and is illustrated in FIG. 1. The mass balance of Pu and actinides in ESFR-SMART during fuel depletion is near zero. To increase the Pu enrichment and realize the Pu and, optionally, actinides burning, the height of the core is reduced, and the lower blanket material is replaced with steel pellets of the same diameter as the inner diameter of cladding. The fissile column height is reduced from 75 cm to 50 cm in the inner core, and from 95 cm to 65 cm in the outer core. The Pu fuel enrichment is increased from 18.7% in ESFR-SMART to 22.5% in the inner core and to 21.5% in the outer core. As the core height is reduced by about 1/3, the reactor power is also reduced from 3600 MWth to 2400 MWth and the primary coolant flow is reduced from 18705 kg/s to 12550 kg/s. In the "moderate" Pu burner core, 36 fuel subassemblies (SAs) in the inner core and 48 SAs in the outer core—for a total of 84 SAs (17%)—are replaced with empty SAs as shown in FIG. 2. The "moderate" Pu burner core has a reduced pin diameter, the number of pins in the assembly has been increased from 271 in the ESFR-SMART to 397. The Pu fuel enrichment is increased to 31.5%. The reactor power of the "moderate" Pu burner with about the same linear power as ESFR-SMART is 3000MWth.

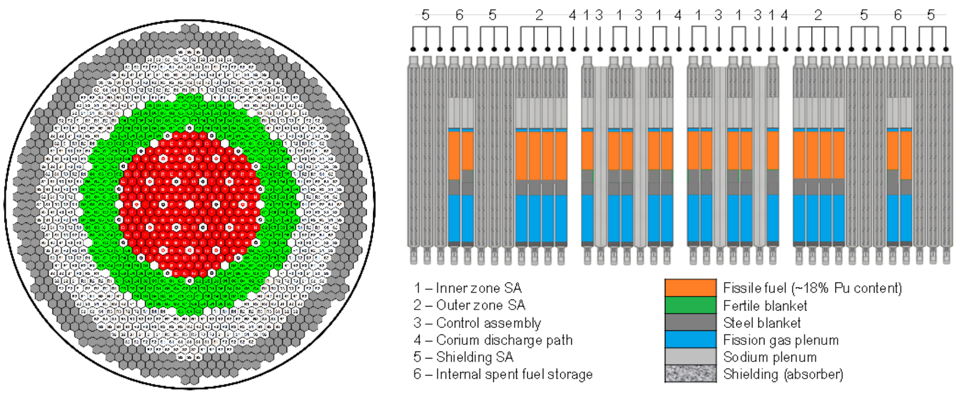


FIG. 1. Radial and axial core map (red: inner core, green: outer core)

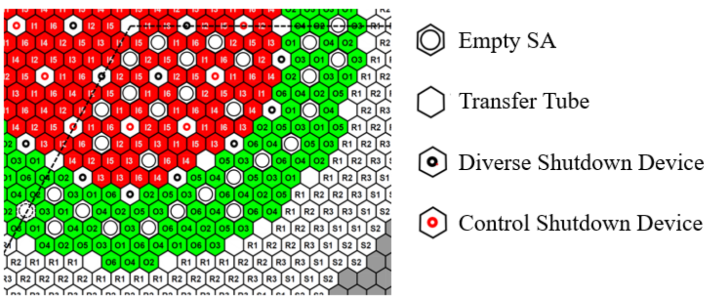


FIG. 2. Radial core map of "moderate" Pu burner with Empty SA

3. SIMMER MODELING

The cylindrical 2-dimensional SIMMER-III model is set up as shown in FIG. 3. The inner core is divided into 8 or 10 ("mild" or "moderate") fuel assembly (FA) rings, while the outer core has 3 or 4 ("mild" or "moderate") FA rings. The secondary loop and the intermediate heat exchanger are modelled in order to simulate the heat exchange with the primary loop and the natural convection circulation in the primary loop after the loss of pump thrust. The calculation with constant rated power and flow rate was performed for 600 seconds to obtain a stabilized steady-state thermal condition as the initial condition for the subsequent ULOF transient calculation with the flow halving time of 10 seconds.

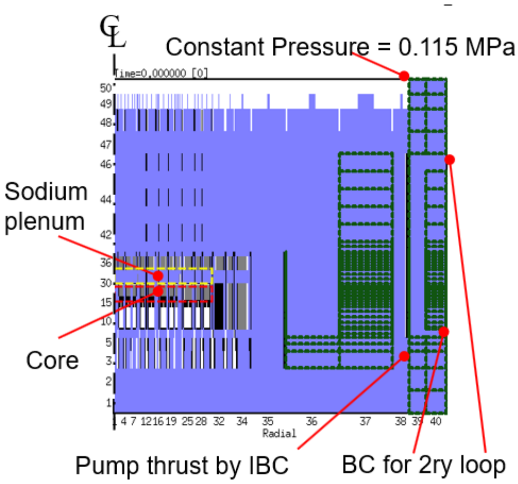
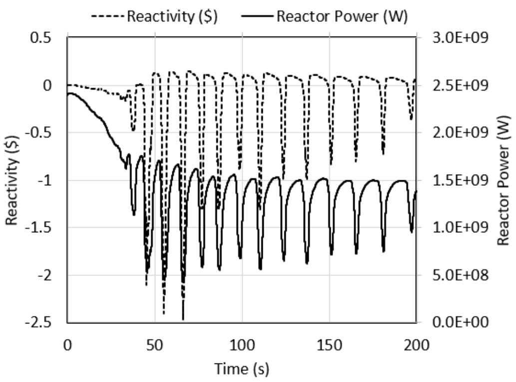


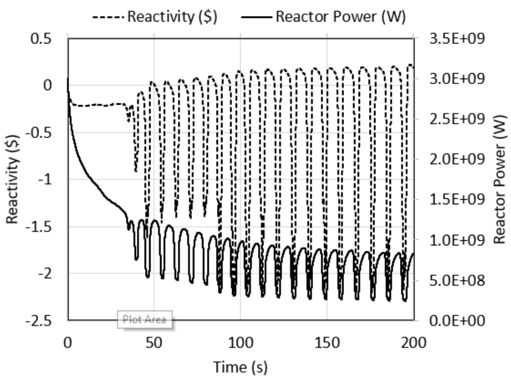
FIG. 3. SIMMER III overall simulation model

4. RESULTS AND DISCUSSION

FIG. 4 shows the reactivity and reactor power transients of the "mild" and "moderate" Pu burners. In these analyses, the reactivity feedback from either the control rod drive line (CRDL) thermal expansion or the core thermal expansion is not considered. Similar to ESFR-SMART, the reactivity and reactor power transient decrease initially during the transient due to a neutron leakage increase caused by sodium boiling in the sodium plenum, followed by a subsequent reactor power increase as the boiling subsides, leading to an oscillatory behaviour of reactivity and reactor power in the same manner thereafter. The reactor power in the "moderate" Pu burner decreases more rapidly due to the larger negative coolant reactivity coefficient than the "mild" Pu burner. The reactivity peaks during the oscillation in both cases are less than about 0.3$, and the possibility of prompt criticality driven by these oscillations is thought to be quite low.



(a) "Mild" Pu burner



(b) "Moderate" Pu burner

FIG. 4. Reactivity and reactor power transients in the "mild" and "moderate" Pu burner

5. THE EFFECT OF GEM (GAS EXPANSION MODULE) IN EMPTY SA

The original concept of Gas Expansion Module (GEM) is to put empty SAs with inert gas region above the fissile column at rated operation in the periphery of core. When ULOF occurs, the pressure at the assembly inlet decreases, allowing the gas to expand into the core region and increasing the leakage of neutrons from the core. The purpose of GEM is to prevent core damage by the negative reactivity effect of this neutron leakage increase. In general, GEM is effective in small reactors; however, in large reactors, the effect of neutron leakage becomes relatively small compared to the size of the core. In the Empty SA presented in this study, the inert gas region in rated operation can be placed within the upper shield, thereby limiting gas expansion during ULOF to the upper sodium plenum as shown in FIG. 5. This increases neutron leakage from the top of the core, making GEM effective even in large reactors.

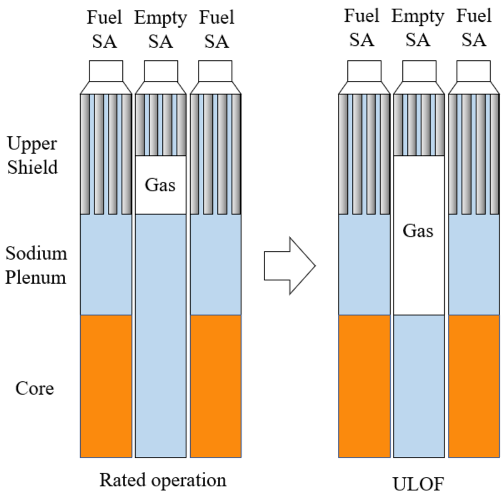
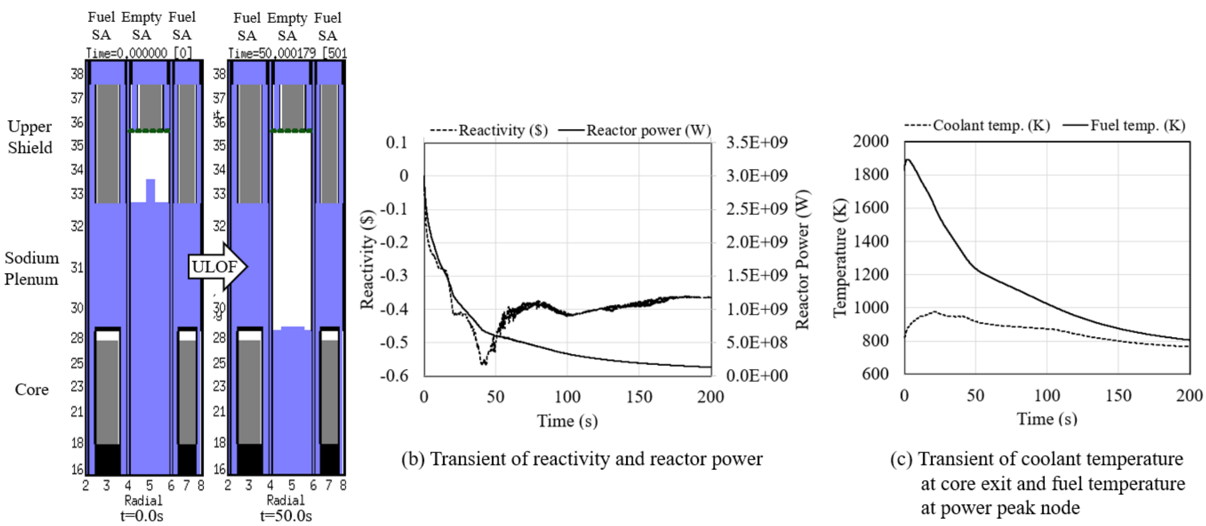


FIG. 5. GEM installation in Empty SA

The results of the SIMMER-III analysis of ULOF transient with GEM in Empty SA are shown in FIG. 6. FIG. 6 (a) shows a plot of the material distribution in the three innermost SA rings of the SIMMER-III analysis model, including the Empty SA. The gas in the upper shield in the rated operation expands into the sodium plenum after ULOF onset, increasing the amount of neutron leakage from the core. This reduces reactivity and reactor power as shown in FIG. 6 (b). The coolant temperature at the core outlet increases to about 980K and subsequently decreases, preventing coolant boiling. The fuel temperature at power peak node rises slightly for a few seconds after ULOF initiation, but then decreases as shown in FIG. 6 (c).



(a) Material distribution in the innermost 3 SA rings before (t=0.0s) and after (t=50.0s) ULOF

(b) Transient of reactivity and reactor power

(c) Transient of coolant temperature at core exit and fuel temperature at power peak node

FIG. 6. Calculation results of ULOF transient with GEM in the Empty SAs

These results show that the GEM installed in the upper part of the Empty SA is effective in preventing core failure in ULOF even in a large-scale fast reactor. In addition, it should be noticed that even if core disruption occurs, the empty fuel SAs are a potential destination for the discharge of molten core material from the core. This is expected to contribute significantly to the improvement of the safety against severe accidents.

6. CONCLUSION

"Mild" and "moderate", Pu burner designs has been proposed for the PuMMA project. They were designed by modifying the ESFR-SMART reactor design and their safety performance was analysed using the SIMMER-III code. Similar to the ESFR-SMART reactor, oscillations in reactivity and reactor power were observed due to the onset and cessation of sodium boiling in the sodium plenum adjacent to the top of the fissile column. The prompt criticality is judged not to occur in the Pu burner core because the peak reactivity during the oscillation is less than 0.3$. This is due to the increased negative coolant density and void reactivity in the sodium plenum, which is caused by the reduction in core height of the Pu burner cores. This demonstrates that the Pu burner cores have a high tolerance for the ULOF transient. In addition, a new GEM concept was proposed to confine the gas region expansion within the sodium plenum during ULOF for the empty SAs in the core. The analysis of ULOF transient using SIMMER-III demonstrates that the combination of this GEM and the sodium plenum constitutes an effective measure to prevent core damage, even in large reactors.

ACKNOWLEDGEMENTS

This study contributes to the European PuMMA project, Plutonium Management for More Agility, receiving funding from the EU Horizon 2020 program, grant agreement 945022.

The authors would like to express their gratitude to the JAEA for the provision of SIMMER under a JAEA-KIT/CEA agreement on the exchange of information and collaboration to develop the code.

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