ESFR-Like Plutonium Burners: Design and Safety Studies

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Introduction

PuMMA
Plutonium Management for More Agility

https://pumma-h2020.eu/

- **Define different options for Pu management** in Generation IV nuclear reactors
- **Evaluate the impact of high plutonium (Pu) content** on the whole fuel cycle, reactor safety and performance
- **Several Pu burning scenarios** have been investigated, using Pu burner reactor whose design is based on ESFR-SMART, but with reduced core height and increased Pu content.

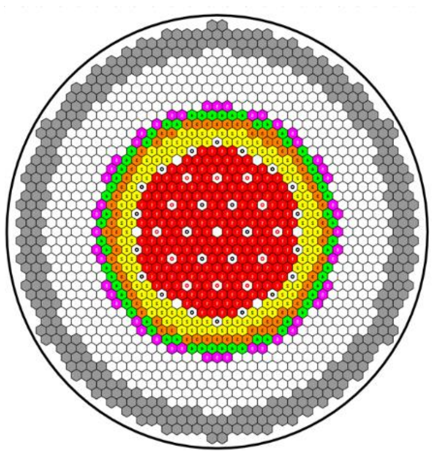
KIT

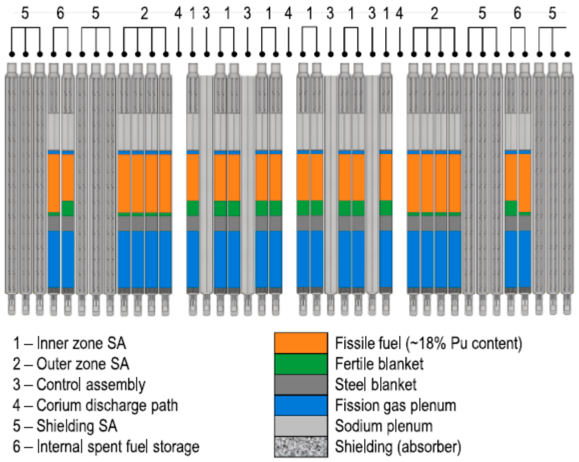
Overview

- Two types of Pu burner core with different Pu contents have been investigated;
  - Mild Pu burner: The same pin diameter as ESFR-SMART, but reduced axial dimension and power with increased Pu content of 22.5% from 18.7% of ESFR-SMART.
  - Strong Pu burner: Thinner fuel pins and introduced inert pins (Mo+B pins), higher Pu content of 36%, which were investigated in PuMMA scenario studies.
- “Moderate” Pu burner is proposed which has the intermediate Pu content to ensure the flexibility of Pu burning capacity in responding to possible future societal demands.
  - Some of the fuel subassemblies (SAs) are replaced with empty SAs in the mild Pu burner
  - Thinner fuel pins as in “strong” burner but without inert pins
- This study investigated the followings by the analysis using the SIMMER code
  - The effect of upper sodium plenum against the severe accidents such as ULOF
  - The effect of GEM (Gas Expansion Module) installation to the empty subassembly
  - Empty SAs as a discharge path for molten core materials

Core configuration of ESFR-SMART and mild Pu burner

ESFR-SMART

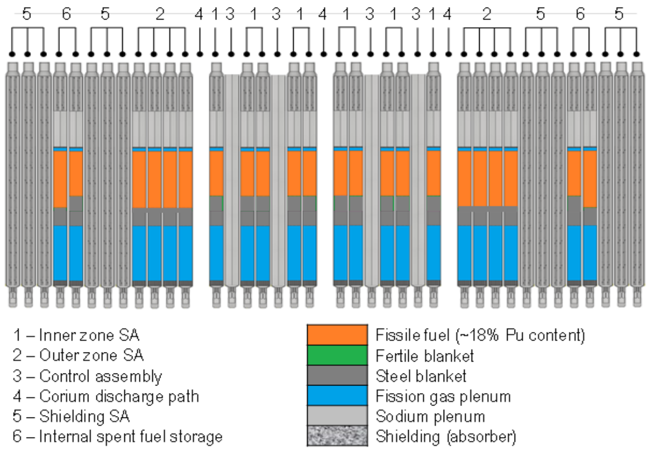




- 3600 MWth, 1500 MWe
- 216 I.C. SAs, 288 O.C. SAs
- 24 CSDs, 12 DSDs
- 31 Corium discharge tubes

- I.C. / O.C. height 75 / 95 cm
- Pu content 17.9%
- Sodium plenum height 60cm

Mild Pu burner



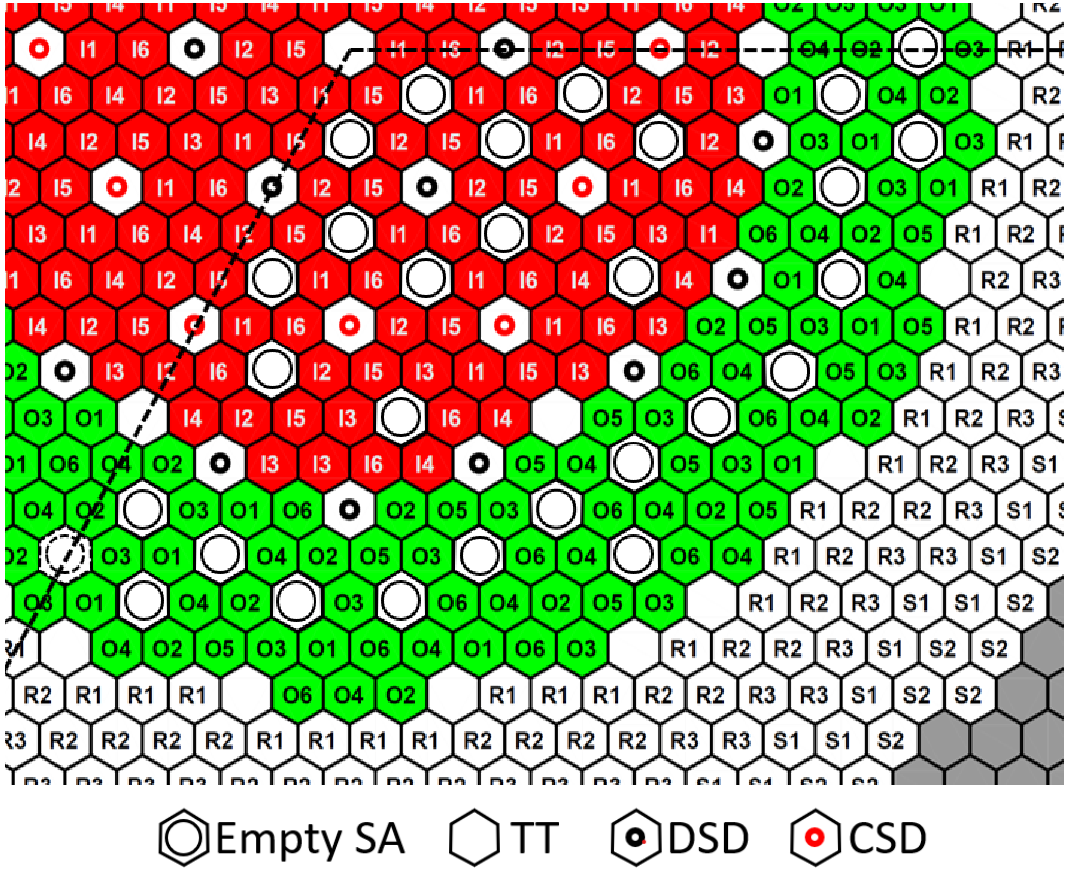
- I.C. / O.C. height 50 / 65 cm
- Pu content 22.5%
- Lower blanket → Steel Blanket
- 2400MWth
- Sodium plenum height 60cm

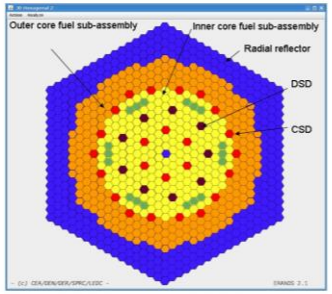
- Horizontal configuration is kept same.

→Both designs could be implemented in the same commissioned reactor if desired.

Core configuration of moderate Pu burner

- 36 SAs in I.C. and 48 SAs in O.C., for total of 84 SAs (17%) are replaced with empty SAs in the mild burner.
- Pu content in ESFR-SMART: 18.7%
  - in mild burner: 22.5%
  - in strong burner: 36%
  - in moderate burner: 33%
- Thinner pin (271 ➔ 397 pins/SA) increased the reactor power (2.4 GWth in mild burner ➔ 3.0 GWth).





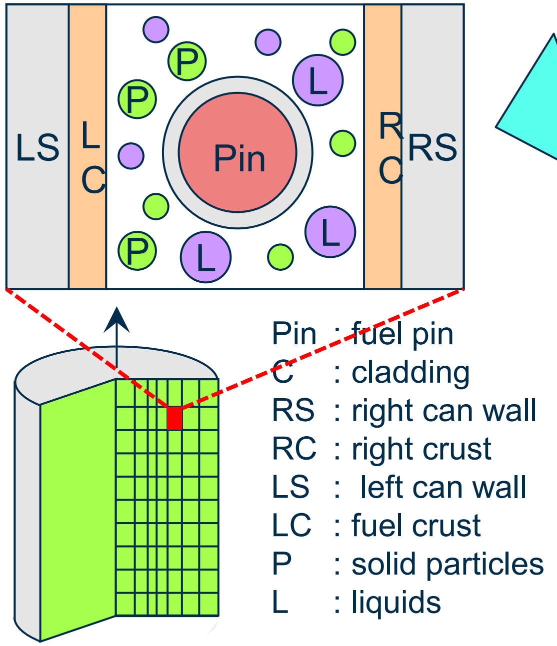
	REF	CONF-2, UOX+Am	CONF-2, UOX+Am + 18 empty SAs
Parameter at BOL	pcm		
Core void effect	1402	1270	1166
Extended void effect, including empty SA voiding	1014	-243	-1244

The introduction of empty SA to CP-ESFR was investigated in 2008-2012 to reduce the sodium void reactivity.

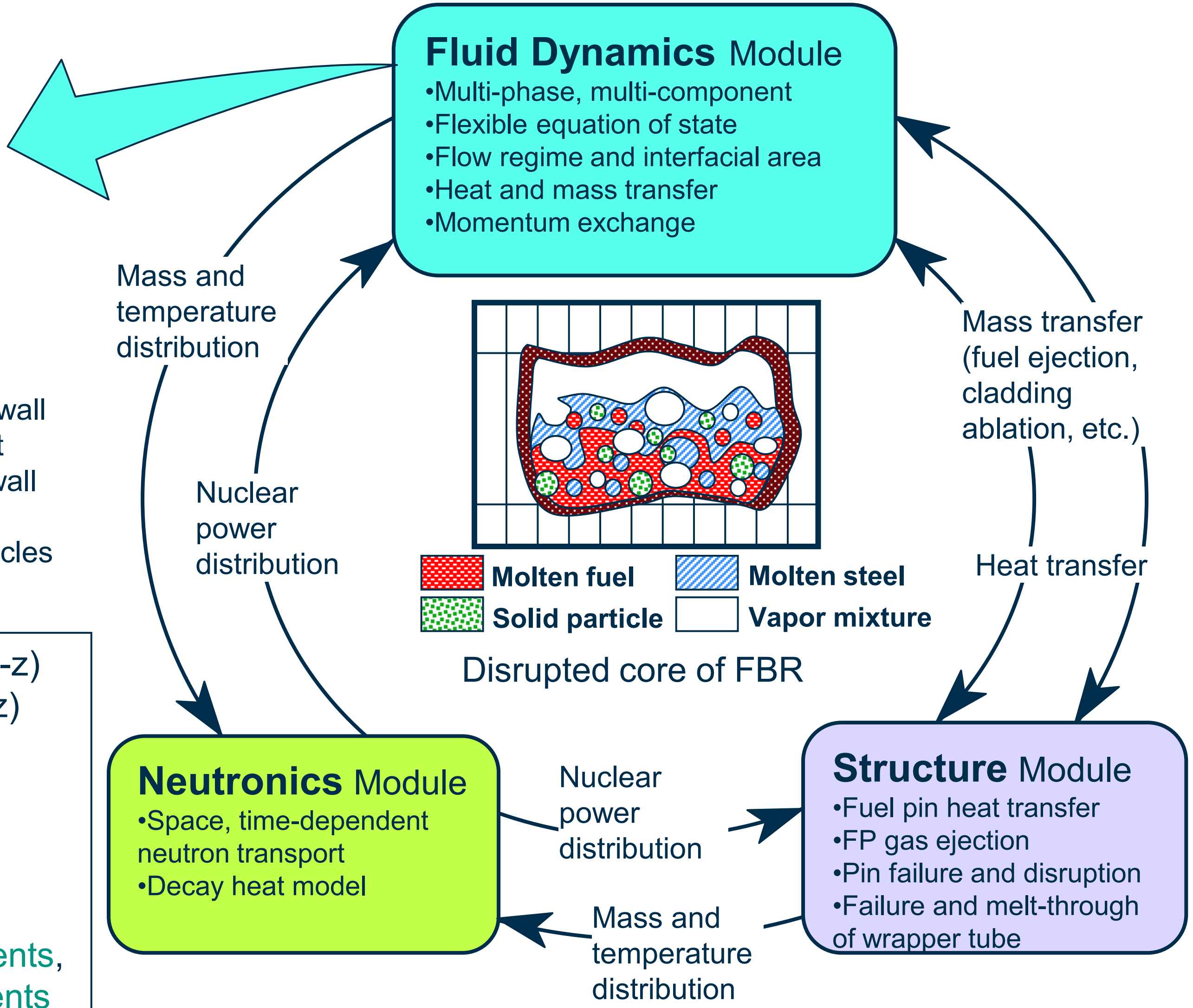
A. Rineiski, et al., Transactions ANS | Volume 104 | Number 1 | June 2011 | Pages 720-721

The SIMMER code

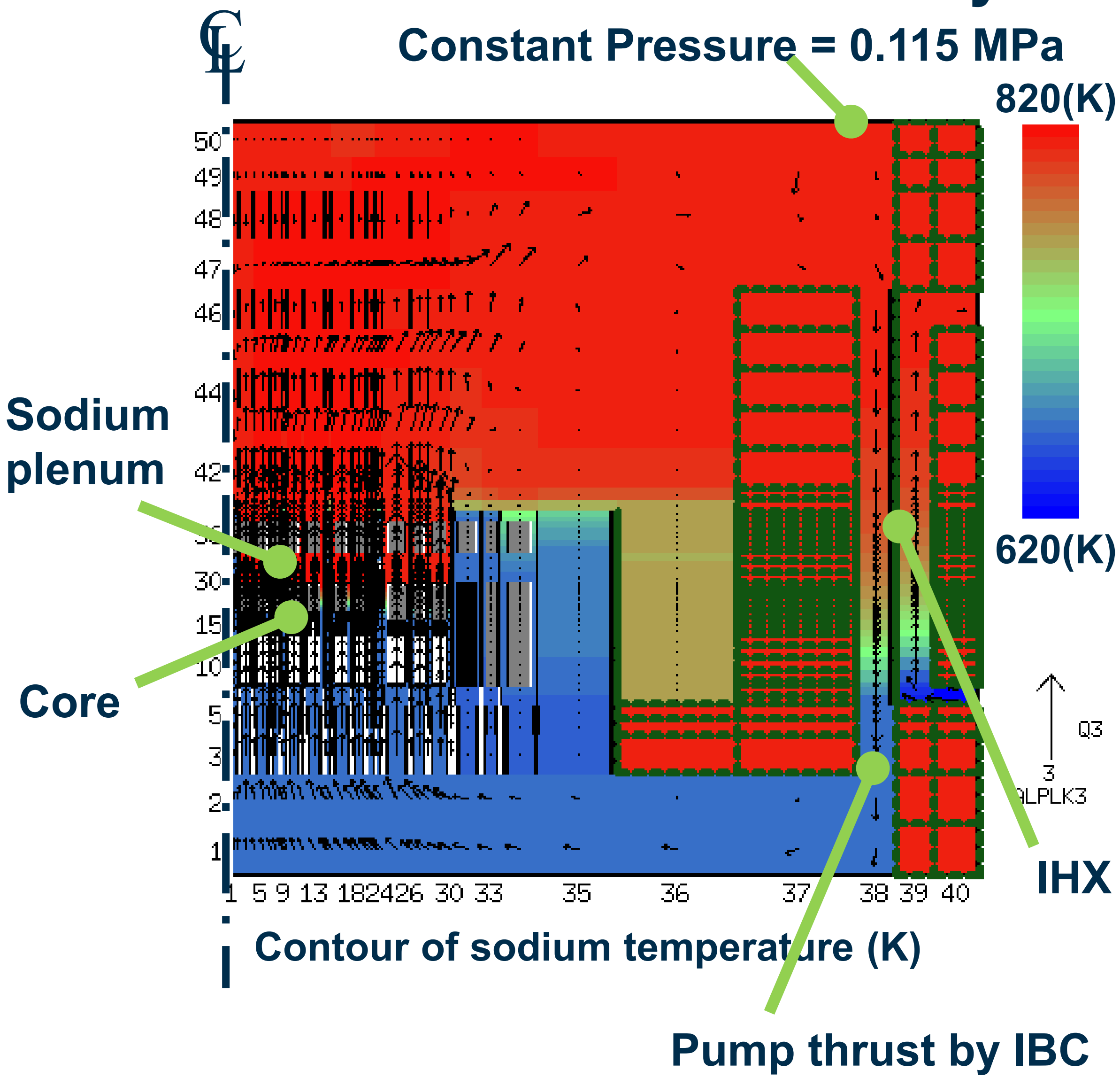
- A Computer code for analyzing the behavior of disrupted core of fast reactors
- Developed by JAEA under the international cooperation with KIT and CEA.



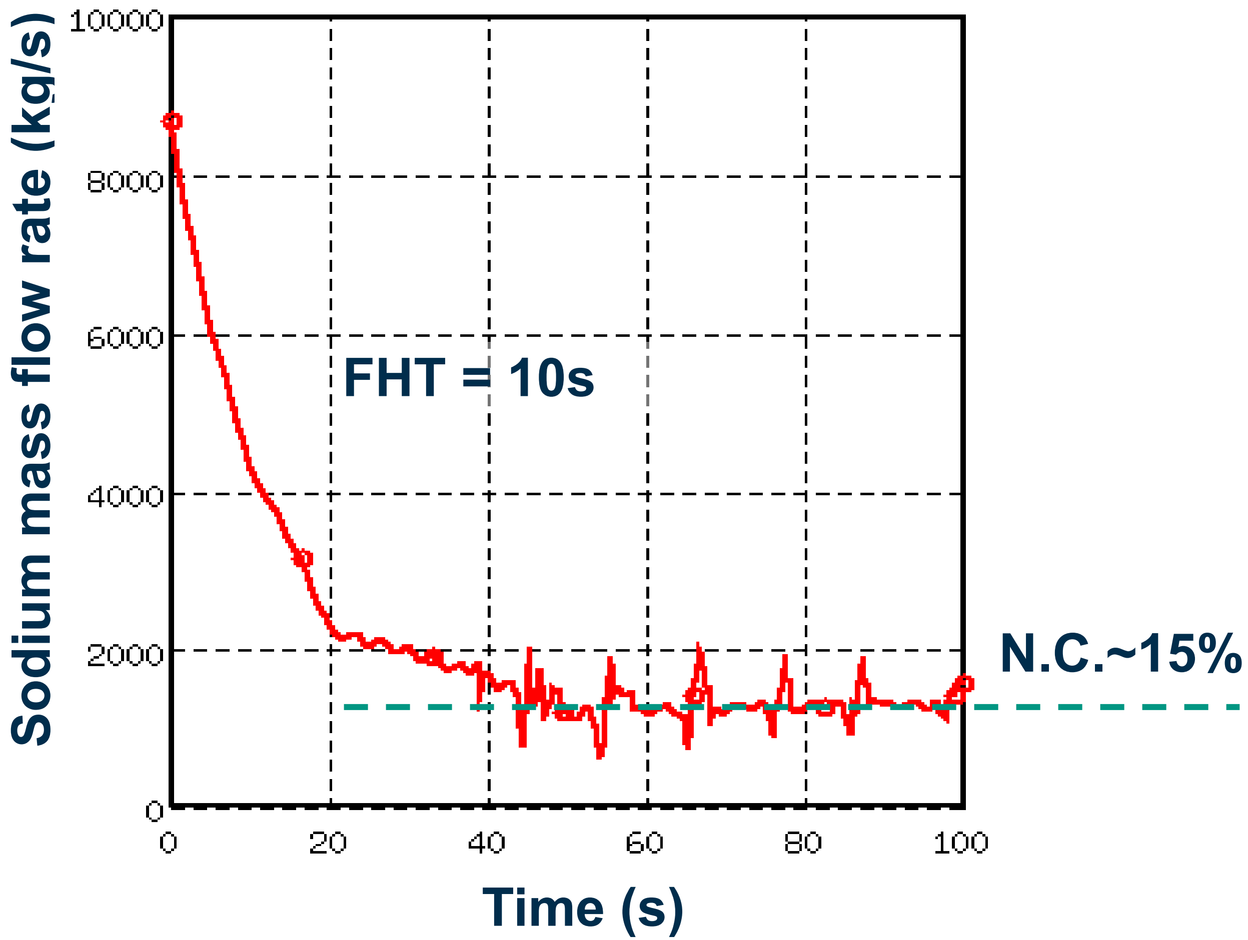
- 2-D (SIMMER-III, r-z or x-z) or 3-D (SIMMER-IV, x-y-z)
- 8-velocity fields
- Multi-phase
  solid, liquid, vapor
- Multi-components
  5 material components,
  27(38) density components,
  16(23) energy components



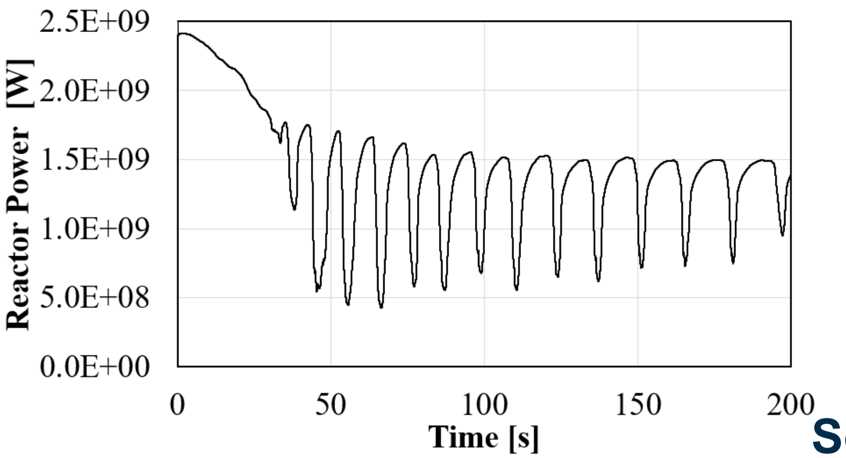
Procedure of ULOF analysis

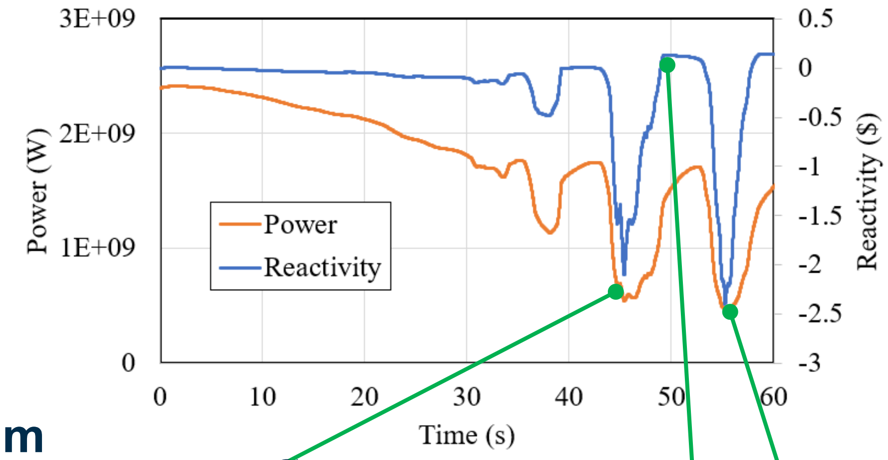


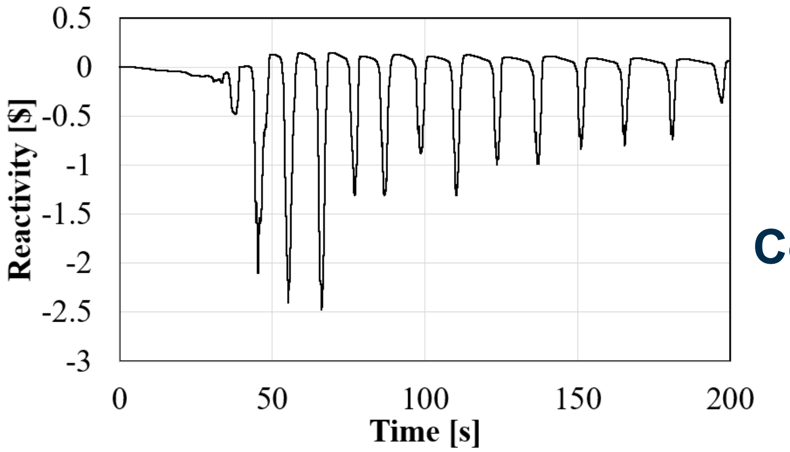
Contour of sodium temperature (K)

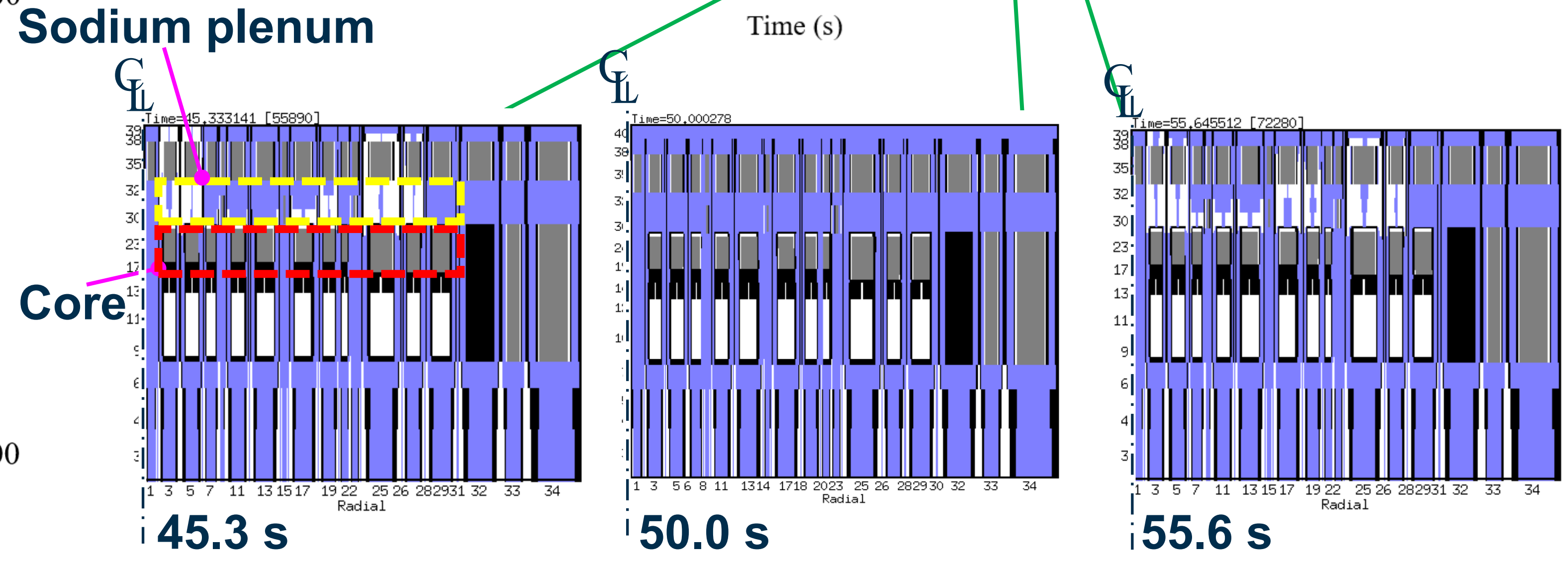


ULOF analysis of mild Pu burner

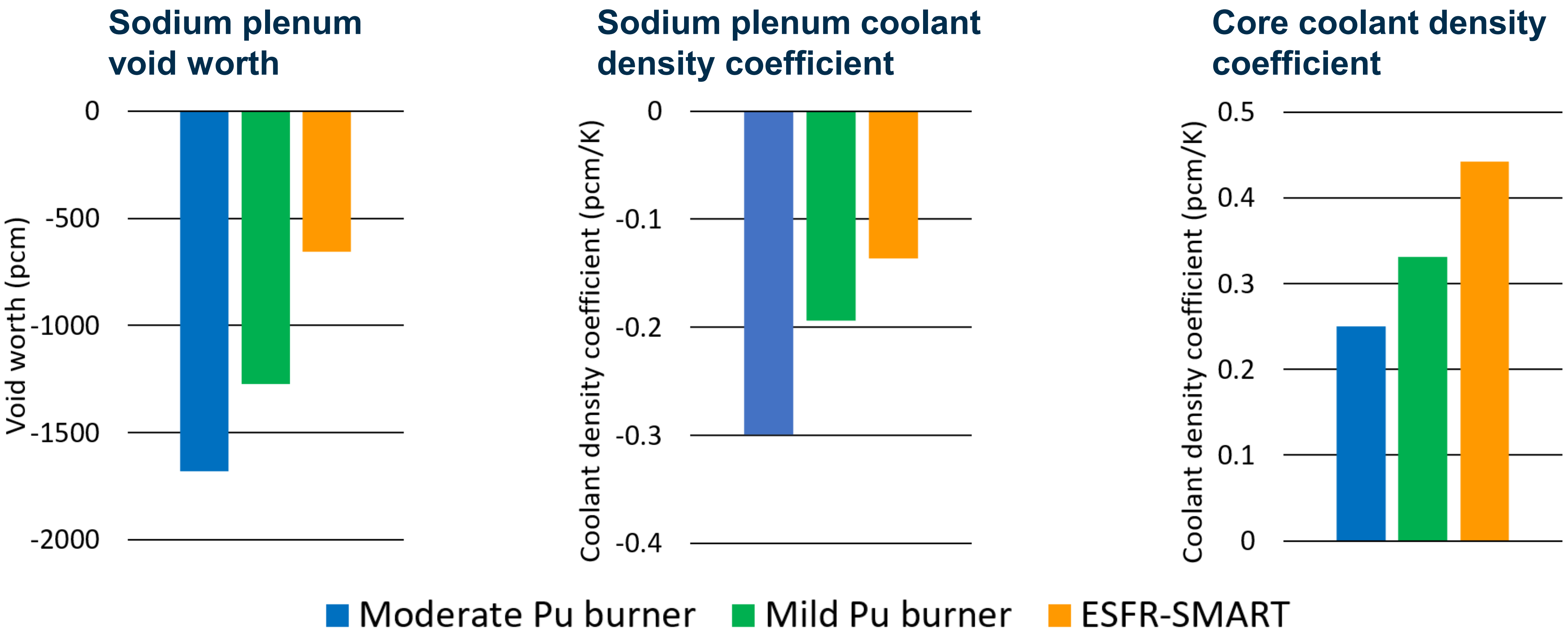






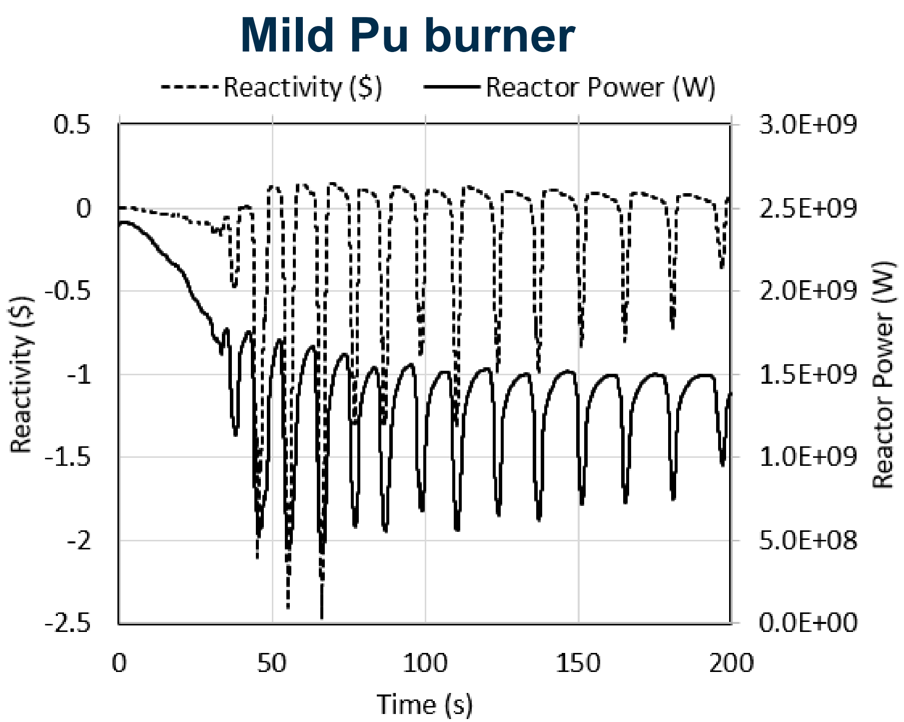


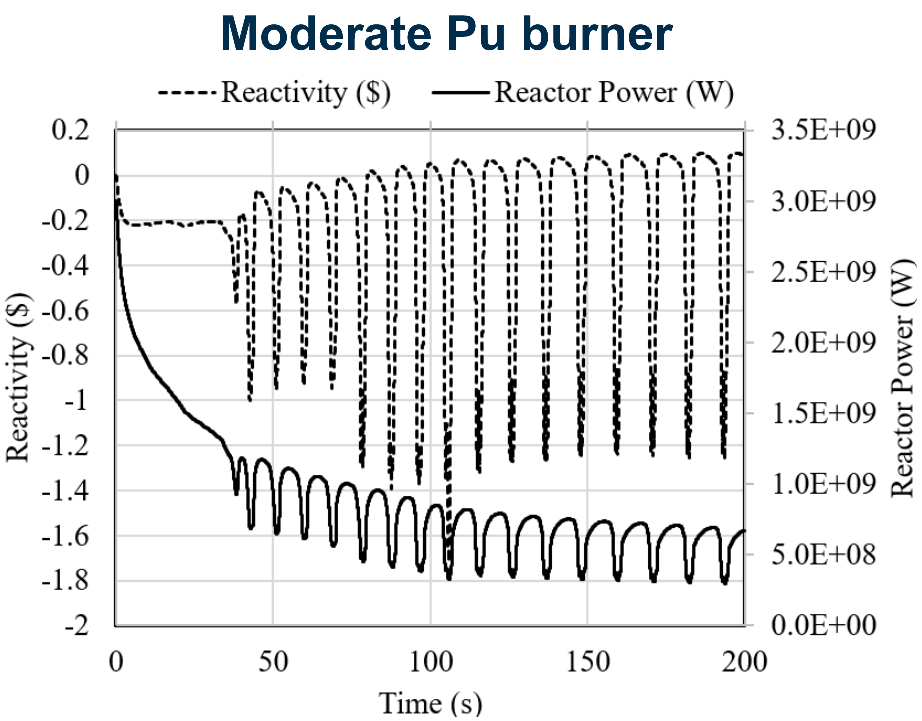
Reactor kinetics parameters



- These reactor kinetic parameters relating to core safety in the “Moderate” Pu burner is improved due to the increase of neutron leakage through empty SAs.

ULOF analysis of moderate Pu burner



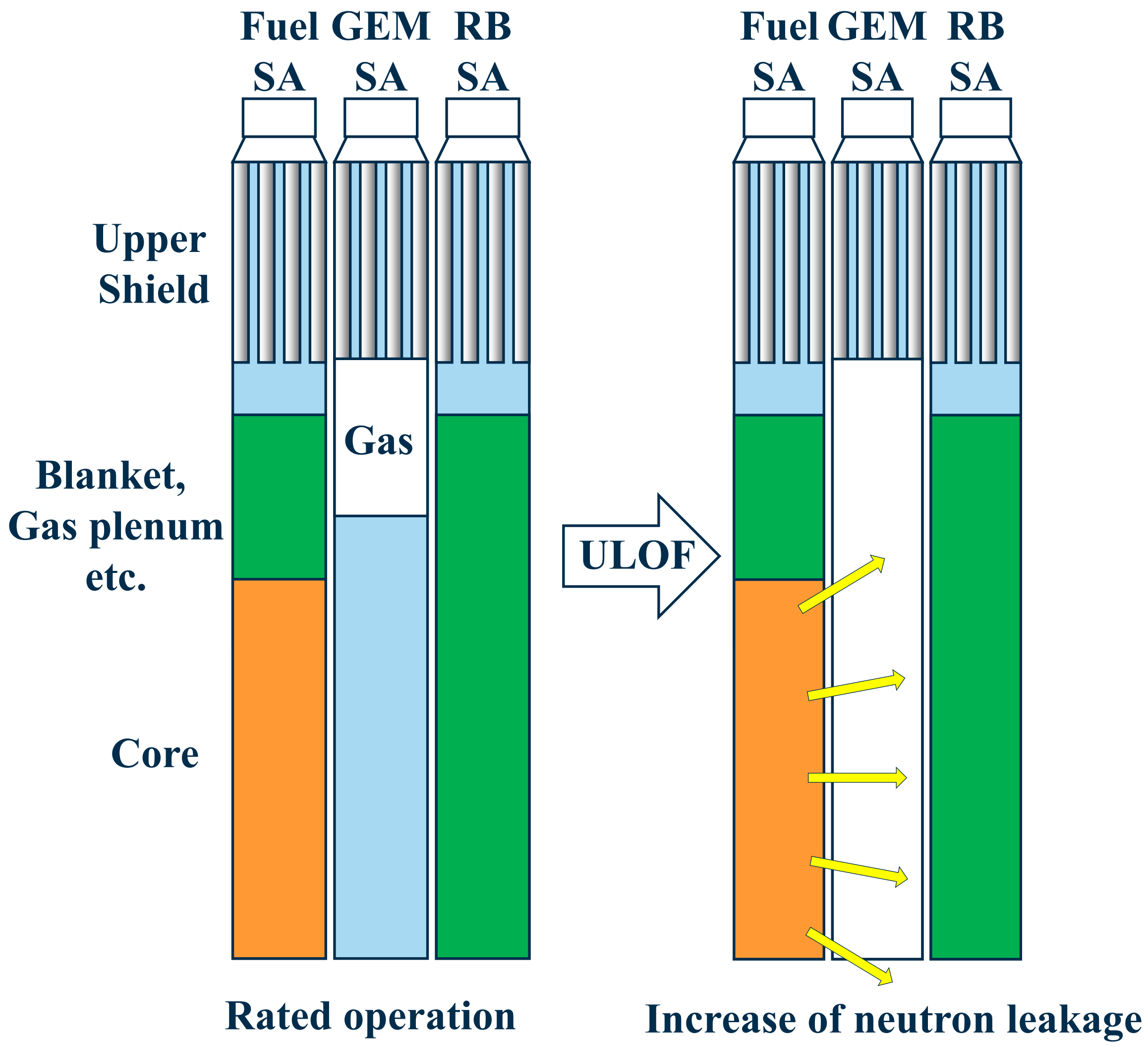


- Larger negative void reactivity of sodium plenum than mild Pu burner
  - Boiling of sodium plenum in only one SA ring is enough to terminate the boiling.

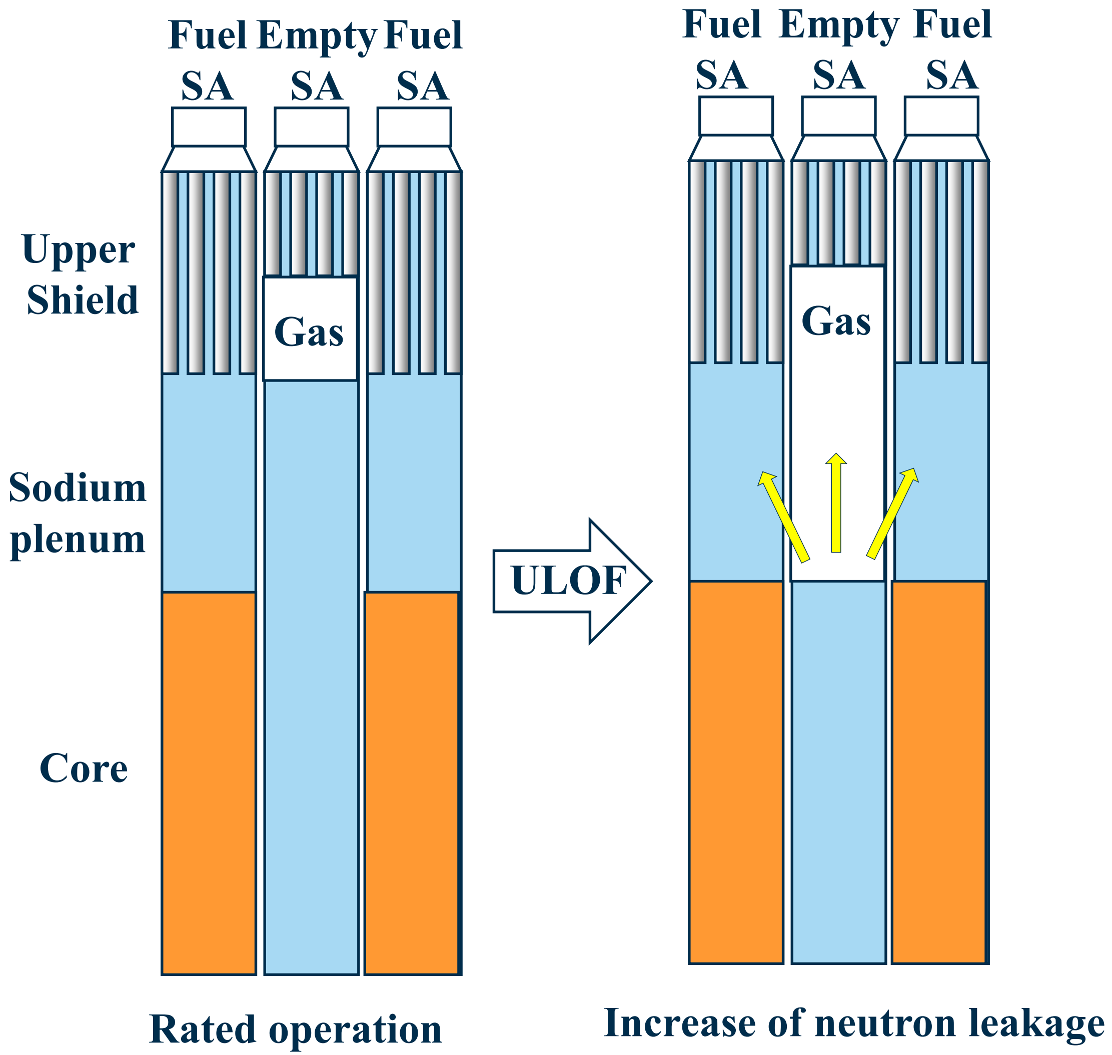
    ➔ This increased the frequency of the oscillation.
  - Larger negative reactivity in the oscillation ➔ decrease of the amplitude of reactor power oscillation
  - Thanks to the improved reactor kinetic parameters, the reactor power decreases more quickly than that of a mild Pu burner..

Installation of GEM in the empty SA

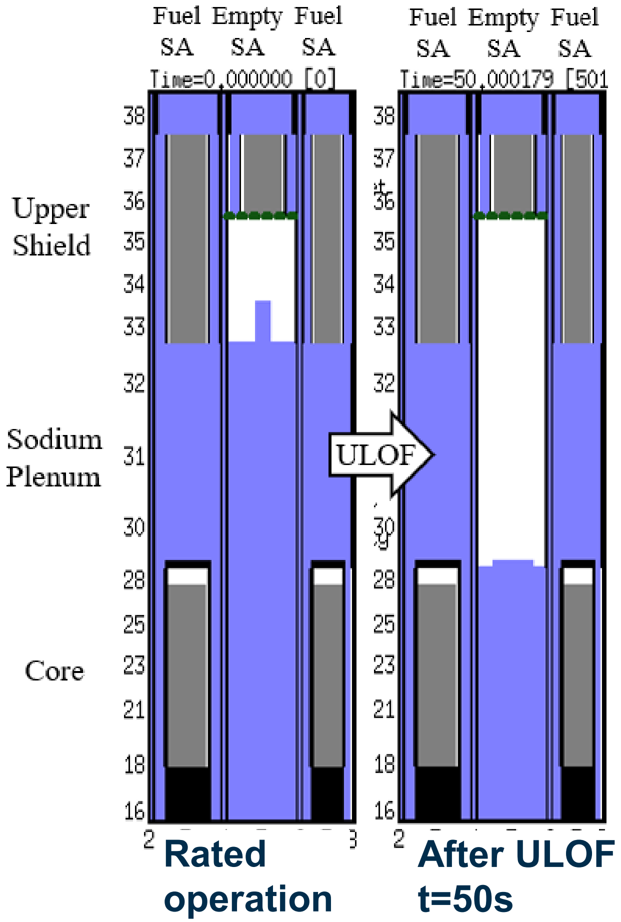
- Ordinary GEM (Gas Expansion Module)



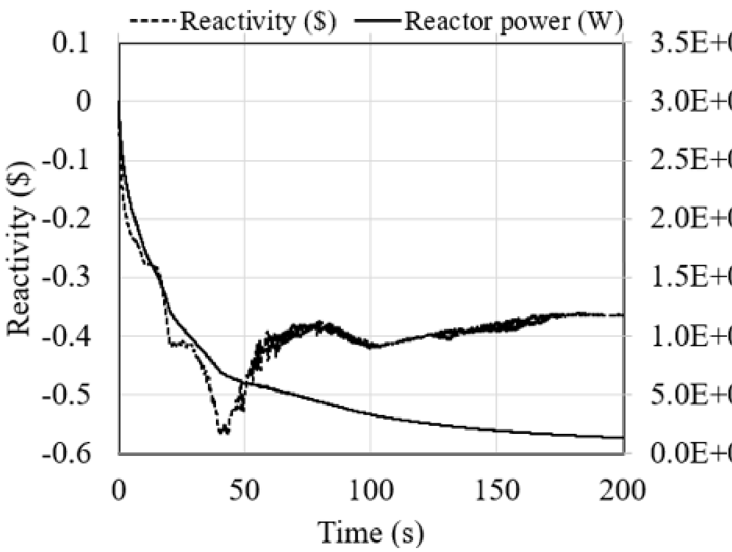
- GEM in the empty SA (short GEM)



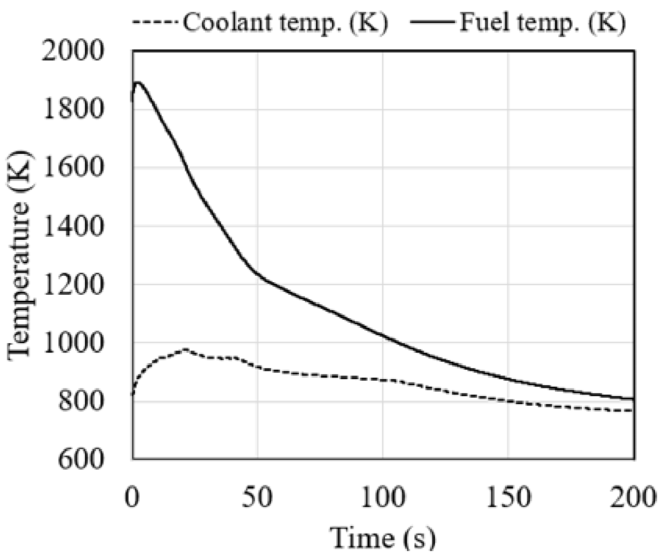
Analysis of ULOF in moderate Pu burner with short GEM in the empty SAs



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

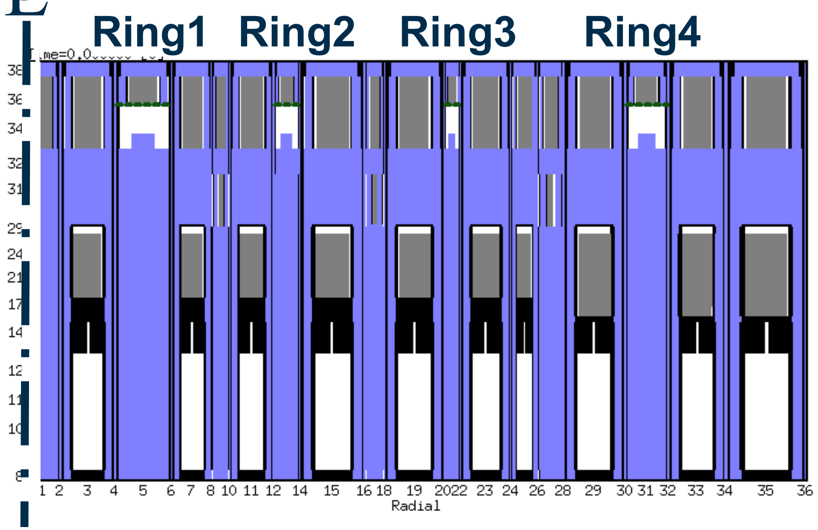


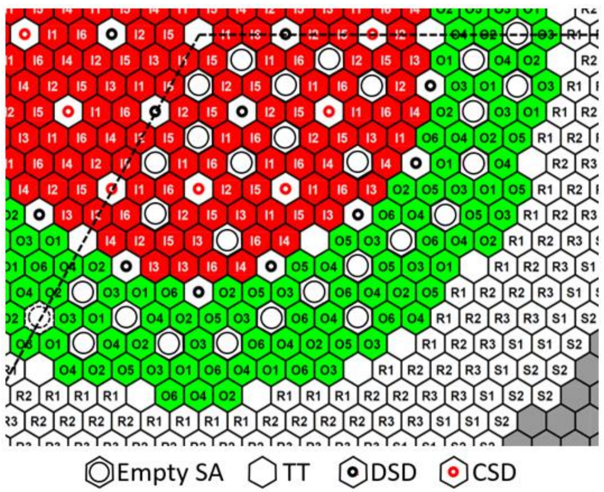
(b) Transient of reactivity and reactor power



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

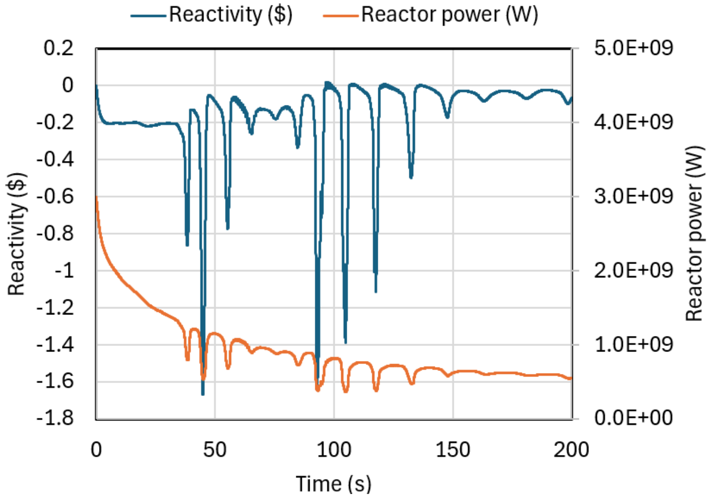
Parametric study on the number of short GEMs



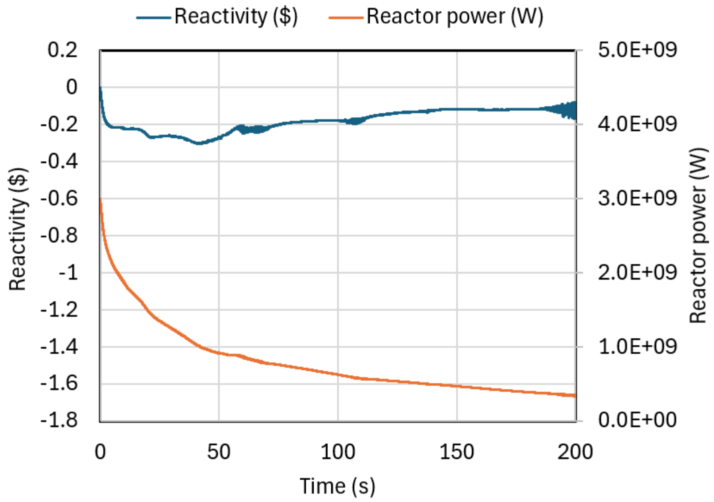


- The empty SAs are modelled with 4 radial rings (i=5, 13, 21, and 31) with the number of SAs (12, 12, 12, and 48, respectively).
- The number of short GEMs required to prevent the coolant boiling in ULOF is between 12 and 24.

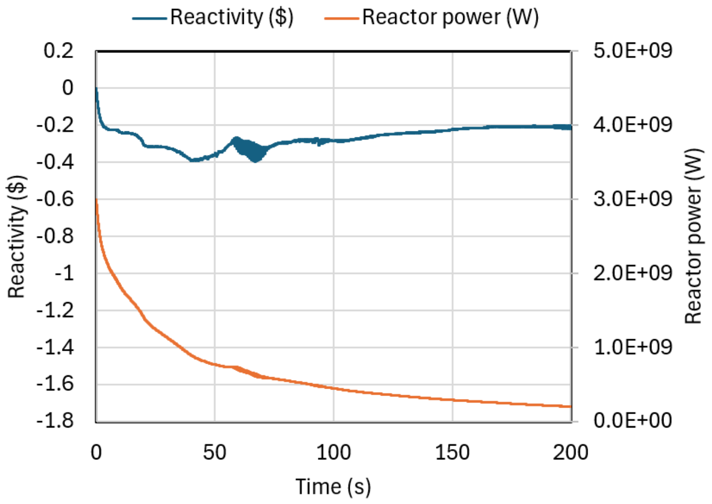
Case 1 : Ring1 (12 SAs)



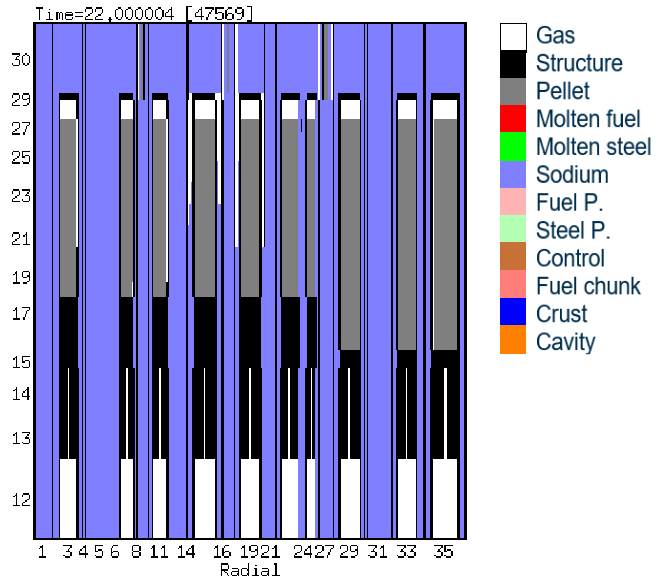
Case 2 : Ring1+Ring2 (24 SAs)

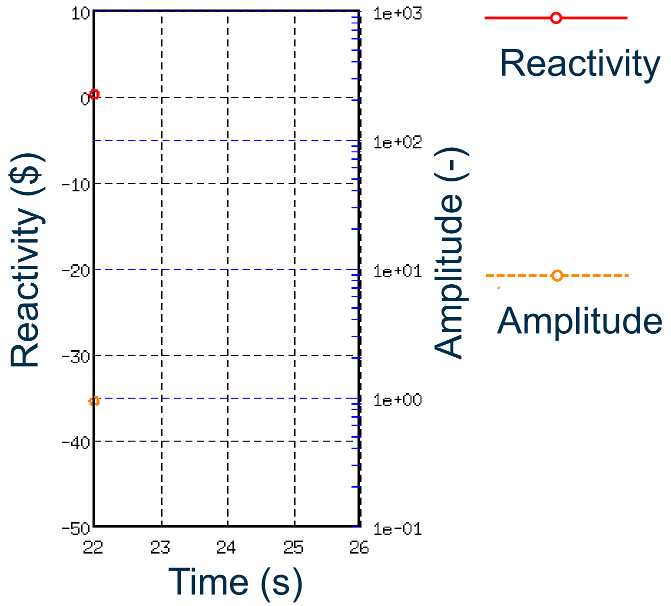


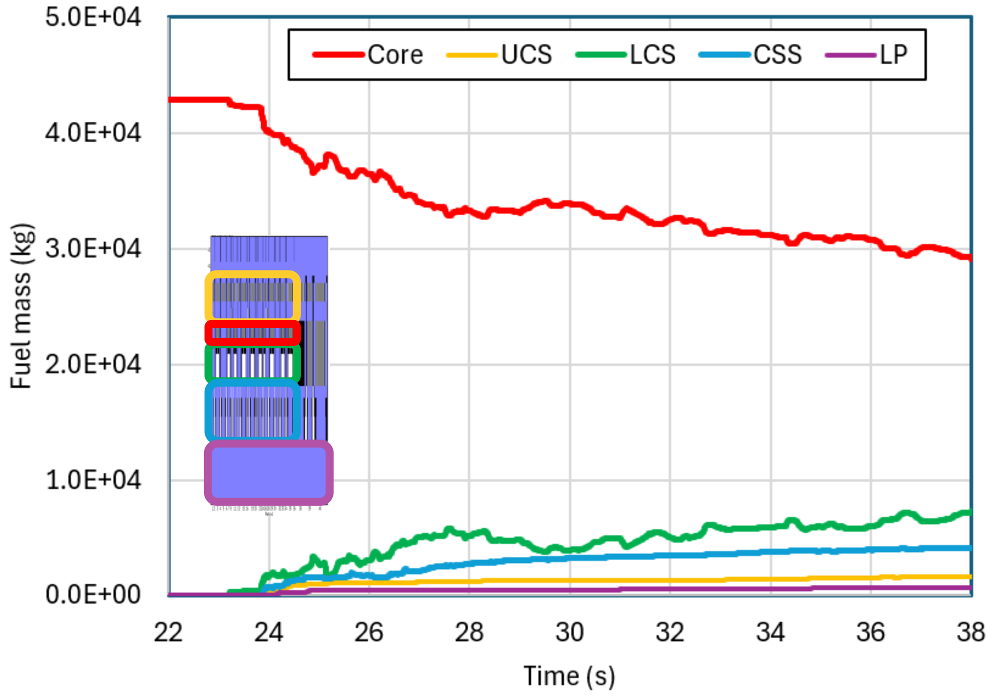
Case 3 : Ring1+Ring2+Ring3 (36 SAs)



Empty SA as a discharge path of molten fuel







- To force disruption in this core, boiling in the sodium plenum was intentionally suppressed.
- The fuel began to disrupt after the boiling of sodium in the core at around 22 seconds, and the power excursion melted the fuel at around 23 seconds. The maximum core average temperature of the molten fuel is about 3,400 K.
- At about 24 seconds, molten fuel began to discharge downward through the empty SAs and CRGTs, leading the core into deep subcriticality.

Summary (1/2)

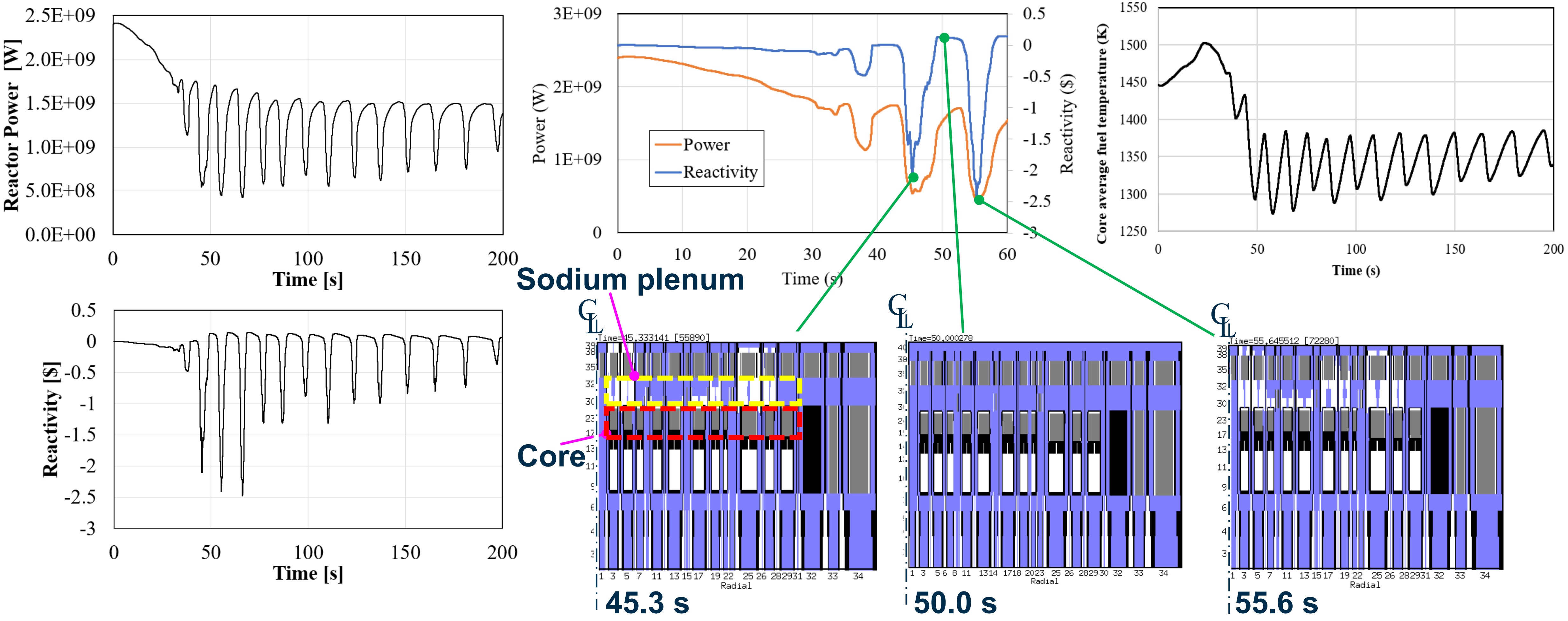
- A new ESFR burner core is proposed with the same geometric configuration of fuel SAs as the previous ESFR burner, but with several empty SAs. The Pu content with ESFR-BURN Pu vector is approximately 35% and the thermal power is approximately 3.0GWth.
- Due to more favorable reactivity feedbacks, the power oscillation amplitude is reduced, and the reactor power decreases faster than that of a mild Pu burner.
- A new concept of GEM (i.e., short GEM) is proposed that is installed to the sodium plenum in the empty SA. Analysis of ULOF showed that short GEM is highly effective even on a large scale SFR, in preventing coolant boiling and returning the coolant outlet temperature to the rated operating temperature within 200 seconds after ULOF initiation.

Summary (2/2)

- Even if fuel disruption and melting are hypothetically assumed to occur, the empty SAs provide an effective discharge path for molten core materials, which prevents severe recriticallity.
- The empty SA concept, as implemented in the Moderate Pu burner, exhibits a high degree of flexibility, enabling Pu burner reactors to respond to social demands for Pu burning. This adaptation also has the potential to significantly enhance the core safety against severe accidents.

Thank you for your attention

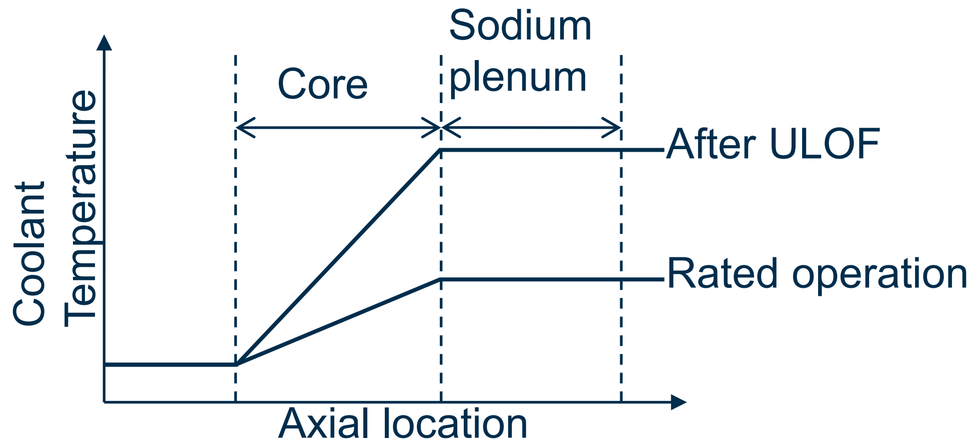
ULOF analysis of mild Pu burner



Reactor kinetics parameters

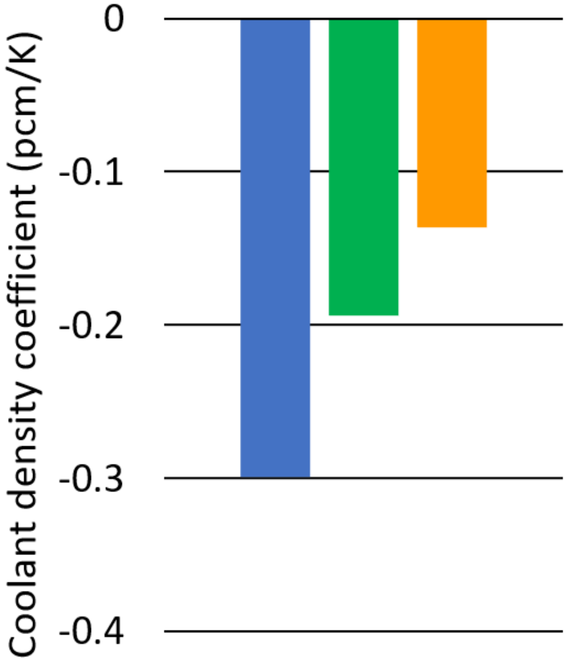
Parameter	Moderate Pu burner SIMMER-III	Mild Pu burner SIMMER-III	ESFR-SMART SIMMER-III
Keff	1.00238	1.00320	1.00937
Prompt Neutron Lifetime	4.629E-7 s	4.66E-7 s	4.25E-7 s
Beta effective	338 pcm	350 pcm	347 pcm
Doppler Coeeficient ΔT=300K	-635 pcm	-564 pcm	-808 pcm
Core void worth	970.2 pcm	1277 pcm	1727 pcm
Upper gas plenum + Gap void worth	-198 pcm	-69.0 pcm	-41.3 pcm
Sodium plenum void worth	-1680 pcm	-1275 pcm	-656 pcm
Coolant density reactivity (core)	0.250 pcm/K	0.331 pcm/K	0.442 pcm/K
Coolant density reactivity (sodium plenum)	-0.299 pcm/K	-0.194 pcm/K	-0.136 pcm/K
Axial thermal expansion coefficient	-0.193 pcm/K	-0.119 pcm/K	-0.0715 pcm/K
Radial Thermal Expansion Coefficient	-1.305 pcm/K	-0.980 pcm/K	-0.711 pcm/K
Control Rod Drivelines Expansion Coefficient	-423/14.5 pcm/cm	-423/14.5 pcm/cm	-423/14.5 pcm/cm

Reactor kinetics parameters

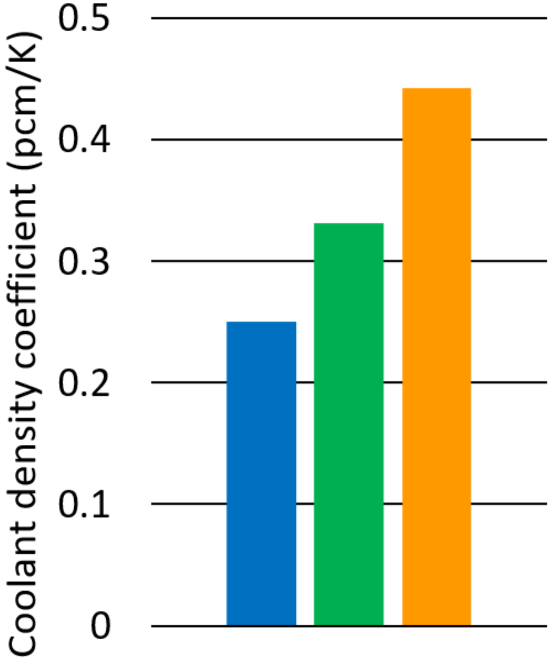


$$\Delta T_{core} = \frac{1}{2} \Delta T_{sodium\ plenum}$$

Sodium plenum coolant density coefficient

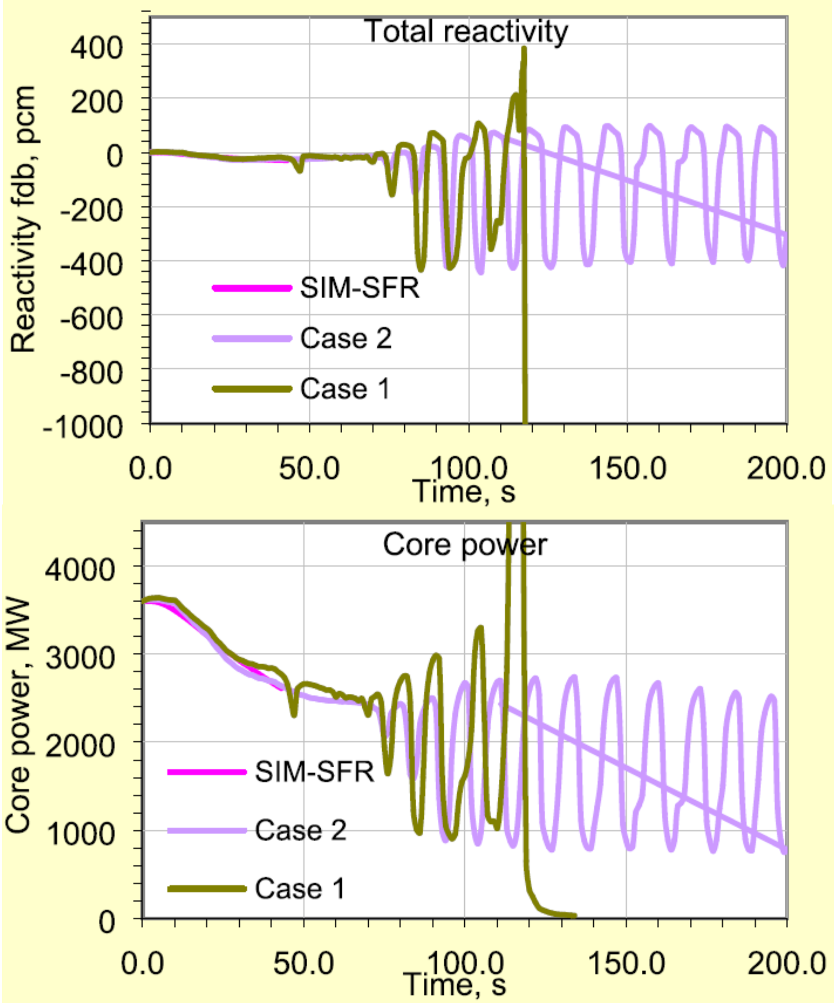


Core coolant density coefficient



If $C_{dens,core} > 2\left|C_{dens,\ sodium\ plenum}\right|$, sodium temperature increase during ULOF will cause a positive reactivity increase.

ULOF analysis for ESFR-SMART*



- Reactivity feedback mechanisms **

Case	CRDL thermal expansion	Core thermal expansion
Case 1	on	fuel pellet
Case 2	on	cladding

- Even with the negative reactivity feedback by thermal expansion of CRDL, the reactivity oscillation exceeded prompt criticality and the core disrupted at about 115s in Case 1.

* Chen, Xue-Nong, Rineiski, A., Perez-Martin, S., Bubelis, M. and Flad, M., Annals of Nuclear Energy 183 (2023) 109642
** Andriolo, L., Rineiski, A., Vezzoni, B., Gabrielli, F., et al., Proceedings of ICAPP 2015, pp. 504-512, Paper 15292, May 03-06, 2015, Nice (France)