

UTOP Studies for Small SFR and LFR

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ABSTRACT

This study investigates the safety performance of small fast reactors under severe accident conditions by comparing sodium- and lead-cooled small modular reactor (SMR) designs. The reference system is the 360 MWth European Sodium Fast Reactor SMR (ESFR-SMR), currently studied in the EURATOM ESFR-SIMPLE project. Derived from the large-scale ESFR concept, the ESFR-SMR features improved reactivity feedbacks, including a reduced coolant void reactivity effect.

A lead-cooled fast reactor design (LFR-SMR) with a core configuration similar to that of the ESFR-SMR, including the same number of fuel subassemblies, is developed for comparison. A hypothetical unprotected transient overpower (UTOP) accident involving a rapid reactivity insertion of 1.5\$ within three seconds is simulated for both reactors.

Results indicate that the reactivity insertion leads to power excursions in both designs, causing fuel melting and core degradation. However, the accident progression differs. In the ESFR-SMR, sodium boiling occurs during the reactivity insertion without cladding failure, and the main power excursion occurs later with fuel melting. In contrast, in the LFR-SMR cladding failure occurs during the insertion phase, leading to immediate fuel pin degradation and a prompt power excursion. Despite this earlier degradation, the LFR-SMR shows lower thermal and mechanical energy release than the ESFR-SMR.

KEYWORDS

SODIUM FAST REACTOR, LEAD FAST REACTOR, SMALL MODULAR REACTOR, SEVERE ACCIDENT, UNPROTECTED TRANSIENT OVERPOWER

1. INTRODUCTION

A small 360 MWth European Sodium Fast Reactor with MOX fuel (ESFR-SMR) is currently being studied within the EURATOM ESFR-SIMPLE project [1]. The design is largely derived from the previously developed large-scale ESFR concept but shows more favorable reactivity feedbacks, particularly a reduced coolant void reactivity effect, which enhances inherent safety. Safety analyses of the ESFR-SMR under an unprotected loss-of-flow (ULOF) transient indicate a lower probability of core degradation compared with the large ESFR core. A hypothetical unprotected transient overpower (UTOP) scenario is also considered, which may lead to core melting. One scenario involves a reactivity insertion of 1.5\$ within three seconds.

In this work, a new lead-cooled fast reactor design (LFR-SMR) is developed with a core configuration similar to that of the ESFR-SMR, including the same number of fuel subassemblies. The fuel pin and

subassembly geometries in the radial plane are based on a previously studied lead-cooled design [2]. Compared with the ESFR-SMR, the LFR-SMR operates with a lower coolant velocity and at a lower reactor power. The UTOP scenario described above is simulated numerically using the SIMMER III code [3] up to severe accident conditions. The objective is to investigate the specific characteristics of different reactor types under severe accident conditions and to compare key safety metrics, including thermal and mechanical energy release.

Preliminary results show that the imposed reactivity insertion leads to power excursions in both reactors, resulting in fuel melting and core degradation. However, the accident progression differs significantly due to the different boiling temperatures of sodium and lead. The boiling point of sodium is significantly lower than the melting temperature of steel, whereas the boiling point of lead is higher. In the ESFR-SMR, sodium boiling occurs during the reactivity insertion phase, leading to a power decrease due to a negative reactivity effect after voiding the above-core coolant plenum, preventing cladding failure. A larger power excursion occurs later due to sodium reflooding. In contrast, in the LFR-SMR cladding failure occurs during the insertion phase, leading to immediate fuel pin degradation and a prompt power excursion. Despite this earlier degradation, the LFR-SMR exhibits lower thermal and mechanical energy release than the ESFR-SMR. The mechanisms influencing the energy release will be analyzed and discussed in the paper.

2. OVERALL CONFIGURATION AND CORE DESIGN

We keep the overall reactor configuration for the new LFR-SMR the same as for the ESFR-SMR and modify the core arrangement with as few modifications as possible. The ESFR-SFR core [1] is shown in Fig. 1. The short gas plenum (height 50 mm) and pin plugs (height 18 mm) between the core and sodium plenum are not shown in Fig 1.

We take another Lead-cooled design, European Facility for Industrial Transmutation, EFIT [2], as the reference for our current modification. Since the EFIT fuel assembly (FA) size is very similar to that of the ESFR-SMR, we can use for LFR-SMR the FAs with the same can-wall geometry in plane as in ESFR-SMR, but with EFIT pins and EFIT pin arrangement inside the can-wall. The LFR-SMR FA geometry is shown in Fig. 2. The LFR-SMR core map in plane is the same as in ESFR-SMR, shown in Fig. 1. Therefore, the overall reactor configuration and its numerical modeling are similar to those for the ESFR-SMR. In the following, we often refer to ESFR-SMR and LFR-SMR designs as SFR and LFR, respectively. The SFR and LFR fertile/fissile fuel compositions are the same.

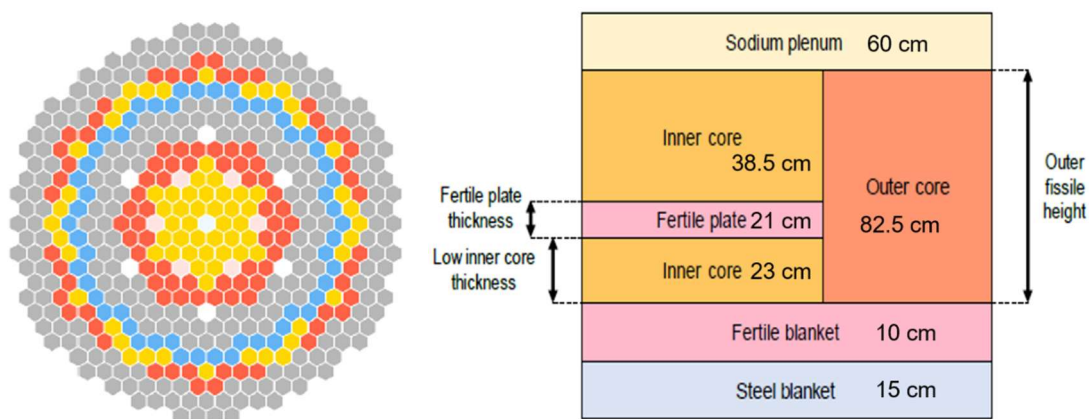


Figure 1: Core map and arrangement of ESFR-SMR [1]

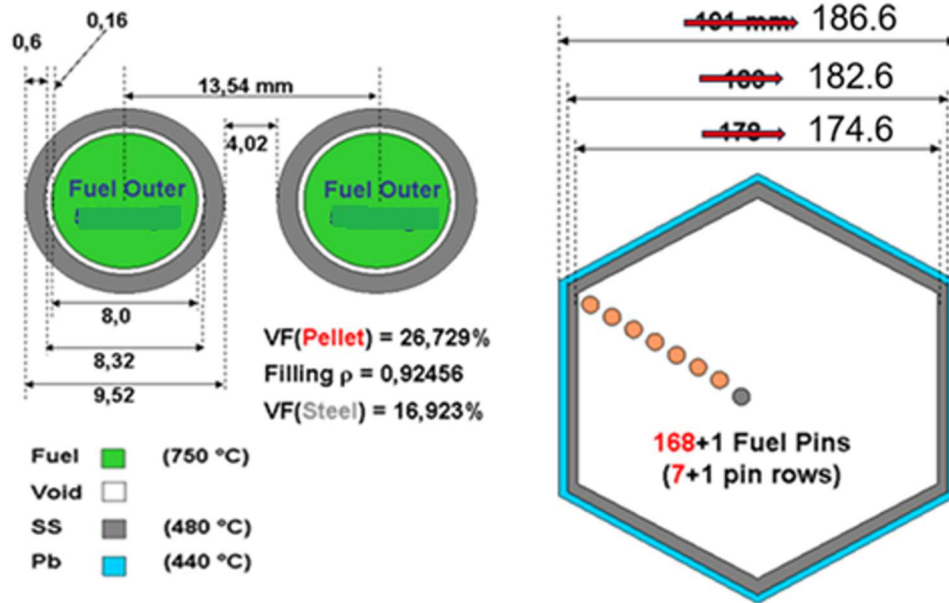


Figure 2: Fuel assembly geometry in LFR-SMR

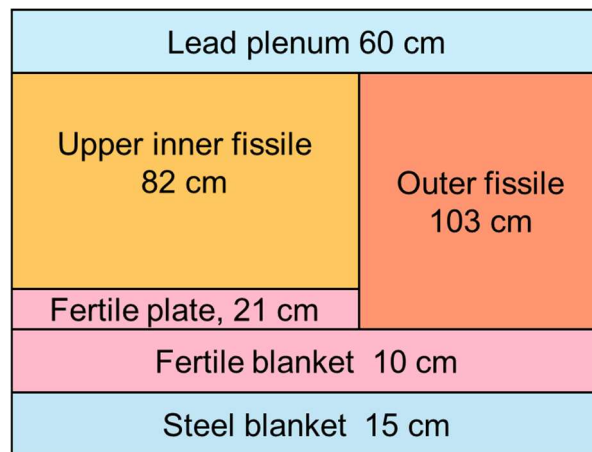


Figure 3: LFR-SMR Core arrangement

The core axial arrangement and core heights in LFR are shown in Fig. 3. The inner and outer fissile core heights are increased as compared to SFR, therefore the total core (fissile and fertile regions together) height is larger by 20.5 cm. This is done in order to get a near-critical core. In LFR, the fertile plate is shifted downward to touch the fertile blanket. Heights of regions outside of the core, in particular steel blanket and regions below, upper gas plena and plugs (not shown in Fig. 3), coolant plenum and regions above are kept the same as in ESFR-SMR. The SFR and LFR axial dimensions are compared in Fig. 4.

The geometrical parameters of SFR and LFR are summarized in Tables 1. The number of FAs in LFR is the same as in SFR, i.e. 84, and the number of pins per FA in LFR is the same as in EFIT [2], i.e. 169. In LFR, the pins are distant by grids instead of wire. The main thermal hydraulic parameters are shown in Table 2 and the neutronic parameters are given in Table 3. It is noteworthy that the void worth of the upper coolant plenum is negative and has a comparatively large magnitude for both reactors.

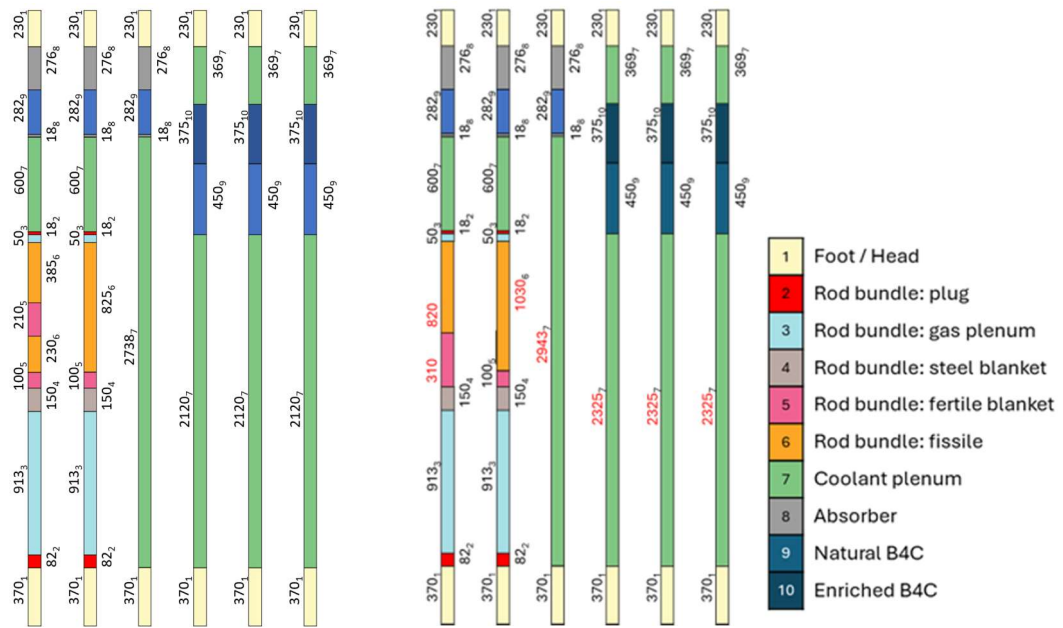


Figure 4: SFR (left) and LFR (right) axial dimensions

Table 1: Main geometric parameters of SFR and LFR

Parameter	Unit	SFR	LFR
Fuel assemblies pitch	mm	186.6	186.6
Wrapper inner width	mm	174.6	174.6
Wrapper thickness	mm	4.0	4.0
Fuel pins per S/A	No.	217	169
CSD	No.	6	6
DSD	No.	1	1
Inner fuel SAs	No.	36	36
Outer fuel SAs	No.	48	48
Inner and outer reflector SAs	No.	88/54	88/54
Cladding outer diameter	mm	10.67	9.52
Cladding thickness	mm	0.50	0.60
Wire diameter	mm	1.0	0
Pellet outer diameter	mm	9.36	8.0
Pellet inner diameter	mm	3.12	0.0
Fuel-clad radial gap	mm	0.155	0.160
Fissile core height, inner/outer	mm	615/825	820/1030

Table 2: Main thermal hydraulic parameters of SFR and LFR

Parameter	Unit	SFR	LFR
Core thermal power	MW	360	300
Coolant inlet temperature	°C/K	395/668	395/668
Coolant outlet temperature	°C/K	545/818	475/748
Coolant temperature rise over core	°C/K	150	80
Coolant mean velocity	m/s	4.3	2
Coolant density at 773 K	kg/m ³	829	10444
Coolant boiling point at 1 bar	K	1156	2016

Table 3: Main neutronic parameters of SFR and LFR

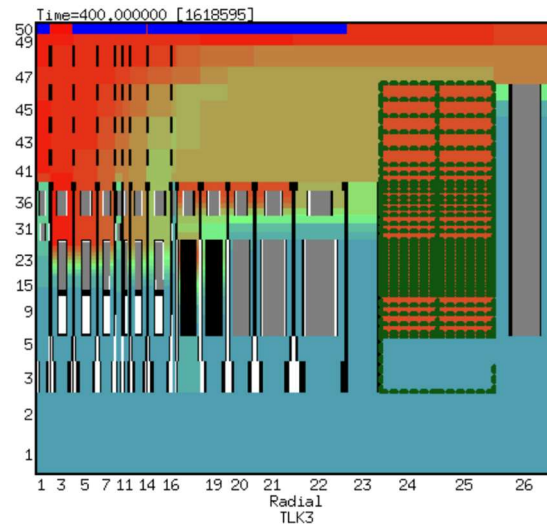
Parameter	Unit	SFR	LFR
k-eff		1.01286	1.00486
Void worth of fissile region	pcm	762	299
Void worth of upper coolant plenum	pcm	-1386	-1713
Doppler constant of fissile regions between 1500K and 1800K	pcm	-585	-432

3. NUMERICAL RESULTS

The steady-state results for the SFR have been presented in [4]. In this paper, the corresponding results for the LFR are briefly summarized in the next subsection.

3.1 Steady State Results of LFR

Fig. 4 shows the coolant temperature distribution in the primary system at the steady state. The heat exchanger (HX) model is simplified by imposing the constant IHX temperature, as the density of steel in the HX region is defined as infinitely large, so that it becomes a perfect heat sink. The core outlet and the clad temperature values are shown in Fig. 5. The axial distribution of temperature in the hottest FA and the fuel centerline temperature in the core are shown in Fig. 6.

**Figure 4: Overall configuration and coolant temperature distribution**

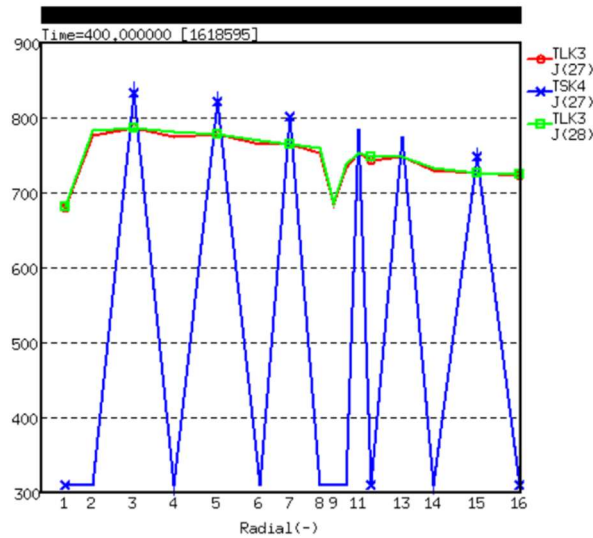


Figure 5: Coolant outlet temperature TLK3 and the associated clad temperature TSK4 in K

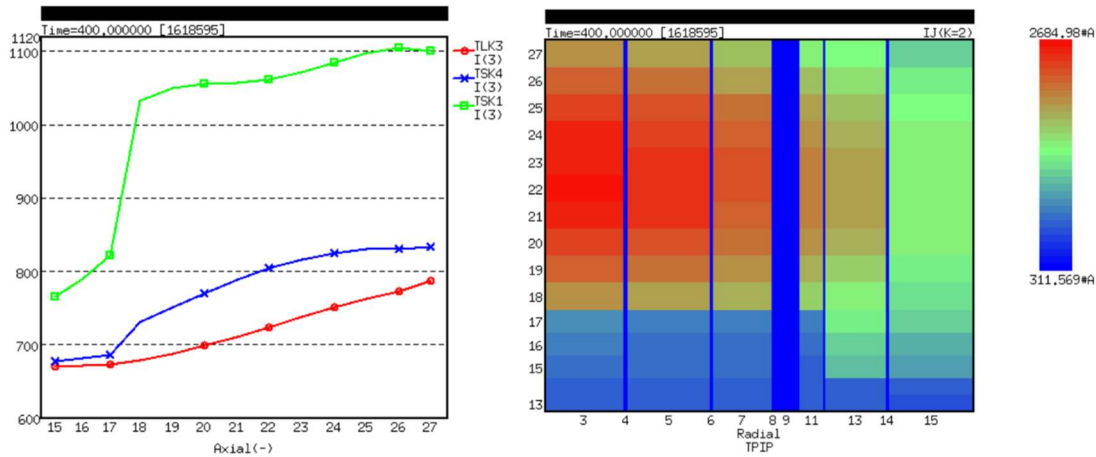


Figure 6: Axial temperature distributions of coolant (TLK3), cladding (TSK4) and fuel surface (TSK1) in the hottest FA (left plot) and the fuel centerline temperature in the core (right plot)

3.2 UTOP Results of SFR and LFR in Comparison

An unprotected transient over power (UTOP) with a reactivity insertion of 1.5\$ within three seconds is considered and simulated for both designs. In the SFR simulation, the UTOP begins at 600 s, whereas in the LFR simulation it begins at 400 s. The reactivity and power transients for both reactors are shown in Fig. 7. To illustrate the accident progression, material distributions in the core at several time points are presented for the SFR and LFR in Fig. 8 and Fig. 9, respectively.

From an overall perspective, the first power peak in the SFR, occurring within the first 3 s, is much weaker than the later peak, whereas in the LFR the first power peak is the strongest. Examination of the detailed material distributions explains this behavior.

In the SFR, sodium boiling occurs during the initial phase, but no cladding failure takes place. The large void formed in the upper sodium plenum introduces a negative reactivity feedback, which reduces the power and prevents cladding failure. In contrast, in the LFR no lead boiling occurs. Instead, the steel begins to melt, leading to cladding failure during this phase and the formation of fuel chunks and particles. As the molten steel is displaced from the core, fuel compaction may occur, enhancing the first power excursion. Subsequently, the fuel chunks and particles drift with the coolant and expand, causing a significant decrease in reactivity and power about 3 s after the start of the UTOP.

In the second phase, after the reactivity insertion, sodium in the SFR re-enters the previously voided region (e.g., about 6 s after the UTOP start), introducing positive reactivity feedback and leading to cladding failure. Compaction of fuel particles may occur, producing a stronger power excursion. After this excursion, the fuel may partially melt and be discharged from the core. In the LFR, following the first power excursion the core is already degraded. The fuel then gradually compacts and relocates again, leading to the second and third power peaks; however, these are much weaker than the first one.

There is a third power peak in the later phase of the SFR core degradation. This peak is caused by compaction of the fuel, leading to prompt criticality. This phenomenon is referred to as re-criticality, and its details have been discussed in [5].

The thermal energy release can be evaluated by integrating the core thermal power over time, as shown in Fig. 10. From the plot, the first, second, and third power peaks of the SFR correspond to energy releases of 8, 11, and 8 GJ, respectively. In comparison, the corresponding values for the LFR are 5.6, 0.8, and 0.4 GJ. The total thermal energy release is therefore 27 GJ for the SFR and 6.8 GJ for the LFR. The mechanical energy release has also been evaluated. The maximum values are approximately 8 MJ for the SFR [5] and 0.8 MJ for the LFR. Both values are expected to be below the design limits.

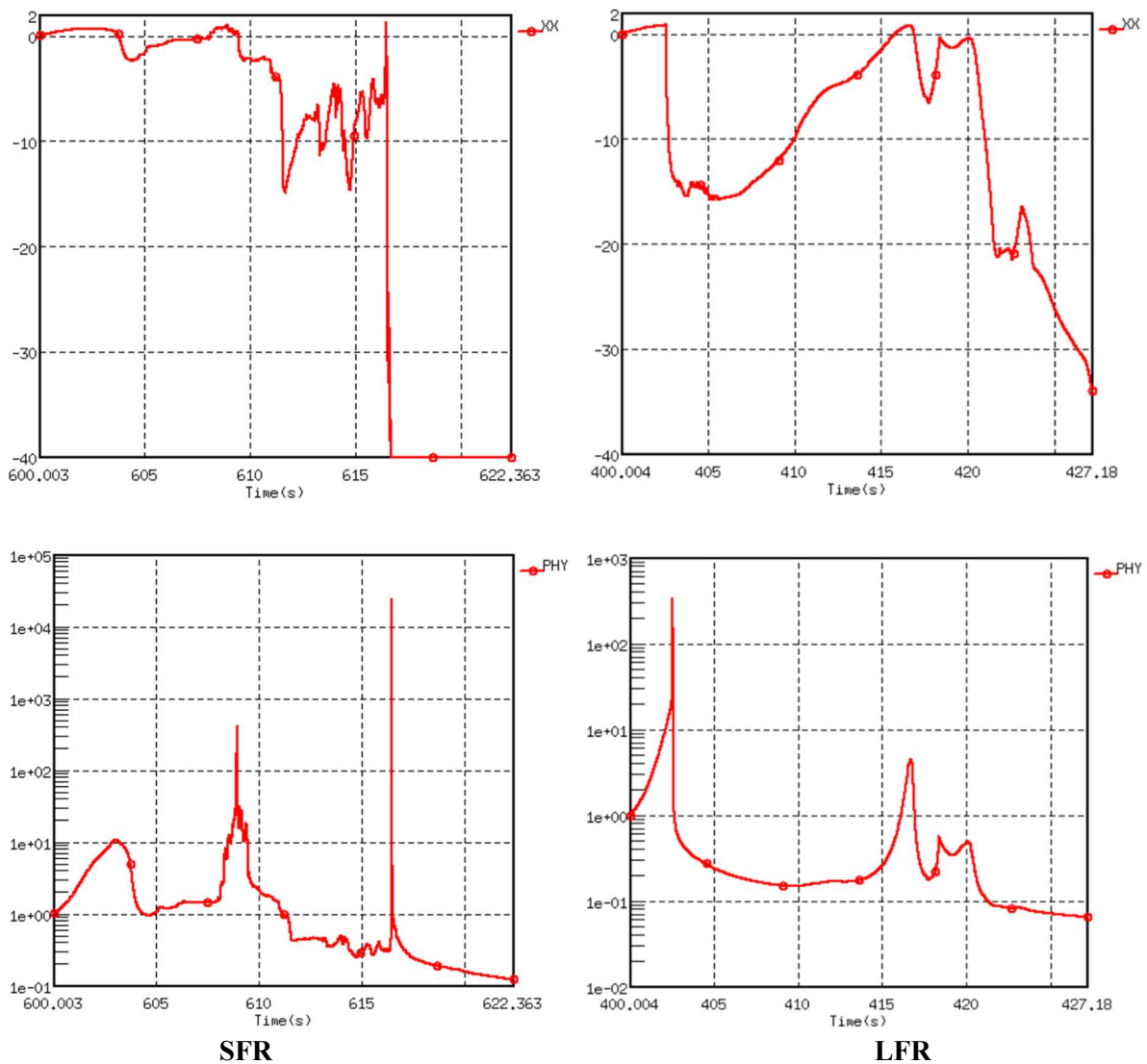
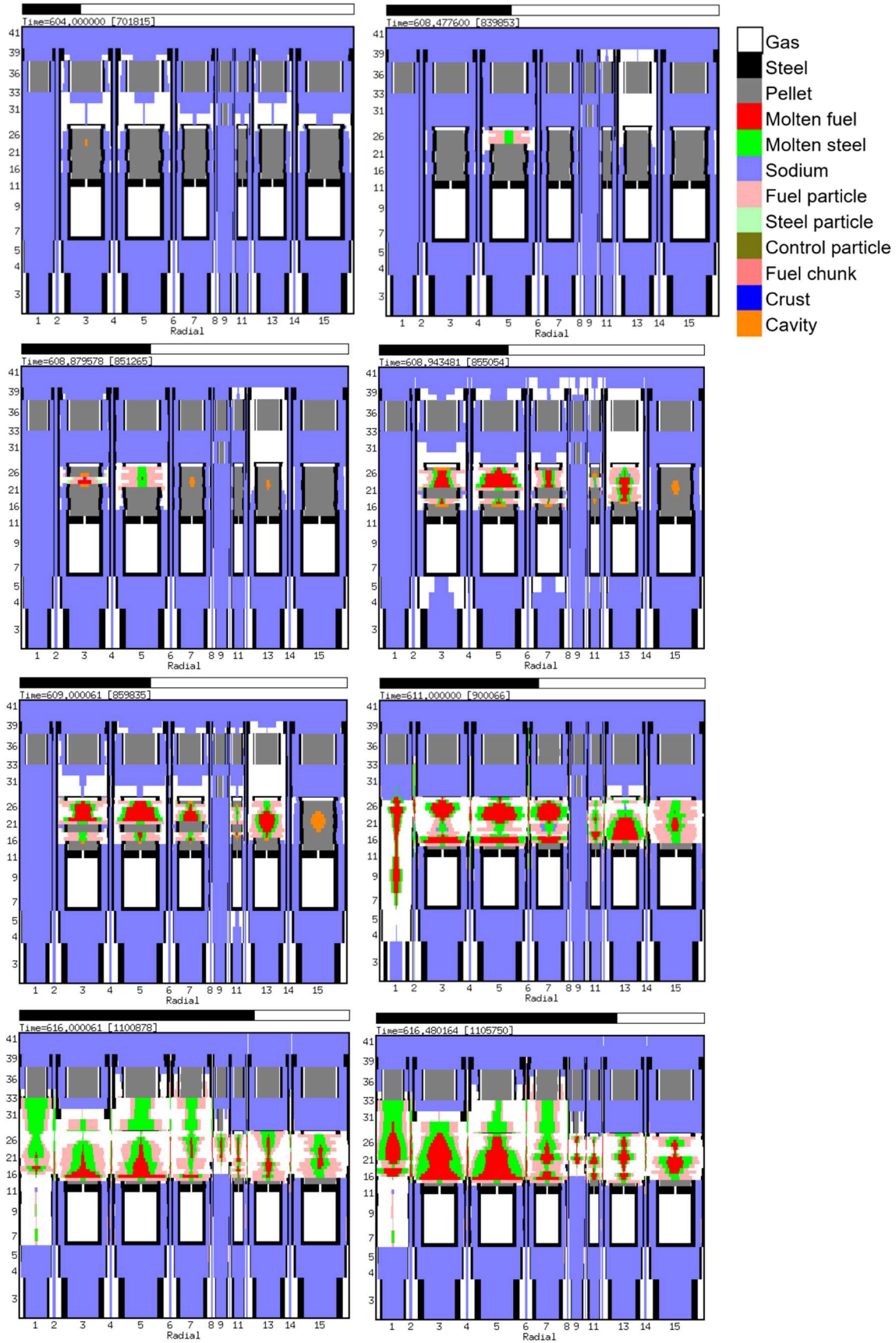


Figure 7: Reactivity XX in \$ and relative power PHY in SFR (left) and LFR (right) during the UTOP transient



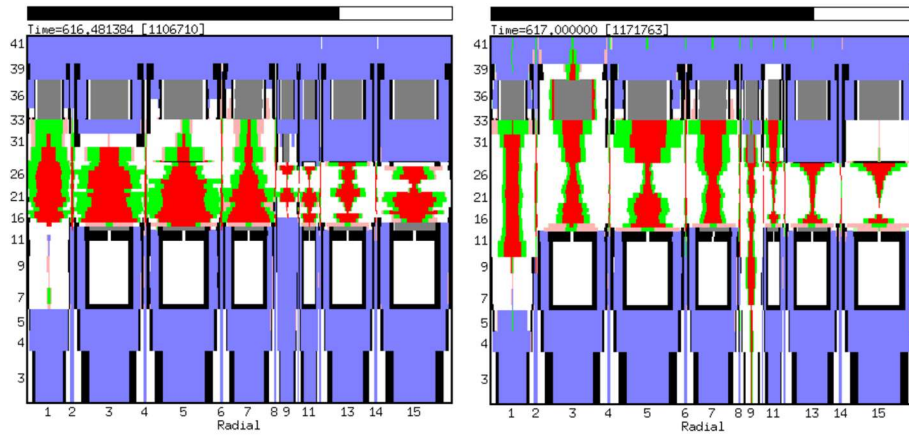
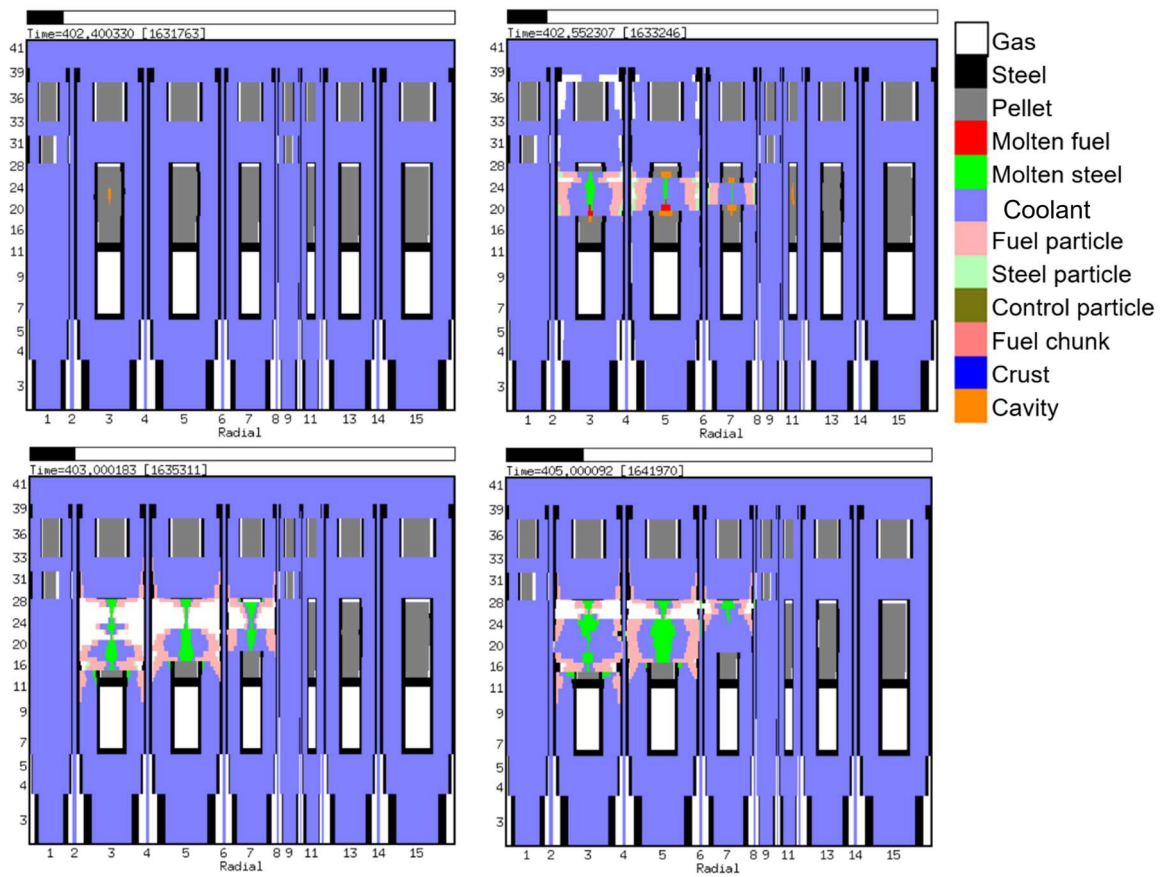


Figure 8: Material distributions at the SFR UTOP transient at various moments



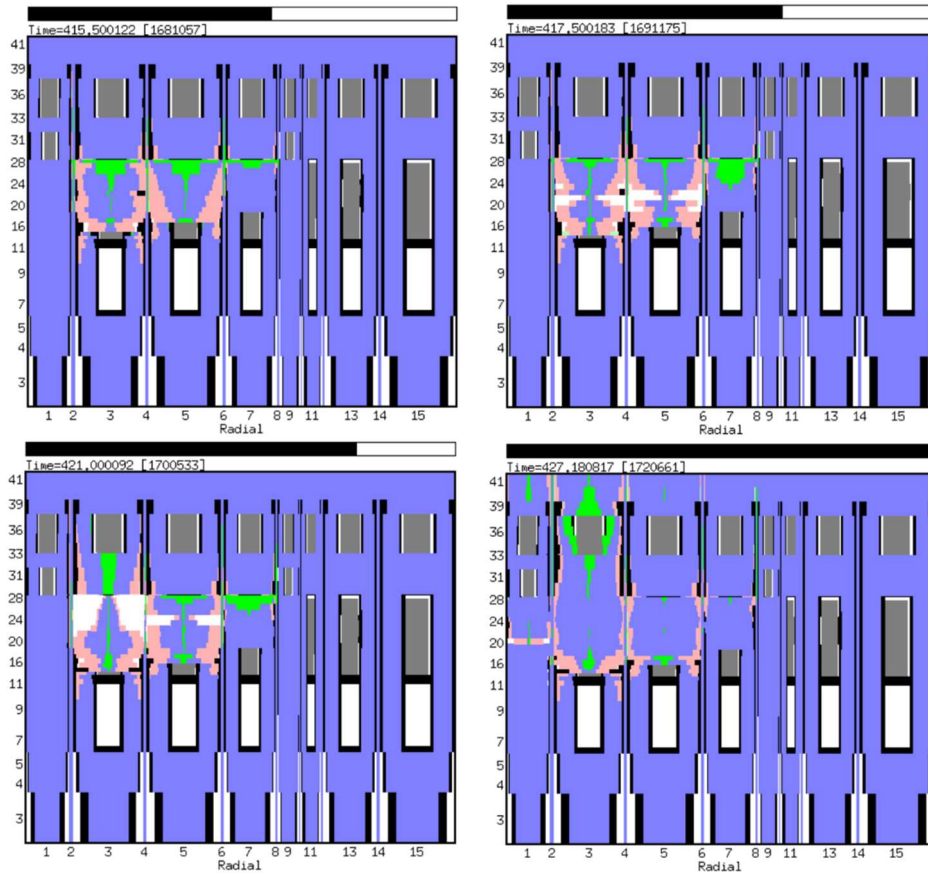


Figure 9: Material distributions at the LFR UTOP transient at various moments

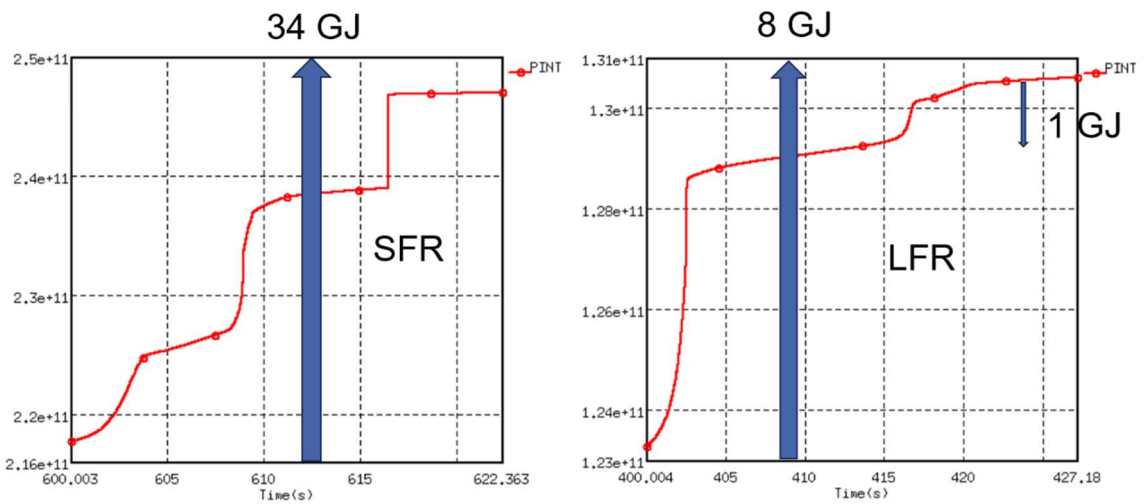


Figure 10: Released thermal energy in SFR (left) and LFR (right)

3. CONCLUSIONS AND REMARKS

In this work, an LFR-SMR model was developed and simulated using SIMMER-III to investigate the reactor response under a 1.5\$ unprotected transient overpower (UTOP) scenario. The results were compared with those obtained for the ESRF-SMR in order to compare the transient behavior and energy release characteristics of the two systems. The analysis shows that the LFR-SMR produces significantly

lower thermal and mechanical energy releases during the accident transient. This indicates a comparatively milder energetic response for the LFR-SMR under the considered conditions.

As follows from the simulation results, the higher energy release in the SFR can be mainly attributed to the lower boiling point and the lower density of sodium, which facilitate displacement of coolant and fuel compaction. In contrast, in the LFR the melting of steel occurs prior to lead boiling. This process also enables fuel degradation, relocation and compaction. The resulting energy release in LFR is significantly smaller in the considered case.

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