SIMULATION OF ULOF INITIATION PHASE IN ESFR-SMART WITH SIMMER-III

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Abstract

A large 3600 MWth European Sodium Fast Reactor (ESFR) design was proposed in 2009 by CEA for the EURATOM CP-ESFR project. ESFR safety and related topics are studied now in the next project, ESFR-SMART. A new core configuration with a near-zero coolant void reactivity effect, mainly due to the introduction of a sodium plenum above the core and core flattening, has been established for ESFR-SMART. We investigate its safety by simulating transients such as unprotected loss of coolant flow (ULOF) with the SIMMER-III code, starting from nominal conditions till and beyond the sodium boiling onset. In the initiation transient phase, before core structure and fuel melting, sodium boiling starts in the core and in the plenum above. In order to better understand phenomena involving interaction of different flow channels during sodium boiling, we use different modelling options. We apply new SIMMER capabilities for taking into account core thermal expansion and control rod drivelines expansion reactivity effects, and show their influence on transient simulation results. Similar to earlier ULOF studies for reactors with the sodium plenum, we observe power/reactivity oscillations after the sodium boiling onset. The reason for the oscillations is that the sodium boiling and reflooding events in the upper core part result in a negative and positive reactivity variations, respectively. The oscillation may occur for some time and then lead to a power excursion (and a core degradation), if the negative reactivity feedback component, mainly due to plenum voiding and thermal core expansion, is not strong enough. If it is strong enough, the sodium boiling oscillation may decrease and finally disappear, thus the reactor approaches a new steady state (asymptotic state) at an elevated temperature.

1. INTRODUCTION

A European Sodium Fast Reactor (ESFR) design was proposed by CEA for the CP-ESFR Project in 2009. The reactor power was 3600 MWth, each of 453 fuel subassemblies (SAs) with a pitch of about 21 cm contain 271 pins, the fissile height being 1 m. The pin diameter of more than 1 cm is higher, if compared to EU designs proposed before 2000, that leads to a higher fuel volume fraction and a lower sodium one. A higher fuel volume fraction makes utilization of fuel with a lower enrichment and elimination of fertile blankets around the core possible, while the Pu mass balance remains near zero. A lower sodium volume fraction reduces the sodium void effect in the core. On the other hand, optimization studies performed for CP-ESFR have shown that a lower sodium void effect can be achieved that would be favourable for reactor safety [1].

The next project on ESFR, ESFR-SMART started in 2017. For this project, a new core configuration [2] with a near-zero coolant void effect, mainly due to introduction of a sodium plenum above the core and core flattening, has been established. A lower axial blanket was introduced that is favourable for the void effect. Also other safety measures, such as special tubes for molten fuel discharge to the core catcher and passive shut-down rods were introduced.

Several project partners study ESFR safety and perform simulation of transients, including an unprotected loss of coolant flow (ULOF). Most codes employed in ULOF studies can be applied till coolant boiling or structure/fuel melting onset, i.e. during the ULOF initiation phase. For the simulation of later ULOF phases, such as transition to full core melting (transition phase), a 2D RZ code, called SIMMER-III and referred as SIMMER in the following, is applied.

The multi-velocity-field, multi-material-component and multi-phase formulation of SIMMER is based on Advanced Fluid Dynamics Model (Bohl et al. 1990 [3]), in which the macroscopic modelling for fuel pins, subassembly hexcan, etc. are implemented and with which a space-, time- and energy-dependent neutron transport model is coupled. The heat and mass transfer and the momentum exchange between different phases and materials are modelled explicitly. In addition, an analytical equation-of-state (EOS) model is available to close and complete the fluid dynamics conservation equations. The code has been originally developed and applied for safety analyses in the severe accident domain of sodium fast reactors (SFRs) (Kondo et al., 1992 [4]). At KIT the SIMMER code has been developed and applied as a versatile and flexible deterministic tool, for the safety analysis of fast reactors with different neutron spectra and coolants, including modern SFR designs (Chen et al. 2016 [5]) and accelerator driven systems (ADS) (Suzuki et al. 2005 [6]; Chen et al. 2017 [7]).

In the past, SIMMER calculations for SFRs were mainly done after initiation phase calculations performed with another code. One of the reasons for using another code was that the core and control rod drivelines (CRDL) thermal expansion reactivity feedback models were not included in SIMMER. Around 2015, a model for core expansion was included in SIMMER [8]. For the ESFR-SMART project, a new CRDL expansion model was developed. While the core expansion model relies fully on the SIMMER neutronics part, the CRDL model employs a CR-worth table computed with an external neutronics code: because the homogeneous treatment in SIMMER neutronics is approximate for CR-worth calculations. During the transient, an average (taking into account all CRs) value of CRDL elongation is computed by employing CRDL temperatures calculated in the fluid-dynamics part of SIMMER and considered at user-specified locations; then the reactivity effect is computed using the above mentioned table.

A SIMMER model for ESFR-SMART has been set up and its neutronics part was assessed, with respect to major reactivity feedback coefficients, before doing transient simulations. Besides the usually analysed fuel, coolant and structure temperature and density reactivity feedbacks, the thermal expansion effects (axial and radial) and the control rod drivelines expansion effects were considered. All SIMMER feedback coefficients agree well with the design reference values. A particular feature of this reactor design should be mentioned here: the sodium void effect in the fissile core region is positive, but the effect in the sodium plenum above the core is negative. Steady state results, including temperature and velocity distributions of the coolant, as a starting point for transient calculations, have been also obtained and compared with results of other project partners. Good agreement between the results of the partners has been achieved.

The major objective of this paper is to study transient behaviour during ULOF, when the primary pump is coasted down. Four cases are considered, with two core thermal expansion models and with two CRDL thermal expansion coefficients. In all cases we get sodium boiling and its consequent oscillations. In three cases, as in earlier studies [1], we see finally a power excursion that is delayed compared to the transient in the core with the plenum studied in [1]: due to a lower sodium void effect in ESFR-SMART and due to consideration of thermal expansion feedbacks. In the last fourth case, with the largest negative feedback due to the clad-driven axial thermal expansion and the largest CRDL coefficient, recommended by the project, we observe no power excursion. The sodium boiling oscillations are associated with (1) the boiling in the upper core region and in the plenum above, which results in a negative reactivity feedback, and (2) the sodium reflooding into the voided region which gives a positive reactivity feedback. If the sodium boiling oscillations grow, the reactivity can approach the prompt super-criticality, then a power excursion takes place, as one may see in the first three cases. On the other hand, if the negative feedback is strong enough, the oscillation amplitude decreases with time, so that finally it disappears and a new steady state (an asymptotic steady state) is established, as one may observe in the last case. The reason for the amplitude reduction is a pressure increase in the system, driven by the temperature, gas volume and accumulated sodium vapour mass variations in the cover gas region. The pressure may increase so, that the sodium boiling no longer happens. Therefore one may consider the nominal pressure in the cover gas and its volume as values that may influence the ULOF transient progression. The three cases with power excursions and earlier cases simulated without expansion feedbacks offer a good basis for SIMMER-based studies of molten ESFR core behaviour after a hypothetical accident, which will not be reported here.

2. SIMMER SIMULATION MODEL AND STEADY STATE RESULTS

2.1. Core configuration and SIMMER model

The radial and axial core layouts and the SIMMER geometric model are shown **in Fig. 1** and **Fig. 2,** respectively. The core includes the following subassemblies (SAs): 1 central dummy assembly, 216 inner core fuel assemblies with the fissile height of 75 cm, 288 outer core fuel assemblies with the fissile height of 95 cm, 24 Control and Shutdown Devices (CSDs) and 12 Diverse Shutdown Devices (DSDs), three rows of 264 reflector assemblies and 252 spent fuel storage assemblies. A particular aspect of this SIMMER model is that the inter-wrapper flow spatial regions and therefore the radial heat transfer between the SA rings have been explicitly taken into account. In earlier SIMMER simulations, no radial meshes dedicated to gaps between SAs were usually employed, and the gaps shared meshes together with SA internals. That reduced computer time, but introduced additional uncertainties in the results of calculations. In **Fig. 2** one can see that the secondary system is included in the model together with a simple heat exchange model. TLK3 in Fig. 2 means sodium temperature, green/red colours being for low/high temperatures. In the past, the secondary cooling system was usually not treated with SIMMER explicitly. That reduced computer time, but did lead to approximate results for some transients, in particular for loss of heat sink transient.

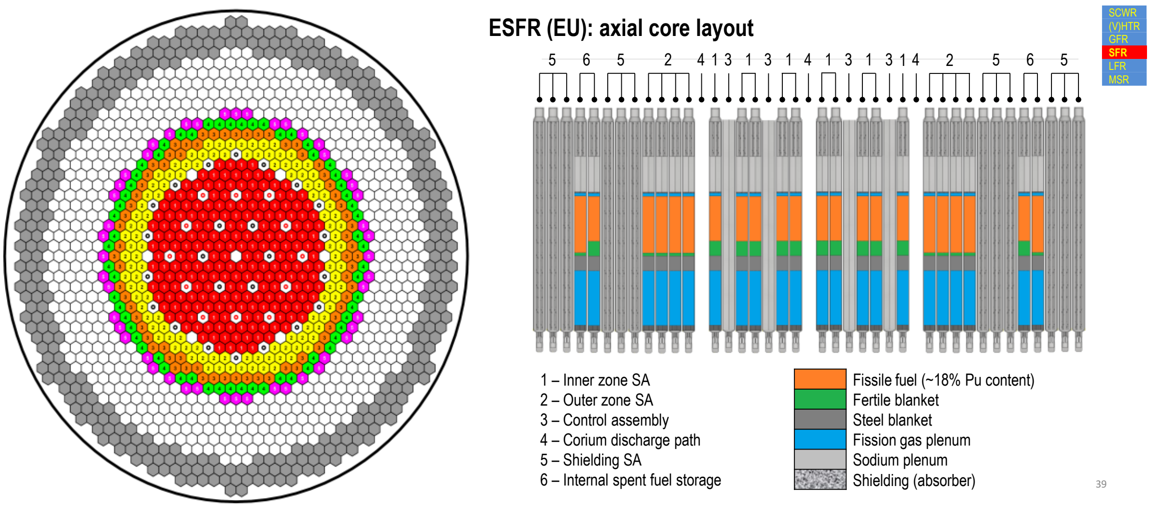


FIG. 1. Radial core map and axial core layout [9].

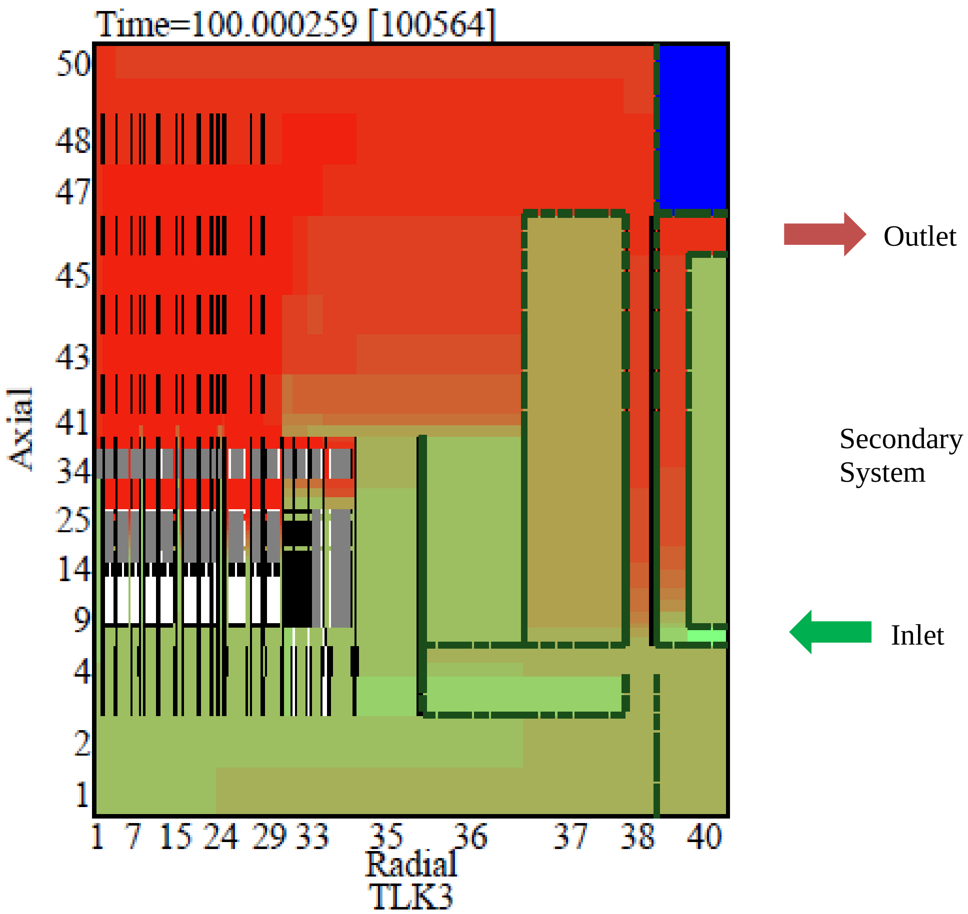


FIG. 2. SIMMER III overall simulation model.

2.2. Neutronics modelling and feedback effects

The ESFR-SMART core consists of two zones, inner and outer cores, loaded with fuel of the same enrichment, but different fissile heights. The average Pu content in the fissile core part is about 17.9 at% at the End Of Equilibrium Cycle (EOEC), see Ref. [9], that includes results of neutronics calculations, referred in the future as Vademecum. In the SIMMER neutronics model the fuel composition is determined by two isotopic vectors, for “fertile” and “fissile” components, and by location-dependent values of fuel enrichment. For the ESFR-SMART, we determined initially the “fertile” vector as the average blanket isotopic composition and the fissile vector as the average core isotopic composition, the core enrichment as 100% and the blanket enrichment as zero. This approach, however, gives an approximate power distribution, mainly due to (1) a higher than average Pu content in the upper part of the lower blanket, and (2) a lower than average fuel burn-up at the radial core periphery. Then, the enrichments in the blanket and the last radial core ring were adjusted, i.e. slightly increased and decreased, respectively, the total fertile and fissile masses being kept. The adjustment improved SIMMER neutronics results. The computed with SIMMER axial and radial power profiles are shown in **Fig. 3** and **Fig. 4**, respectively, and they are in reasonable agreement with the project reference (Vademecum) results. IF/OF in Fig. 3 refer to inner/outer fissile core sub-regions with the lower axial blanket heights of 25/5 cm.

The reactivity feedback coefficients computed with SIMMER and some related values are shown in **Table 1** and compared with the reference ones. The SIMMER values are in general agreement with the reference ones, the differences being related to approximations in the SIMMER neutronics model, such as the employed RZ geometry, 11 energy groups, etc. It is important to notice that the sodium void worth above the core, where sodium boiling onset takes place, is negative.

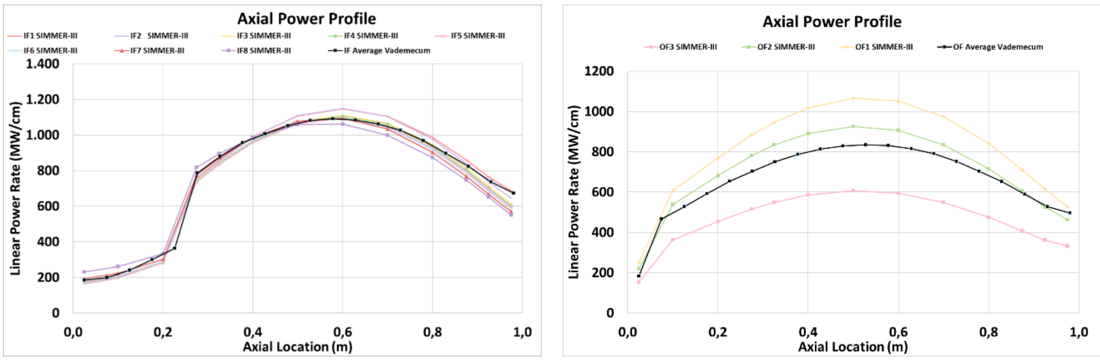


FIG. 3. Axial power profiles, upper plot for the inner core and lower plot for the outer core.

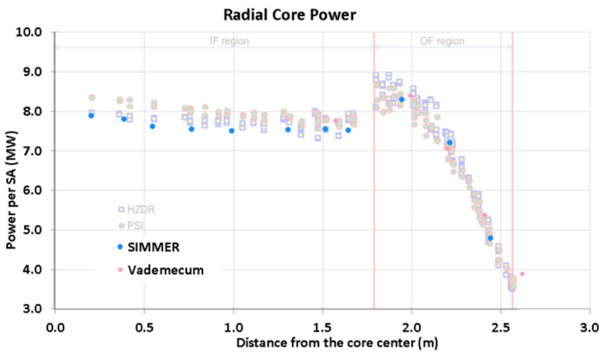


FIG. 4. Radial power profile, SIMMER vs Reference.

TABLE 1. NEUTRONIC FEEDBACK COEFFICIENTS

Parameter	Unit	SIMMER	Reference (Serpent calculations)
K_{eff}		**1.00937**	**1.00471**
Prompt Neutron Lifetime	[s]	**4.25E-07**	**4.74E-07**
Beta Effective	[pcm]	**347**	**362**
Doppler Constant Fissile 1500 K -> 1800 K Fertile 900 K -> 900 K	[pcm]	**-808**	**-685**
Core Void Worth without Voided Gaps at T_{cool} 763.2 K	[pcm]	**1755**	
Core Void Worth with Voided Gaps	[pcm]	**1727**	**1542**
Upper Gas Plenum + Plug Void Worth	[pcm]	**-41.3**	**-62**
Coolant Density Reactivity Coefficient	[pcm/K]	**49/110.8= 0.442**	**48/110.8 = 0.433**
Axial Thermal Expansion Coefficient	[pcm/K]	**-0.0715**	**-0.083**
Radial Thermal Expansion Coefficient	[pcm/K]	**-0.711**	**-0.646**
Control Rod Drivelines Expansion Coefficient	[pcm/cm]	**-423/14.5**	**-423/14.5**

2.3. Thermal-hydraulic parameters and steady state

The main core thermal hydraulic parameters under steady-state conditions are shown in **Table 2**. The core is subdivided into five cooling groups as shown in the radial core map in Fig. 1 with different colours, where the cooling group 1 is assigned to the inner core and the other 4 groups to the outer core. The mass flow rate is determined so that the core outlet temperature distribution is almost uniform, around 545 °C (818 K).

SIMMER results at steady state, including coolant mass flow rates and temperatures at EOEC conditions, have been compared and checked in an ESFR-SMART project benchmark. They are consistent with those computed by other partners. Therefore they serve as a good basis for further ULOF transient calculations.

TABLE 2. ESFR-SMART CORE THERMAL-HYDRAULIC CONDITIONS

Parameter	Unit	Value
Reactor power	[MWth]	3600
Core mass flow rate	[kg/s]	18705
Core bypass mass flow rate	[kg/s]	831
Core inlet temperature	[°C]	395
Core outlet temperature	[°C]	545

3. SIMMER ULOF SIMULATIONS AND RESULTS

Based on the steady state results, the ULOF transient has been simulated with SIMMER. The pump is coasted down with a halving time of 10 s. Since the coolant inlet temperature varies slightly during the transient, the radial thermal expansion - that is assumed to be driven by the diagrid temperature so that only a small core radial size variation in the cylindrical expansion mode happens - does not introduce a significant reactivity effect. If the fuel-clad gap is closed due to irradiation, the axial core thermal expansion is driven by clad expansion; if the gap is open, it is driven by fuel expansion. Both options are considered in the following. Moreover, two thermal expansion coefficients of 1.53 10^{-5} and 1.82 10^{-5} for CRDL model have been applied, one of which is smaller and was used for similar studies in the past and the other one is the reference value of the project. Therefore we consider 4 cases in total as listed in Table 3. The times for major events as the boiling onset and the power excursion start are shown there as well. As we see, there is even no power excursion in Case 4, which is characterized by the largest negative feedback that is the closest to the reference. Case 4 is analysed in the following in more details.

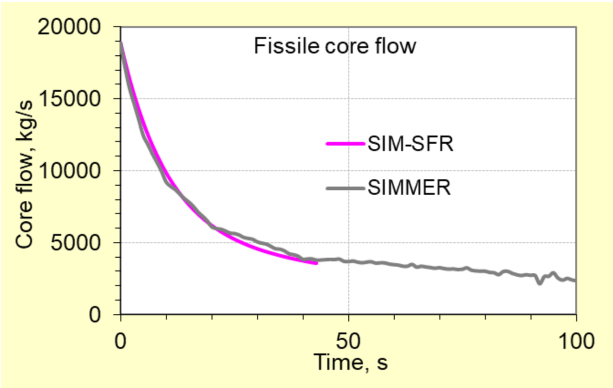
TABLE 3. ESFR-SMART CORE THERMAL HYDRALIC CONDITIONS

Case No.	**Case Description**	**Boiling Onset**	**Power Excursion**
1	Fuel-Driven and 1.53 10^{-5} CRDL	42 s	Yes at 102 s
2	Clad-Driven and 1.53 10^{-5} CRDL	69 s	Yes at 129 s
3	Fuel-Driven and 1.82 10^{-5} CRDL	45 s	Yes at 117 s
4	Clad-Driven and 1.82 10^{-5} CRDL	73 s	**No**

3.1. Case 4 results

Fig. 5 shows SIMMER results for the mass flow rate, total power and total reactivity, compared with results of another code used at KIT, SIM-SFR [10]. SIM-SFR employs fast-running models, it is to be compared with other codes applied in the project for ULOF analyses in a paper to be published separately. SIM-SFR results are truncated up to the sodium boiling onset, while SIMMER ones are shown also after the sodium boiling onset. The general agreement with results of other projects partners till the boiling onset is also good. After the sodium boiling onset, one can see significant oscillations of power and reactivity. The reason is that the sodium boiling above the core gives a negative feedback and forces the power to decrease; afterwards, as sodium comes back into the voided region due to pressure and condensation, we see a coolant reflooding, that augments the reactivity and power. This procedure repeats with a period of about 10 s. **Fig. 6** shows the scenarios at the moments of coolant voiding and reflooding, corresponding to the power/reactivity trough and peak ones. As the reviewer also pointed out, this simulation is 2-D, where there is an artificial coincident effect in the simulation. Therefore the oscillation could be overestimated in the 2-D numerical simulation with coarse meshes.

Fig. 7 shows core coolant inlet and outlet temperatures. The inlet temperature is slightly decreasing and the outlet temperature is increasing as expected. The agreement with SIM-SFR and other unpublished results is again good. As the outlet temperature reaches the sodium saturation point, the sodium boiling onset occurs and the power oscillates afterwards.



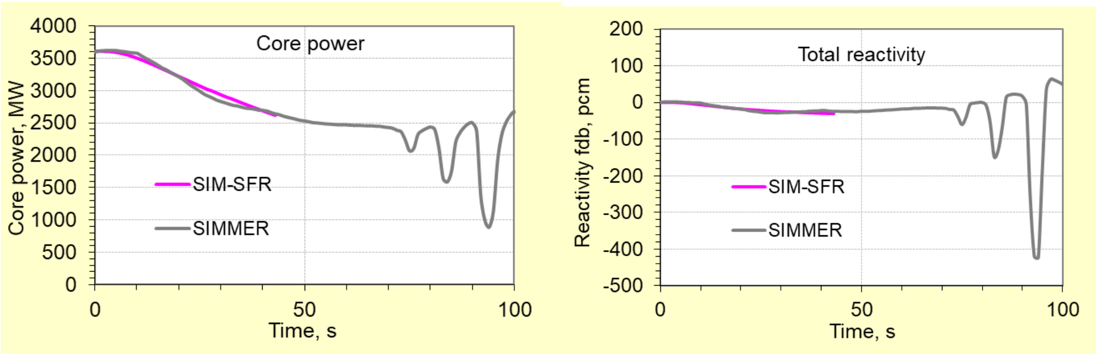
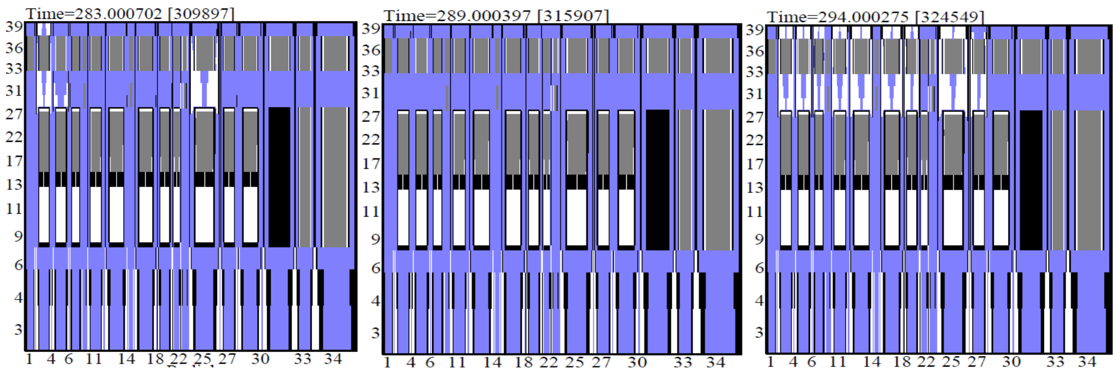


*FIG. **5**. ULOF benchmark of mass flow rate, power and total reactivity, where SIMMER results are the longer one in grey.*



(a) t= 83 s *(b) t= 89 s* *(c) t= 94 s*

FIG. **6**. SIMMER calculated coolant void and reflooding scenarios, which corresponds exactly to the moments of power trough and peak.

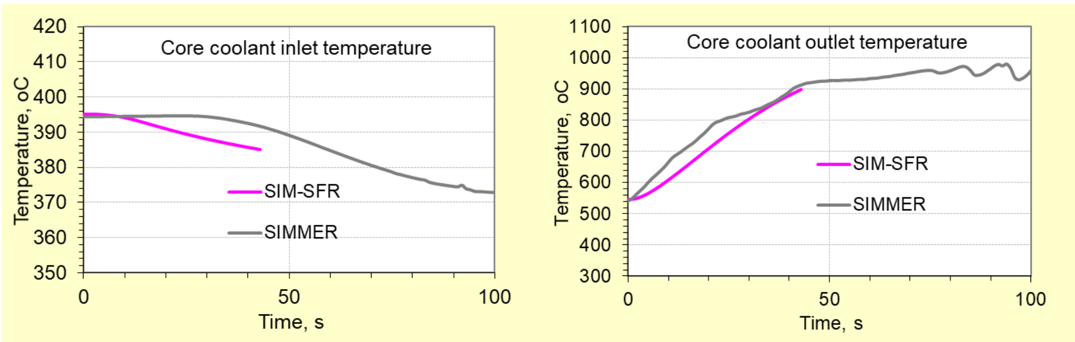


*FIG. **7**. ULOF benchmark of core coolant inlet and outlet temperatures, where SIMMER results are the longer one in grey.*

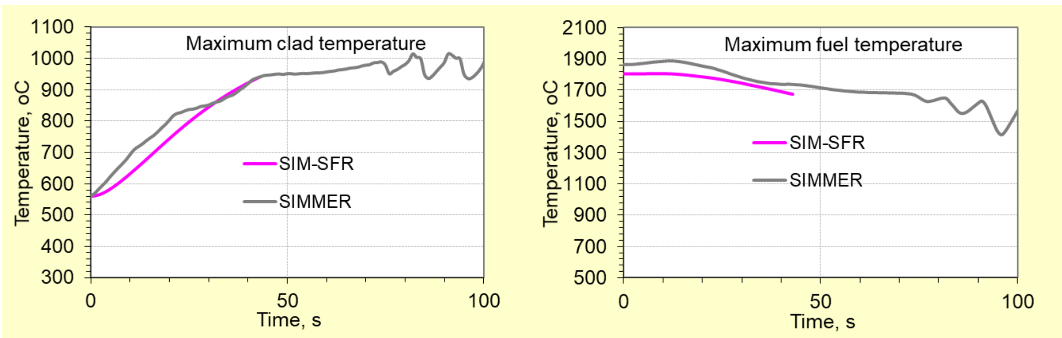


*FIG. **8**. ULOF benchmark of maximal clad and fuel temperatures, where SIMMER results are the longer one in grey.*

Fig. 8 shows the maximal clad and fuel temperatures during the ULOF transient. The clad temperature increases significantly, while the fuel temperature decreases. The agreement with SIM-SFR is good again.

3.2. Effect of the axial thermal expansion (comparison of Case 3 and Case 4)

If the fuel gap is open, which is the case of fresh or low burn-up fuel, the axial fuel thermal expansion is driven by the fuel temperature (Case 3). If the fuel gap is closed in the high burn-up case, it is driven by the clad temperature (Case 4). Note that the fuel- and clad-driven axial thermal expansion effects give reactivity feedbacks of different signs: the fuel-driven one is positive in Case 3, while the clad-driven one is negative in Case 4. **Fig. 9** shows the comparison of Case 3 and Case 4 together with SIM-SFR long-run results. The difference is due to fuel-driven and clad-driven axial thermal expansion options for Case 3 and Case 4, respectively. Case 3 results in a power excursion and core degradation, while Case 4 results only in sodium boiling, no power excursion. This is in line with earlier studies showing that the sodium boiling can lead to a power excursion, if the negative reactivity feedback is not good enough.

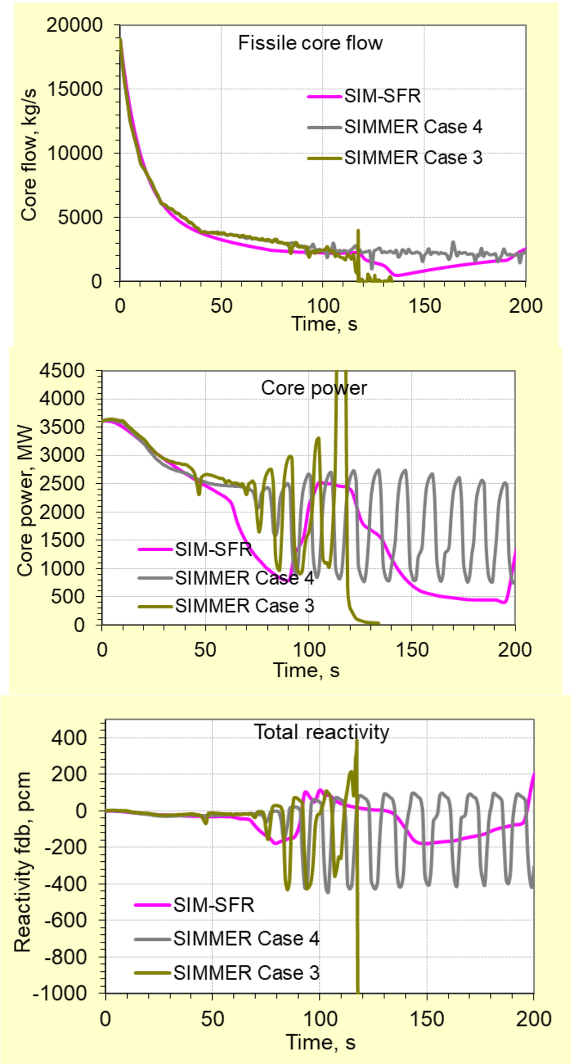


FIG. 9. Comparison of ULOF Case 3 and Case 4 results of mass flow rate, power and total reactivity.

3.3. Long-time calculation results in Case 4

A long-time calculation of Case 4, up to 1000 s, has been carried out. **Fig. 10** shows its results for the mass flow rate, power and total reactivity. It is surprising to see that after 900 sthe sodium oscillation disappears finally.

The reason is that the cover gas pressure is increasing from 1.15 bar to 2.70 bar, so that the sodium boiling is suppressed, because the sodium saturation temperature becomes higher,

As pointed out by the reviewer that the cover gas pressure can be regulated by safety gas valves during the transient, the closed cover gas plenum condition used here is not so realistic. Nevertheless this result gives a hint that the increased cover gas pressure can prevent the sodium boiling in the core, therefore its power oscillation, for this reactor. This means that the cover gas pressure could be initially increased.

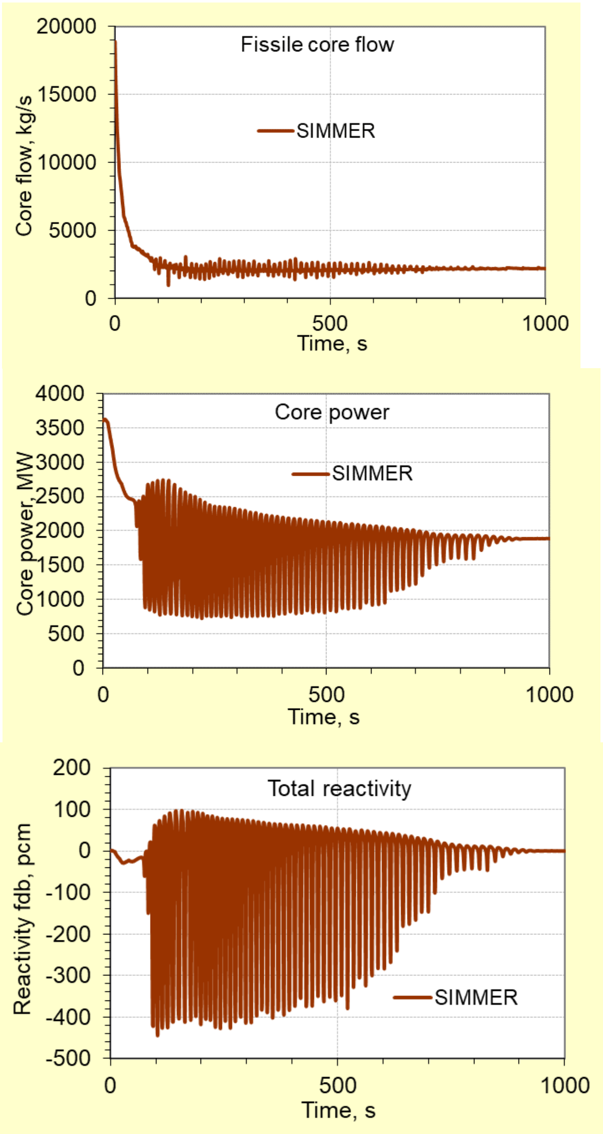


FIG. ***10****. Long time ULOF results of mass flow rate, power and total reactivity in Case 4.*

4. CONCLUSIONS

Within the ESFR-SMART project the ULOF transient has been simulated with the SIMMER-III code. The SIMMER results agree well with those of other project partners before the sodium boiling onset. After the sodium boiling, SIMMER results show power and reactivity oscillations. This is an instability effect related to the sodium voiding and reflooding events under ULOF conditions. These oscillations can lead to a power excursion under conservative assumptions. Molten core configurations obtained under conservative conditions provide a good basis for SIMMER-based studies of the ESFR molten core behaviour after a hypothetical accident.

The long-time calculation under non-conservative assumptions shows that the sodium boiling oscillation may decrease and finally disappear, after the reactor approaches a new steady state (asymptotic state), at an elevated pressure and temperature. It is suggested that an increase of the initial pressure in the cover gas region can result in a non-sodium-boiling asymptotic state after ULOF.

ACKNOWLEDGEMENTS

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