Preliminary Safety Performance Assessment of ESFR CONF-2 Sphere-Pac-Fueled Core

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Abstract. A preliminary safety assessment of the CONF-2 version of the European Sodium Fast Reactor core loaded with both pellet and sphere-pac fuels was performed. The reference Unprotected Loss Of Flow (ULOF) and an Unprotected Transient Over-Power (UTOP) accidents were simulated, along with a set of sensitivity studies aimed at evaluating the influence of uncertainties affecting both safety coefficients and the fuel thermal conductivity. Among the major outcomes, it could be preliminarily concluded that the use of sphere-pac fuel may bring some disadvantages from the safety point of view in the event of a UTOP accident, whereas no concerns are raised for a ULOF scenario. Consistently, uncertainties in the determination of the fuel thermal conductivity and Doppler constant were found to have no significant impact on the ULOF transient predictions, but to influence the UTOP simulations, making their accurate determination critical for the system safety assessment.

Key Words: Sodium-cooled Fast Reactors (SFRs), sphere-pac fuel, safety assessment, unprotected transients.

1. Introduction

Within the European FP-7 project PELGRIMM [1], oxide fuel forms for Minor Actinides (MAs) transmutation were researched for both homogeneous and heterogeneous recycling in Sodium-cooled Fast Reactors (SFRs).

Among the investigated fuels, sphere-pac fuels were given priority emphasis, as they offer great advantages compared to pellet fuels when MAs are to be embedded[1], while presenting, however, one major drawback, the latter being their low thermal conductivity, especially at Beginning of Life (BoL).

In order to determine the actual suitability of such particulate fuel forms for use in SFRs, safety analyses were planned, so as to provide a first assessment of both the transient behavior of sphere-pac-loaded cores as compared to the reference ones incorporating classical pellet MOX fuel, and the relative safety margins. In a broader perspective, such studies were expected to help identify potential hindrances preventing the use of MOX sphere-pac fuels, as well as needs for further code developments and validations.

A preliminary safety assessment of the CONF-2 version of the European Sodium Fast Reactor core (ESFR) [2] at BoL, loaded with both pellet and sphere-pac fuels, was performed by using the BELLA [3] and the SAS4A/SASSYS-1 [4] system codes; core neutronic characteristics

[1] For instance, concerning burn-up performances, sphere-pac macrostructure enables to accommodate fission gases during irradiation, therefore reducing the interactions between fuel and cladding (*i.e.*, FCCI and FCMI).

and safety parameters were calculated by means of the Monte Carlo code Serpent [5] associated with the nuclear data library JEFF3.1.1 [6], and complemented with both ERANOS [7] and MCNPX [8] results.

Unprotected Loss Of Flow (ULOF) and Unprotected Transient Over-Power (UTOP) accidents were simulated, along with a set of sensitivity studies that was performed aimed at assessing the influence of uncertainties affecting both safety coefficients and the fuel thermal conductivity. The investigation of such uncertainties impact on the system transient behavior allowed drawing conclusions concerning also the effects of burn-up and MA loading (detrimental to reactivity coefficients and kinetic parameters), and of fuel form (namely, sphere-pac *vs.* pellet fuel).

2. Reference System Configuration

The CP-ESFR optimized CONF-2 core was selected as the candidate core configuration to be loaded with sphere-pac fuel. The main technical specifications and properties of the ESFR primary system and CONF-2 core are discussed in the following sections.

2.1. Primary System

The plant design [9, 10] is based on an industrial SFR of 1500 MW_e (3600 MW_{th}). The pool-type primary system includes the core, three mechanical primary pumps (PP) and six Intermediate Heat Exchangers (IHXs). The coolant flows upward through the reactor core into the upper sodium pool of the main vessel. From the upper plenum the sodium flows downward through the IHXs and discharges into a lower sodium pool (general dimensions reported in Table I). The vertically oriented primary pumps draw the coolant from the lower pool and drive it into the core inlet plenum.

TABLE I: ESFR CONF-2 PRIMARY SYSTEM CALCULATED VOLUMES.

Parameter	**Value**
Sodium plenum volume	9.6 m^3
Coolant hot pool volume	1444 m^3
Coolant cold leg volume	1107 m^3
Coolant cold pool volume	158 m^3

2.2. Core

The CP-ESFR CONF-2 core is composed of 453 Fuel Assemblies (FAs) subdivided into two radial regions with different plutonium contents. The fuel sub-assembly consists of a hexagonal wrapper tube containing a triangular arrangement of 271 fuel pins with helical wire wrap spacers. The fuel pin consists of $(U,Pu)O_2$ sphere-pac fuel inside ODS steel cladding (BoL conditions); the fissile zone is 1 m high; the lower fertile blanket is filled with UO_2 pellets and is 0.3 m high (Table II).

The CONF-2 design is characterized by a large sodium plenum above a fairly flat core, and thus features - at BoL - a relatively low sodium void worth (*i.e.*, almost zero) compared with the typical figures for SFRs (*i.e.*, some thousands pcm).

TABLE II: ESFR SPHERE-PAC CONF-2 FUEL PIN DESIGN PARAMETERS AT 20 °C.

Parameter	**Value**
Driver fuel composition	$(U,Pu)O_2$
Pu fraction (inner/outer core)	14.76/17.15 wt. %
Pu isotopic composition	3.57/47.39/29.66/8.23/10.38/0.78
Lower blanket composition	UO_2
Sphere-pac density	9.00 g/cm^3
Blanket pellet density	10.40 g/cm^3
Blanket pellet diameter	9.43 mm
Cladding inner diameter	9.73 mm
Cladding outer diameter	10.73 mm
Fuel column height	1000 mm
Lower blanket height	300 mm
Cladding material	Fe-14Cr-ODS
Clad density	7.73 g/cm^3

Static neutronics calculations were performed by Serpent using the JEFF3.1.1 nuclear data library, with an exception for the neutron generation time, for which the value provided by ERANOS was employed. The calculated neutronic parameters and reactivity coefficients are reported in Table III. Statistical errors (one standard deviation) are ±10 pcm for integral parameters and ±0.01 pcm/K for temperature coefficients.

TABLE III: ESFR SPHERE-PAC CONF-2 SAFETY-RELATED NEUTRONIC PARAMETERS.

Parameter	**Value**
Shutdown reactivity worth (DSD/CSD+DSD)	–806/-4264 pcm
Effective delayed neutron fraction, β_{eff}	401 pcm
Neutron generation time, Λ_{eff}	446 ns
Doppler constant, K_D (core/inner/outer/blanket)	-1009/-512/-546/11 pcm
Na void worth (core/inner/outer/blanket)	+1116/+612/+549/–32 pcm
Na void worth (Na plenum/core+Na plenum)	–756 pcm/+363 pcm
Na density coefficient, α_{Na} (core)	+0.29 pcm/K (+0.17 pcm/kg)
Na density coefficient, α_{Na} (inner/outer/blanket/plenum)	+0.15/+0.12/+0.01/-0.17 pcm/K
Axial expansion coefficient, α_{fuel} (core)	–0.15 pcm/K (– 0.14 pcm/kg)
Diagrid radial expansion coefficient, α_{grid} (SS316)	–0.85 pcm/K

Concerning sphere-pac fuel thermo-physical properties, the use of the recommended correlation for thermal conductivity [11] led to a calculated average value of k = 1.24 W/m/K in nominal conditions. As far as the remaining fuel properties influencing the core transient response are concerned (*e.g.*, heat capacity), the correlations available for solid pellet (U,Pu)O_2 were employed. The main fuel-related calculated parameters are summarized in Table IV.

TABLE IV: SPHERE-PAC FUEL PARAMETERS (BOL, NOMINAL POWER CONDITIONS).

Parameter	**Value**
Fissile fuel average thermal conductivity	1.24 W/m/K
Fertile fuel average thermal conductivity	2.75 W/m/K
Fissile fuel average specific heat capacity	343 J/kg/K
Fertile fuel average specific heat capacity	299 J/kg/K
Fissile fuel total mass	82170 kg
Fertile fuel total mass	27055 kg

3. Transient Analysis

In order to set the bases for the definition of an adequate safety approach, including objectives, principles and provisions for the adoption of sphere-pac fuels in SFRs, a preliminary safety assessment was performed. Representative accident scenarios were selected based on the outcomes of the ESFR Working Horse (WH) safety analyses completed within the CP-ESFR project: as the latter indicated the tendency of a whole core melting and core disruption in the event of a ULOF, this transient was judged the most critical, and was accordingly chosen for the present study.

Indeed, the analysis of ULOF scenarios is traditionally considered priority within SFRs safety assessments, since such accidents typically induce coolant boiling, with consequent global impact on the core and system integrity.

Starting from steady state, the ULOF transient was modeled through a pump coast-down with a flow halving time of 10 s.

Despite ULOF accidents constitute undoubtedly the most harmful scenarios for SFRs safety, the investigation of UTOP transients is more relevant with respect to the specific case of sphere-pac fuel core loading, since prompt power excursions brought by positive reactivity insertions bring rapid fuel temperature increases, which would most likely cause the fuel to melt, owing to significantly lower thermal conductivity compared with pellet fuel.

UTOP accidents are typically initiated by a reactivity insertion corresponding to withdrawal of the control element having the highest worth. It was preliminarily verified that reactivity insertions higher than 0.1 $ (with an insertion rate of 0.2 $ per second) cause the fuel to reach the melting temperature even in the ESFR CONF-2 core average channel, in which event simulations become not reliable (namely, after the occurrence of melting). Consequently, the reference UTOP scenario for the subsequent transient analyses was necessarily set to be initiated by a reactivity insertion of 0.1 $ in 0.5 s.

3.1. Sensitivity Analysis

Sensitivity analyses were performed aimed at assessing the impact of fuel form, of burn-up and MA loading, and of uncertainties affecting reactivity coefficients on the system transient response.

The former effect was studied by varying the fuel thermal conductivity from 1.24 W/m/K to 2 W/m/K [11].

Concerning the latter, the study was limited to the sodium plenum density and the fuel Doppler reactivity effects, since they are determinant for the ULOF and UTOP transient development, respectively. The choice of the variability range for the sodium plenum density coefficient and the Doppler constant was based on the outcomes of the European benchmark on the ASTRID-like low-void-effect core characterization [12]. Accordingly, the former coefficient was varied from its nominal value (-0.17 pcm/K) to a more negative, thus favorable, value of -0.5 pcm/K in order to investigate if the design improvement margins are present, and finally to 0 (most conservative scenario); these analyses were performed for the ULOF case. The nominal values of the Doppler constants (-512 and -546 for the inner and outer core zones, respectively) were increased and decreased by 30 %; its implications were examined with reference to the UTOP case.

4. Computational Tools and Models

Accident simulations were performed by SAS4A/SASSYS-1 (henceforth SAS), which was first used to provide the reference results, and by BELLA, whose flexible structure allowed complementing the safety assessment with sensitivity analyses. Both codes had to be adapted to the specifics of the sphere-pac fuel, in particular as far as thermal conductivity and physical structure. An effort was spent to ensure complete consistency between SAS and BELLA, directed to harmonizing modeling criteria and assumptions.

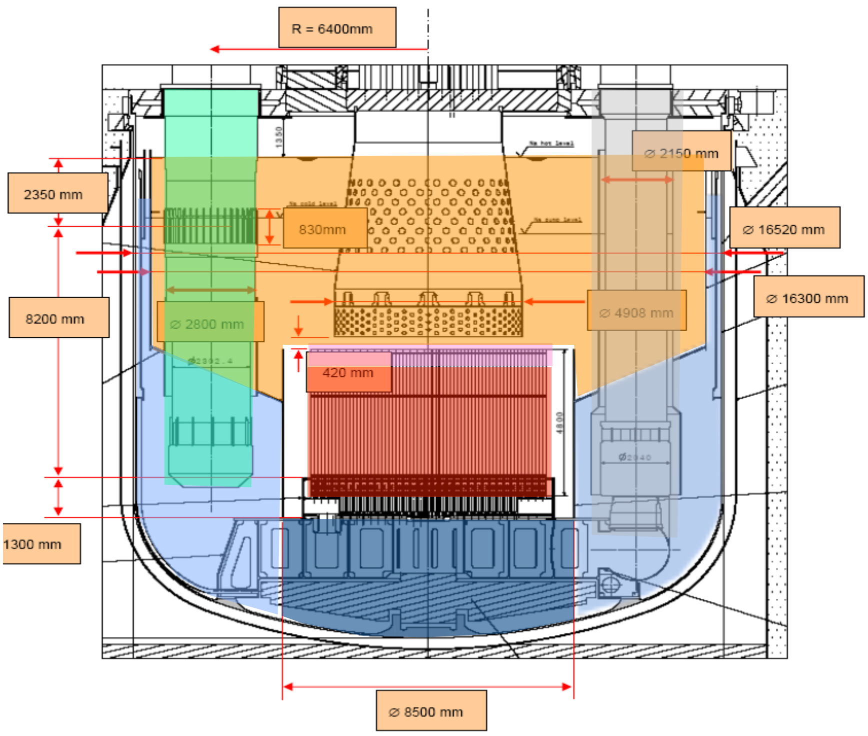

FIG. 1. ESFR CONF-2 primary system components and nodalization.

A core model consisting of one average channel was implemented and employed for the transient calculations, as the use of (multi-)point kinetics limits anyways neutronic analyses to radially core-symmetric transient scenarios.

The primary system was modeled following the technical specifications of the plant; its symmetric configuration allowed the simplification of some systems with different loops, IHXs and primary pumps being lumped together into one or few equivalent nodalizations: in particular, two components (*i.e.*, one IHX and one primary pump) were modeled, along with four incompressible volumes, corresponding to sodium plenum, coolant hot and cold pools, and cold leg (*FIG. 1*).

5. Results

In this section the major outcomes of the ESFR CONF-2 postulated transient calculations are reported. As mentioned above, all the analyses were conservatively focused on the BoL core, since under these conditions the sphere-pac fuel features the lowest thermal conductivity, and consequently peak fuel temperatures are expected.

In BELLA, the steady state was first calculated and the transients were initiated after 100 seconds (at time t = 100 s), whereas in SAS the beginning of the transient is automatically set at time t = 0 s.

In Table V the nominal steady-state parameters are summarized.

TABLE V: NOMINAL, STEADY STATE SYSTEM PARAMETERS.

Parameter	**Value**
Total/inner/outer core thermal power	3600/1788/1812 MW_{th}
Total coolant mass flow rate	18918 kg/s
Coolant core inlet/average/outlet temperature	395/470/545 °C
Cladding surface average temperature	476 °C
Fuel average centerline temperature	2376 °C
Sodium plenum average temperature	545 °C
Coolant hot/cold pool average temperature	545/395 °C
Coolant cold leg average temperature	395 °C

5.1. Transient Simulations

The dynamic response of the CP-ESFR CONF-2 core loaded with sphere-pac fuel to a ULOF event resulted to be essentially not affected by the characteristics and properties of this innovative fuel, as the transient evolution turned out to be analogous to the expected behavior of SFRs with an overall positive coolant density reactivity feedback coefficient, despite the sodium plenum design provision: the mass flow rate decrease causes a mismatch between power and mass flow, consequently leading sodium temperatures to increase (*FIG. 2*).

As a consequence of the active core positive coolant density feedback, higher sodium temperatures trigger a reactivity increase, which is anyways counterbalanced by the core axial expansion driven by the cladding and, in the very first phase of the transient, by the Doppler effect. Further negative reactivity is introduced by the core radial expansion, whose dynamics is ruled by a longer time constant, corresponding to the primary coolant recirculation time.

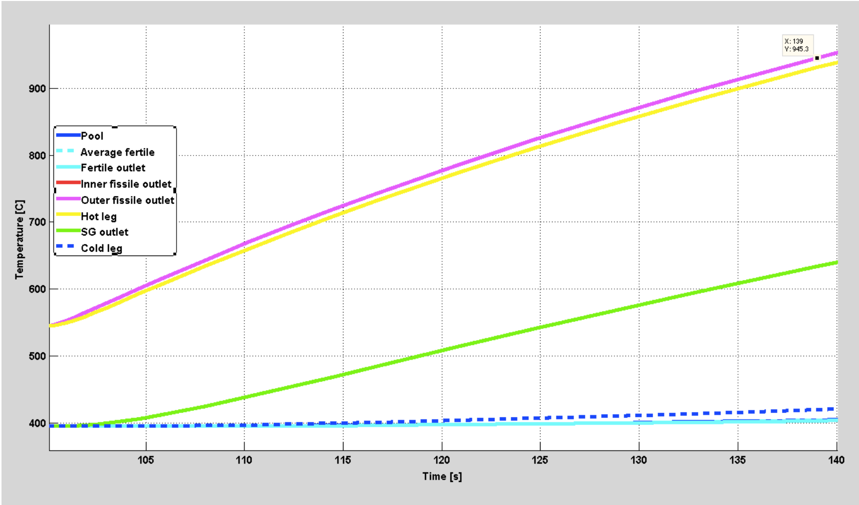

FIG 2. Coolant temperatures time evolution (ULOF, BELLA calculations).

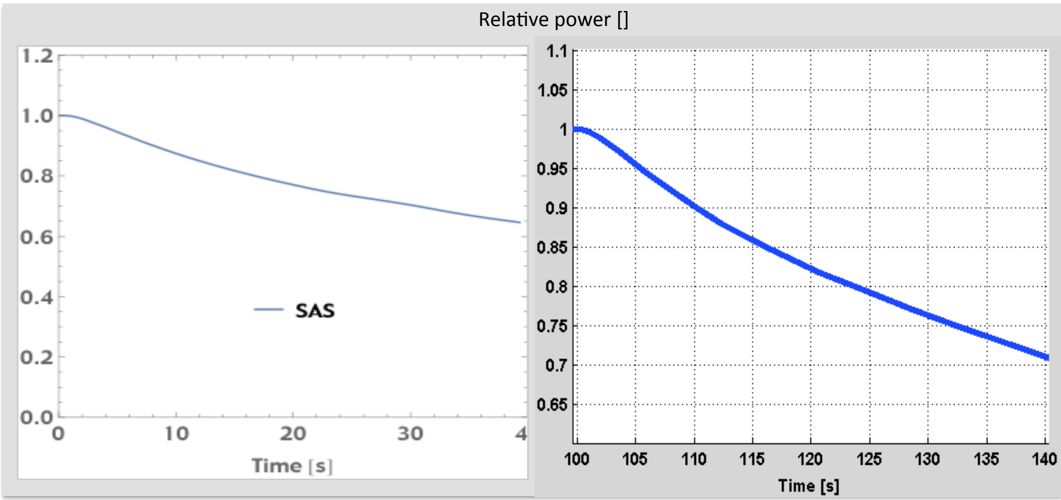

FIG 3. ULOF relative power time evolution (left: SAS calculations; right: BELLA calculations).

The combination of these reactivity effects results in an overall negative net reactivity insertion, which leads the core power to decrease (*FIG. 3*). Despite the power reduction, sodium temperatures notably increase and rapidly compensate the 150 °C safety margin against boiling, reaching the saturation temperature in approximately 40 s after the transient is initiated (average channel situation)[2].

The dynamic response of the CP-ESFR CONF-2 core to a UTOP event resulted to be affected by the adoption of sphere-pac fuel more substantially. As depicted in *FIG. 4*, the introduction of 0.1 $ in 0.5 s leads to a prompt power increase of the order of 13 % (SAS) - 15 % (BELLA), which causes the fuel to reach the limit of melting.

In *FIG. 5*, the peak fuel temperature in the average channel predicted by SAS, and the average

[2] It is noted that the graphs provided below display only the first 40 s of the transient, since SAS terminates the simulations after the onset of boiling is reached.

centerline fuel temperature evolution calculated by BELLA are displayed.

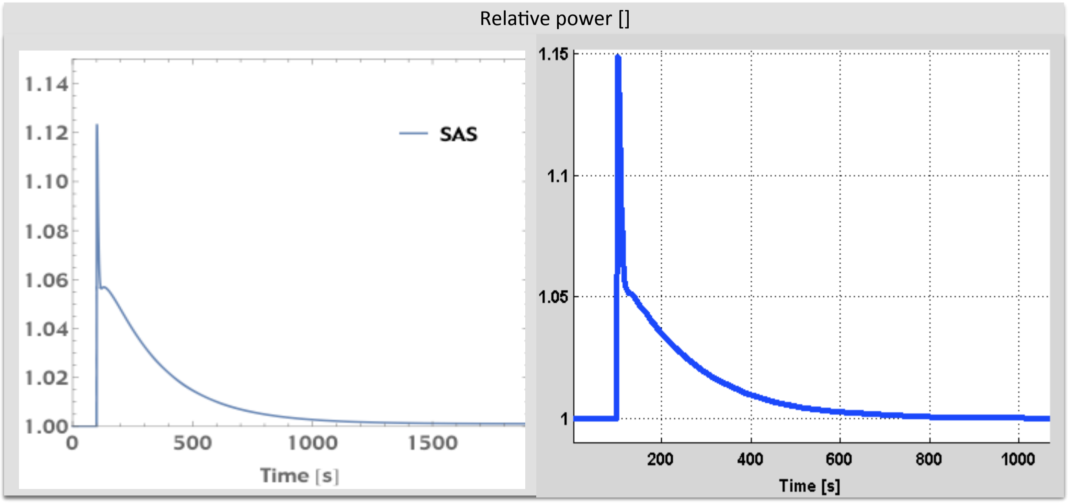

FIG 4. UTOP relative power time evolution (left: SAS calculations; right: BELLA calculations).

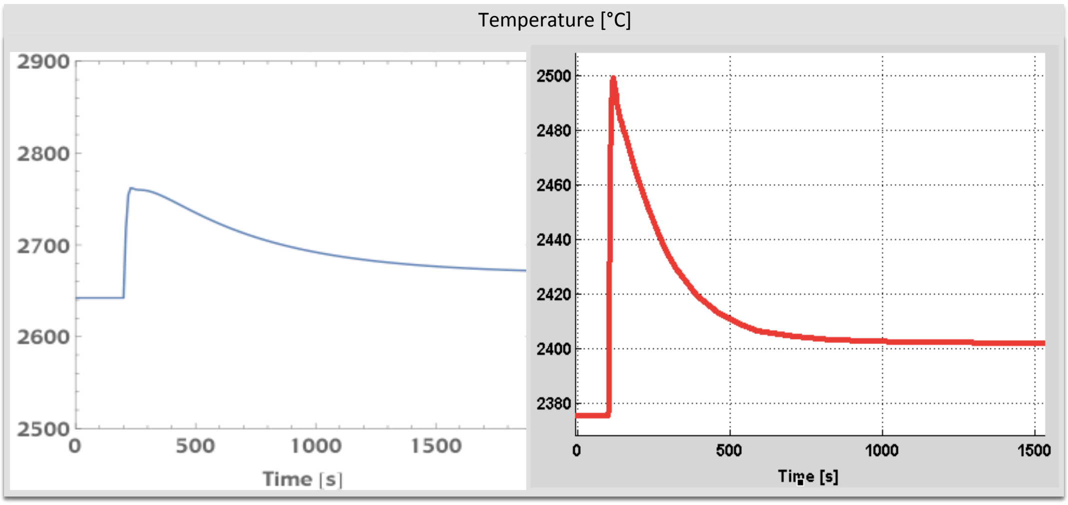

FIG 5. UTOP fuel temperatures time evolution (left: SAS calculations; right: BELLA calculations).

5.2. Sensitivity Analysis

The results concerning the effects of the fuel thermal conductivity on the ESFR CONF-2 transient response are first discussed, aimed at providing a preliminary assessment of the impact of the fuel form on the system safety.

In *FIG.* 6 the transient evolution of core power, average centerline and surface fuel temperatures, coolant temperatures, and reactivity effects is reported in the nominal case (*i.e.*, sphere-pac fuel; solid line) and in the case of higher thermal conductivity (corresponding to the MOX pellet fuel; dotted line), respectively. Consistently with the conclusions driven in the previous paragraph, these results confirmed that no significant changes in the accident scenario are observed when loading the core with sphere-pac fuel instead of pellet fuel up to the occurrence of coolant boiling (*i.e.*, in the first 40-50 s into the transient).

As opposed to the ULOF transient scenario, unfavorable effects were observed to be brought by the use of sphere-pac fuel when analyzing the UTOP accident. As shown in *FIG. 7*, in fact, the power increase due to an insertion of 0.1 $ positive reactivity is responsible for a fuel temperature increase of more than 550 °C in the case of sphere-pac (solid line), with respect to the corresponding steady-state value of 2376 °C; such a huge variation does not occur in the case of pellet fuel (dashed line), where the average centerline temperature is enhanced by approximately 430 °C, starting from a nominal value of 1670 °C. Consequently, the different safety performances between the two fuel forms lay in the respective steady-state temperatures in the first place, with their transient variation magnitudes resulting in an additional disadvantage of sphere-pac compared to pellet fuel.

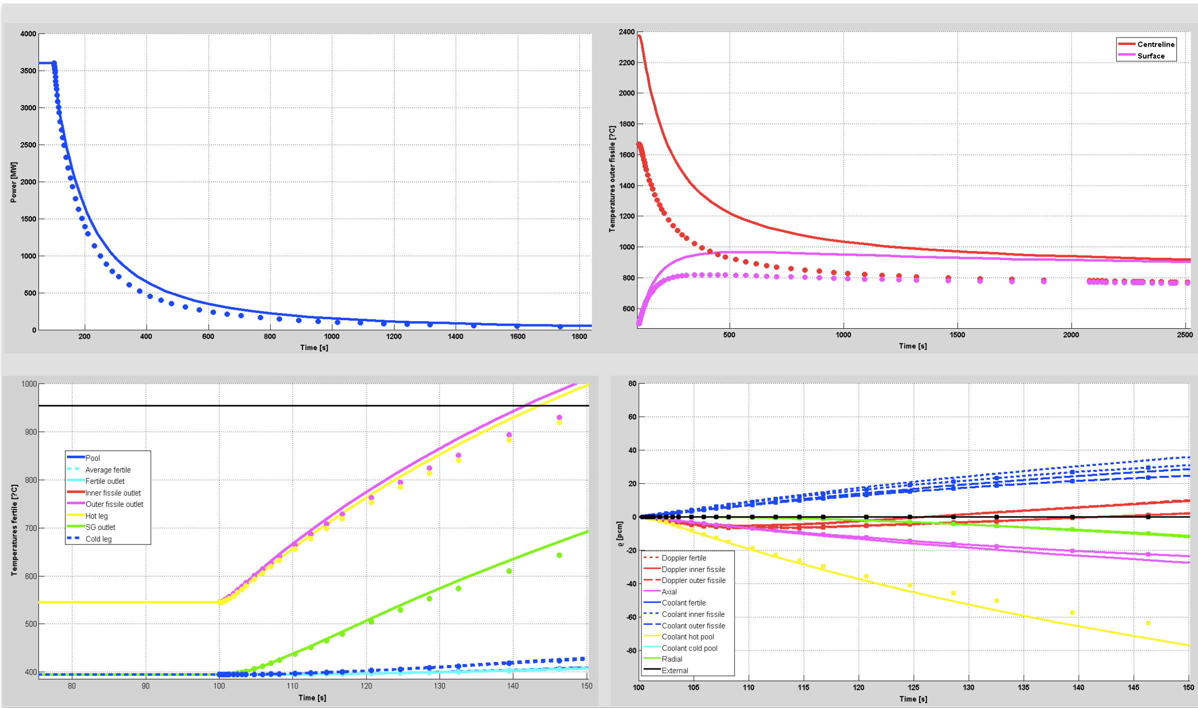

FIG 6. ULOF most relevant parameters time evolution.

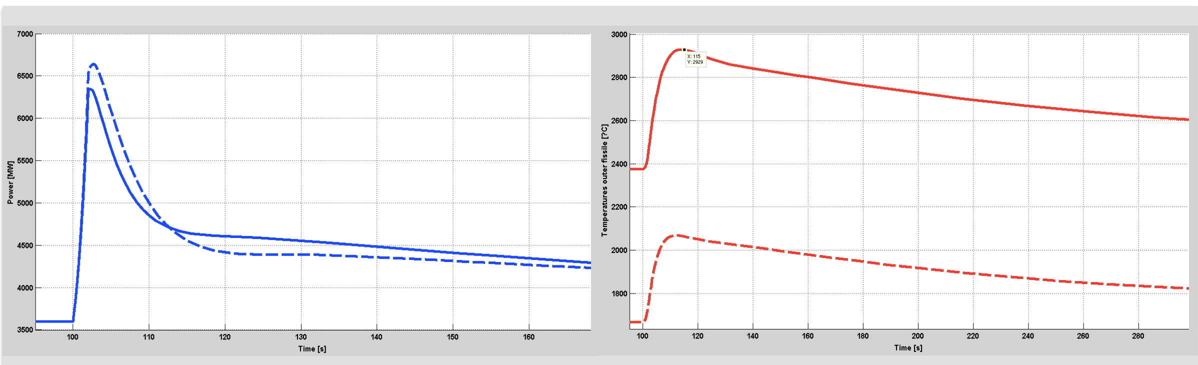

FIG 7. ULOF power and fuel temperature time evolution.

An second set of sensitivity analyses was performed with the purpose of assessing the impact of uncertainties affecting reactivity coefficients on the system transient response. Among the major outcomes, it was concluded that uncertainties affecting the sodium plenum coolant density coefficient determination have a negligible impact of the ESFR CONF-2 transient response to a ULOF event, as they result in a variation of approximately 25 s of the time when the onset of boiling occurs.

As far as the study on the effect of uncertainties affecting the core Doppler constants determination is concerned, the impact of the Doppler reactivity contribution on the power evolution and, consequently, fuel temperatures was primarily examined, as fuel melting constitutes the primary criticality for the UTOP scenario. It was observed that 30 % variations of the nominal Doppler constant values have appreciable effects on the core safety performance, making uncertainties not negligible: in particular, when reducing the Doppler constant value, the fuel average centerline temperature reaches a peak of almost 3200 °C following the prompt power jump, undergoing an increase of approximately 800 °C, which is more than 50 % of the temperature enhancement with respect to the steady-state occurring in the nominal case. Therefore, it can be argued that a 30 % reduction of such safety coefficient may lead to fuel melting. As an extension of these outcomes, inferences can be made also concerning the safety-related implications of burn-up and MA loading, leading to conclude that their detrimental effects on the core reactivity coefficients would be particularly critical when incorporating sphere-pac fuel, due to its reduced thermal conductivity, which would contribute to making fuel melting more easily reachable.

6. Conclusions

A preliminary safety assessment of the CONF-2 version of the European Sodium Fast Reactor core at Beginning of Life, loaded with both pellet and sphere-pac fuels, was performed.

As major outcomes of this study, it could be preliminarily concluded that the use of sphere-pac fuel may bring some disadvantages from the safety point of view in the event of a UTOP accident, whereas no concerns are raised for a ULOF scenario. In particular, the dynamic response of the CP-ESFR CONF-2 core loaded with sphere-pac fuel to a ULOF event resulted to be essentially not affected by the characteristics and properties of this innovative fuel. Conversely, the use of sphere-pac fuel appeared to degrade the CP-ESFR CONF-2 core safety performance in case of UTOP accidents, since safety margins would be reduced, due to the lower thermal conductivity, leading to larger magnitudes of the fuel temperature gradients ensuing from positive reactivity insertions.

Consistently with the previous conclusions, uncertainties in the determination of the fuel thermal conductivity and Doppler constant were found to have no significant impact on the ULOF transient predictions, but to influence the UTOP simulations, making their accurate determination critical for the system safety assessment. As a corollary conclusion, it could be preliminarily inferred that the detrimental effect of burn-up and MA loading on the core reactivity coefficients might be critical when incorporating sphere-pac fuel, due to its reduced thermal conductivity.

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