Benchmarking ATHLET against TRACE as applied to Superphénix start-up tests

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ATHLET is a thermal-hydraulic (TH) system code developed at the GRS for the modeling of Light Water Reactors (LWRs). To extend the applicability of ATHLET to the analyses of Sodium Fast Reactors (SFRs), the code was recently upgraded with the thermal-physical properties of the liquid sodium. The new extension is still under verification and validation phases. The present work contributes to the verification efforts. This study investigated the performance of the extended version of ATHLET as applied to the transient analysis of a set of start-up tests conducted at the Superphénix SFR. The specifications of the corresponding tests such as the simplified SPX reactor core models and the set of reactivity coefficients were adopted primarily from a previous dedicated study performed at PSI and at KIT. The reactivity effects accounted for by ATHLET included fuel Doppler effect and thermal expansion effects of sodium, fuel, diagrid, control rods driveline, strongback, and reactor vessel. The results obtained by ATHLET for main stationary TH parameters, power evolutions, and reactivity feedback components were benchmarked against the reference solutions provided by TRACE. Employing an identical set of reactivity coefficients, either in steady-state or transient calculations, the codes produce consistent and close results.

KEYWORDS: ATHLET for SFRs; Superphénix start-up tests; ATHLET, TRACE

1. Introduction

In connection with the Superphénix (SPX) reactor commissioning phase, several start-up experiments were performed to investigate the plant dynamic response and to evaluate the reactivity feedback coefficients [1], [2]. A set of start-up tests was the subject of a dedicated study performed at PSI and KIT. The reactor system was modeled and successfully validated by the thermal hydraulic (TH) codes TRACE (PSI) and SIM-SFR (KIT) [3].

The best-estimate TH code ATHLET, initially developed at GRS for the modeling of LWRs, has been recently upgraded with thermal-physical properties of the liquid sodium [4]. The properties were implemented according the references [5], [6] and [7]. In principle, this development extends the modeling capability of ATHLET to the SFR applications, although, the new code extension is still under verification and validation.

Considering as a basis the study performed in [3], the present work contributes to the ATHLET verification efforts, through the benchmarking against TRACE, this one being more established and tested for SFR application [8], [9].

The following section provides an overview on the SPX core model. Section 3 is dedicated to the discussion of the results. The main achievements and conclusions are summarized in Section 4.

2. An overview on the SPX simplified core model

The SPX reactor was a 3000 MWth SFR prototype of the pool type, located in Creys-Malville, France. It was connected to the French electrical grid for the first time in December 1986, and from 1997 it is in permanent closure [1], [10]. Its core included a central region of fuel sub-assemblies (SA) mainly loaded with mixed-oxide $(U,Pu)O_2$ with axial blankets, a peripheral radial breeder region of SAs loaded with depleted UO_2, steel reflector and steel radial shielding. The sodium primary mass is about 3200 tons and, by design, a mass flow rate of 16.4 tons per second was conceived to flow through the core [1].

A TRACE simplified core model was developed in [1], for the simulation and the better understanding of the primary circuit response to imposed start-up perturbations. Considering as a basis the specification used for the TRACE model an equivalent ATHLET model has been developed.

A conceptual scheme of the model is presented in Figure 1. It consists of one channel representing all fissile SAs, one channel representing all fertile SAs, upper/lower plena, inlet pipe, and outlet pipe. Fissile and fertile fuel rods, control rods driveline, diagrid and reactor vessel wall, were modeled by means of dedicated Heat Structures (HS), which track the temperatures of the components in time. The inlet core coolant behaviour is defined by time-dependent boundary conditions, which specify the inlet sodium mass flow rate and temperature as a function of time. A constant coolant pressure was imposed at the core outlet.

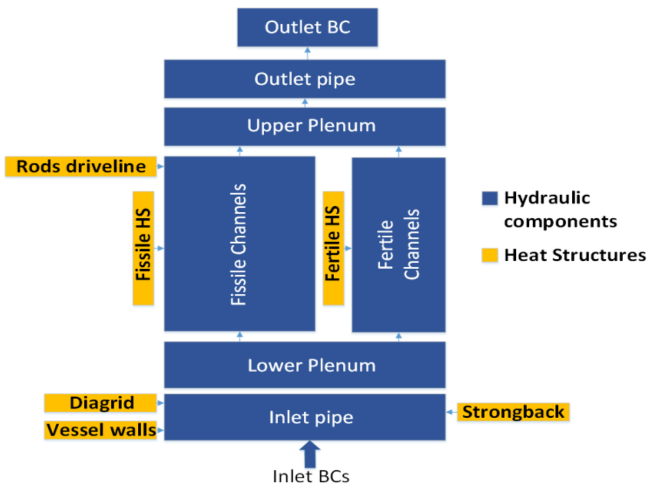

Figure 1: SPX conceptual scheme of the model

The reactivity effects were accounted for by a point kinetics (PK) model. The core average coolant density and the temperatures of the HS, were used as input for the PK model. In particular, the corresponding perturbations were converted to reactivity by means of Equation 1 and Equation 2, and then provided as signals to the PK model.

$$\rho_D(t) = K_D\,[\ln(T_{fuel\,av.}(t) - \ln(T_{fuel\,av.}(0^-))] \qquad \textbf{Equation 1}$$

$$\rho_i(t) = \alpha_i\,[T_i(t) - T_i(0^-)] \qquad \textbf{Equation 2}$$

In Equation 1 ρ_D is Doppler reactivity and K_D is the Doppler constant. In Equation 2, ρ_i is the reactivity component i and α_i is the corresponding linear reactivity coefficient where the considered components include sodium expansion, axial fuel expansion, diagrid expansion, strongback expansion, control rods driveline expansion, and vessel wall expansion. The K_D, and α_i applied in this study were specifically adopted from the TRACE model [3]. Their corresponding values are shown in Table 1.

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Reactivity Component	Coefficient
Doppler Constant [pcm]	-900
Sodium Expansion [pcm/°C]	+0.500
Axial Fuel Expansion [pcm/°C]	-0.60
Diagrid Expansion [pcm/°C]	-1.0
Strongback Expansion [pcm/°C]	-2.0
Rods driveline expansion [pcm/°C]	-1.0
Vessel wall expansion [pcm/°C]	+4.0

Table 1: set of reactivity coefficients

In this study, five start-up tests, summarized in Table 2 were used for the benchmarking ATHLET against TRACE.

Test description	Power
-50 pcm reactivity insertion	692 MW_{th}
-74 pcm stepwise reactivity insertion	1542 MW_{th}
10 % secondary flow rate increase	632 MW_{th}
10 % primary flow rate reduction	663 MW_{th}
10 % primary flow rate reduction	1415 MW_{th}

Table 2: SPX set of start-up tests

3. Results

The new extended version of ATHLET was applied to the modeling of a set of SPX start-up tests shown in Table 2. The main stationary TH parameters, power evolution, and reactivity feedback components computed by ATHLET were benchmarked against the reference solutions provided by TRACE.

For every test the comparison was conducted in two steps. First, to demonstrate the consistency of the models an initial investigation was carried out on the main steady state parameters of the fissile and fertile channels, *i.e.* on the axial distributions of fluid temperature and pressure, and of cladding temperature. Afterwards, to show the capability of ATHLET to predict the transient behaviour of the system, the reactivity components and power evolutions computed by ATHLET were compared to those of TRACE.

- **-50 pcm reactivity insertion**

Before the transient, the reactor power has been stabilized at 692 MW_{th}. The steady state axial profiles computed by the codes are in good agreement as shown in Figure 2(a), (b) and (c). Among the considered axial profiles the largest relative error was found on the fertile channel pressure profile, and it turned out to be of 0.54 % (Table 3).
The transient was initiated by the insertion of control rods, modeled through the insertion of -50 pcm at 250 s. An additional external perturbation was imposed by the inlet core coolant temperature, decreasing as shown in Figure 2(d). As Figure 2(e) shows, the control rods insertion is immediately counteracted by Doppler and fuel expansion feedback effects. Between 500 and 1000 s, the decrease of the inlet core coolant temperature becomes significant, and the power slightly rises. This is due to the contraction of diagrid and strongback, which insert positive reactivity. Finally, a new power level is reached (Figure 2(f)) by the compensation of the vessel contraction effect. The codes comparison showed a good agreement among the trends of the reactivity components, and for the power evolution profiles, only a maximum absolute relative error of 0.18 % has been observed.

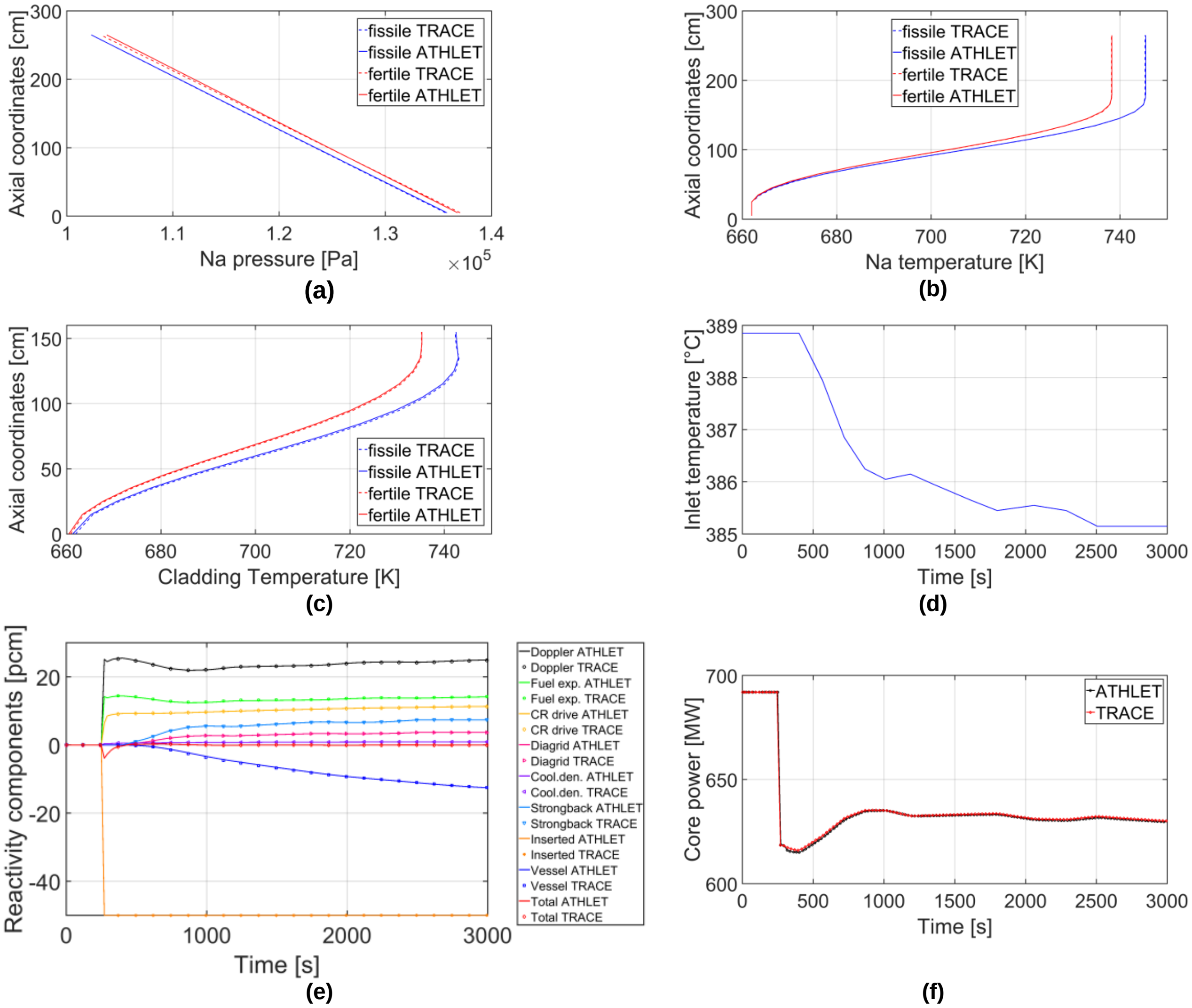

Figure 2: -50 pcm reactivity insertion

	clad temperature	Na pressure	Na temperature
Maximum absolute relative error on axial profile of fissile/fertile channels [%]	0.13 / 0.09	0.1 / 0.54	0.05 / 0.04

Table 3: -50 pcm reactivity insertion,
maximum absolute relative errors on stationary axial profiles

- **-74 pcm stepwise reactivity insertion**

In steady state, the reactor power has been stabilized at 1542 MW_{th}. The calculations on the steady state axial profiles gave consistent outcomes (Figure 3 (a), (b) and (c)). The most diverging absolute relative values found along the profiles are shown in Table 4.

In transient calculations, the control rods were inserted stepwise at 595, 660 and 720 s, inserting -25, -25 and -24 pcm respectively. The imposed inlet core coolant temperature trend is shown in Figure 3(d) Each reactivity insertion step is promptly counterbalanced by Doppler, fuel expansion, and control rod driveline feedback effects (Figure 3(e)). This feedback offsetting causes a power dynamic response which is slightly underestimated at the beginning of the insertion steps and then followed by recoveries Figure 3(f). Vessel, strongback and diagrid expansion effects are responsible for a non-negligible amount of reactivity insertion as well, *i.e.* from -25 pcm of the vessel to 20 pcm of the control rods driveline. The comparison of ATHLET against TRACE showed a good agreement among the corresponding trends of the reactivity components. The same applies to the comparison of the power evolution trends, for which only a maximum absolute relative error of 0.28 % has been observed.

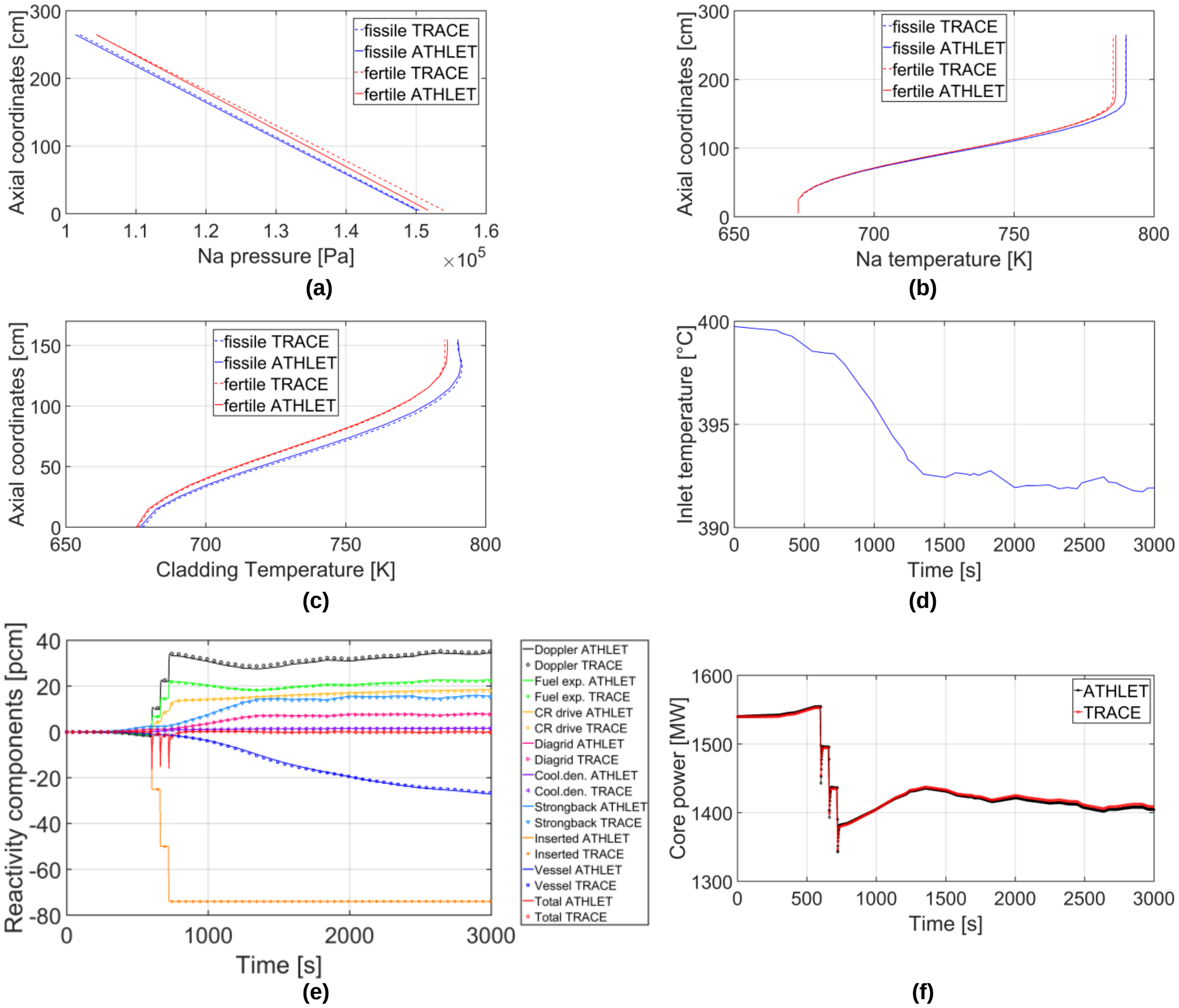

Figure 3: -74 pcm stepwise reactivity insertion

	clad temperature	Na pressure	Na temperature
Maximum absolute relative error on axial profile of fissile/fertile channels [%]	0.29 / 0.13	0.6 / 1.42	0.05 / 0.12

Table 4: -74 pcm stepwise reactivity insertion,
maximum absolute relative errors on stationary axial profiles

- **10 % increase in the secondary flow rate**

In stationary conditions, the reactor power has been stabilized at 632 MW_{th}. No significant divergence has been observed on the steady state axial profiles (Figure 4 (a), (b) and (c)). The consistency and the quality of the results are evident also by Table 5. Among the computed stationary profiles the largest relative error was found on the fertile channel pressure profile, and it turned out to be of 0.53 %.
The transient calculations were performed imposing a perturbation on the inlet core coolant temperature, shown in Figure 4 (d), which accounts for the secondary mass flow rate increase of 10 %. The power excursion shown in Figure 4 (f), (up to 690 MW_{th}), is mainly driven by the positive reactivity insertion caused by the contractions of the diagrid and the strongback. As observed in Figure 4 (e), the vessel contraction feedback opposes to the power level increase, providing a negative reactivity insertion which finally reaches about -35 pcm. A very good agreement has been found among the trends of the reactivity components. A comparison of the power evolution trends revealed a maximum absolute relative error of 0.20 % (around 1 MW_{th}) has been observed.

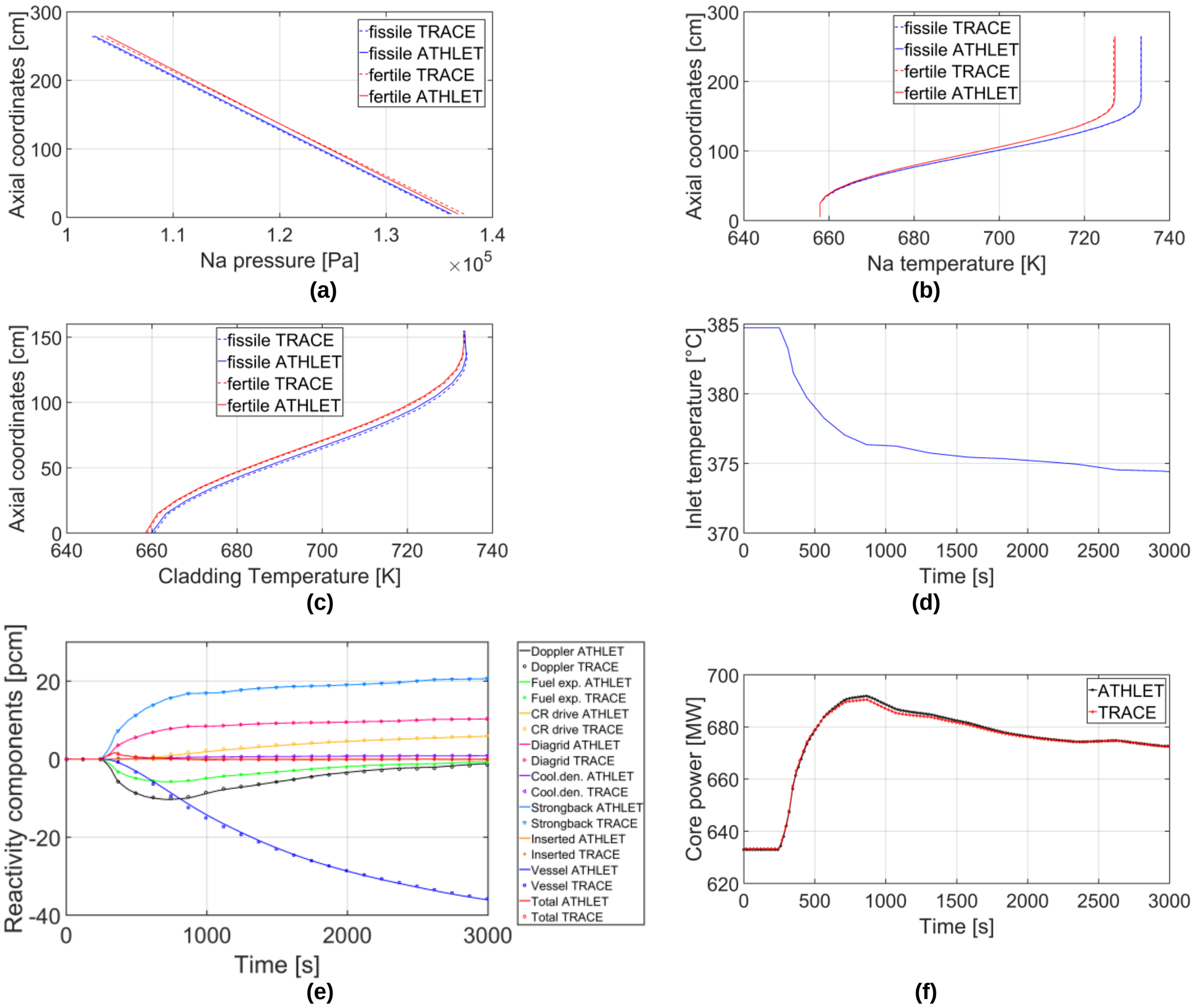

Figure 4: 10 % increase in the secondary flow rate

	clad temperature	Na pressure	Na temperature
Maximum absolute relative error on axial profile of fissile/fertile channels [%]	0.20 / 0.09	0.26 / 0.53	0.04 / 0.04

Table 5: 10% increase in the secondary flow rate, maximum absolute relative errors on stationary axial profiles

- **10 % primary flow reduction at 663 MWth**

Before the transient, the power has been stabilized at 663 MWth. The stationary axial profiles are in good agreement as shown in Figure 5 (a), (b) and (c). Among all the profiles, the largest relative error was found on the fertile channel pressure profile turned out to be 0.54 % (Table 6).
During transient calculations, at 440 s, the primary flow is reduced by 10 % and the inlet coolant temperature decreases (Figure 5 (d)). As a response to the reduction of the sodium flow, the coolant temperature at the core outlet and the control rods driveline temperature are increasing. The expansion of the latter causes a slight insertion of the control rods into the core. The negative reactivity inserted is responsible for the power drop shown in Figure 5 (f) at around 332 s. The diagrid and the strongback contractions counteract the effect of the driveline by inserting positive reactivity, making the power level increase again. After 500 s, the vessel wall effect becomes significant and counteracts the positive reactivity insertion of diagrid and strongback. By the codes comparison, it can be noted that the feedback components profiles almost coincide. Furthermore, a relative error of 0.21 % has been observed on the power trends comparison.

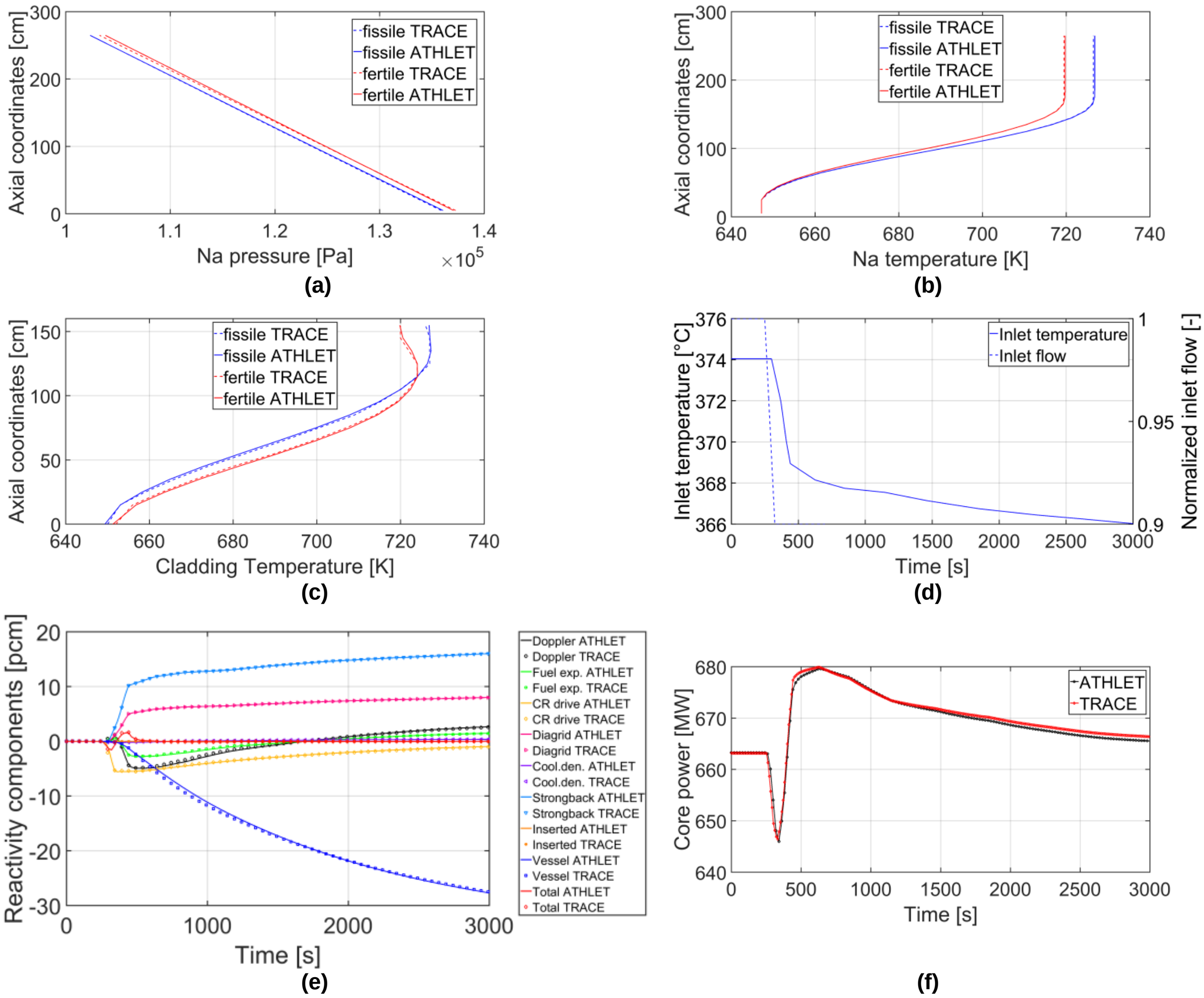

Figure 5: 10 % Primary flow reduction test, at 663 MWth

	clad temperature	Na pressure	Na temperature
Maximum absolute relative error on axial profile of fissile/fertile channels [%]	0.11 / 0.07	0.13 / 0.54	0.05 / 0.04

Table 6: 10 % Primary flow reduction test at 663 MWth, maximum absolute relative errors on stationary axial profiles

- **10 % primary flow reduction at 1415 MWth**

In steady state, the reactor power has been stabilized at 1415 MWth. The calculations of the steady state axial profiles gave consistent outcomes (Figure 6 (a), (b) and (c)). The most diverging absolute relative values found along the profiles are shown in Table 7.
At 440 s of the transient, the primary flow is reduced by 10 %, and inlet coolant temperature decreases, both the perturbations are shown in Figure 6 (d). The transient evolves according to the mechanisms already explained in the test "10 % primary flow reduction, at 663 MW_{th}". After an initial net power drop a fluctuating power transient occurs (Figure 6 (f)). The power fluctuations are caused by the offset of the feedback effects (Figure 6 (e)). Eventually, through the vessel walls contraction effect the power reaches ever lower level.
Despite the transient results obtained by this test were the most diverging, also in this case, the feedback components profiles computed by the two codes coincide, and maximum relative error of 0.41 % has been observed on the power trends comparison.

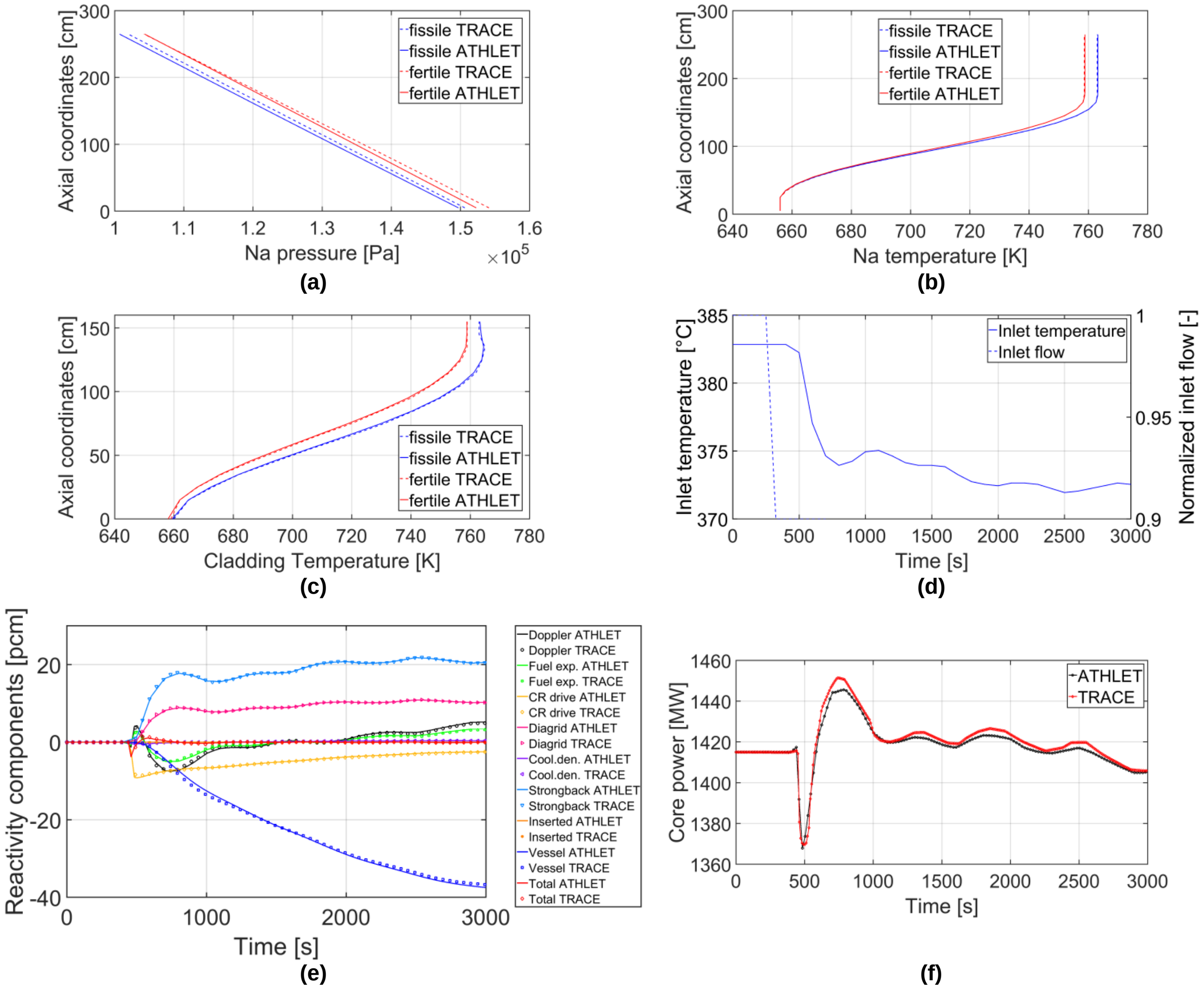

Figure 6: 10 % Primary flow reduction test, at 1415 MWth

	clad temperature	Na pressure	Na temperature
Maximum absolute relative error on axial profile of fissile/fertile channels [%]	0.12 / 0.14	0.27 / 1.34	0.05 / 0.06

Table 7: 10 % Primary flow reduction test, at 1415 MWth, maximum absolute relative errors on stationary axial profiles

4. Conclusions

The same set of reactivity coefficients was imposed for modeling of the start-up tests using the ATHLET and TRACE system codes. Both in steady-state and transients the performed calculations demonstrated that ATHLET and TRACE produce consistent and close results. Similar findings were obtained for all the considered start-up tests. To summarize:

- in the fissile/fertile channels, the steady-state axial distributions of the sodium temperature/pressure, and the cladding temperature were in good agreement with their corresponding profiles computed by TRACE;
- Table 8 shows the most diverging absolute relative errors found from the comparison of power trends between the codes, which are rather low, and in all cases they do not exceed the 0.5%;

- Corresponding feedback effects components basically coincide.

Test description	Power	Error
-50 pcm reactivity insertion	692 MW_{th}	0.18 %
-74 pcm stepwise reactivity insertion	1542 MW_{th}	0.28 %
10 % secondary flow rate increase	632 MW_{th}	0.20 %
10 % primary flow rate reduction	663 MW_{th}	0.21 %
10 % primary flow rate reduction	1415 MW_{th}	0.41 %

Table 8: SPX set of start-up tests and errors

From the evidence, it can be stated that the benchmarking of ATHLET against TRACE as applied to a set of SPX start-up tests, successfully demonstrated the reliability of ATHLET in the modeling of the SPX and supports its further use on a larger domain of SFR applications.

At the next phase the start-up tests will be recalculated as part of the Superphenix neutronics and thermal-hydraulic benchmark [11] conducted in frame of the EU ESFR-SMART project.

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