Analyses of unprotected transients in GFR (ALLEGRO) and SFR reactors supporting the group constant generation methodology

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Abstract. In this study, the fuel, the coolant, the cladding and the wrapper temperature reactivity coefficients were calculated with Serpent Monte Carlo code for the ALLEGRO demonstrational GFR core and for an SFR core with 3600 MW_{th} power. The results were compared with each other and with thermal reactor reactivity coefficients, and it was found that the thermal expansion of the core structural elements has significant effect on the reactivity for fast spectrum reactors. Detailed explanation was given for the reactivity coefficients.

Additionally, the importance of the reactivity coefficients for unprotected transients were determined with thermal-hydraulics simulations using ATHLET 3.1A code. The calculations were based on the determination of evolving maximum fuel, cladding and coolant temperatures. The results can be used for further group constant parametrization.

Key Words: ALLEGRO, SFR, reactivity coefficients, unprotected transients

1. Introduction

The objective of the present paper is to determine the importance of various reactivity coefficients for two fast spectrum reactors in case of unprotected transients. The ALLEGRO demonstrational GFR core and an SFR core with 3600 MWth power were studied. The models and methods applied by using the Serpent Monte Carlo and the ATHLET thermal hydraulic code are described in Section 2. The calculated temperature reactivity coefficients of the fuel pellet, the coolant, the cladding and the wrapper are presented in Section 3.1. The evolving maximum temperatures of the fuel, the cladding and the coolant are determined for an unprotected loss of flow and an unprotected overpower transient, and the results are summarized in Section 3.2. Finally, the importance of each reactivity coefficient is given in Section 3.3.

Our final goal in the future is to provide our 3D kinetic model with group constants parameterized according to temperature and thermal expansion effects. In the future, the 3D model will be used for simulation of unprotected transients where feedback effects play important role. The present study is a preparation of this upcoming task.

2. Models and methods

A Gas-Cooled Fast Reactor is a high temperature reactor with closed fuel cycle. The final goal is to build a GFR with 2400 MW thermal power, but first the technology needs to be tested on a smaller demonstrational reactor. The experimental equipment will be the ALLEGRO with around 75 MW thermal power. Originally, the investigated ALLEGRO core

was specified by the French Alternative and Atomic Energy Commission (CEA) [1]. In this study, a slightly modified definition of the core is used [2].

According to recent plans, a Sodium-Cooled Fast Reactor with 3600 MW thermal power will be built around 2050. Various reactor concepts can be considered with different fuel types. The involved research institutes investigated several cores and narrowed down the list to two promising candidates. In this study, a large oxide core is analysed, which was defined by the CEA within the frame of an UAM-SFR benchmark [3].

To calculate the most important reactivity coefficients, the ALLEGRO and the SFR cores had to be modelled in three dimensions. The chosen tool for modelling was the Serpent 2 Monte Carlo code. Using the determined temperature dependent reactivity coefficients, thermal-hydraulic simulations were performed with the ATHLET 3.1A code.

2.1. Serpent model

Serpent is a three-dimensional continuous-energy Monte Carlo reactor physics burn-up calculation code having been developed at VTT Technical Research Centre of Finland since 2004. The main reason of using this code is that it can be easily applied for spatial homogenization and group constant generation for deterministic reactor simulator calculations. The Serpent website [4] and the Serpent Wiki [5] describe the methods used and the computing settings. It should be noted that the code is currently under development and some methods should be used with caution [6].

For the calculations to be shown in this paper, the most recent 2.1.27 version of Serpent was used and pin-wise 3D models were developed. The horizontal sections of the cores are shown in FIG. 1. and FIG. 2., respectively for ALLEGRO and SFR.
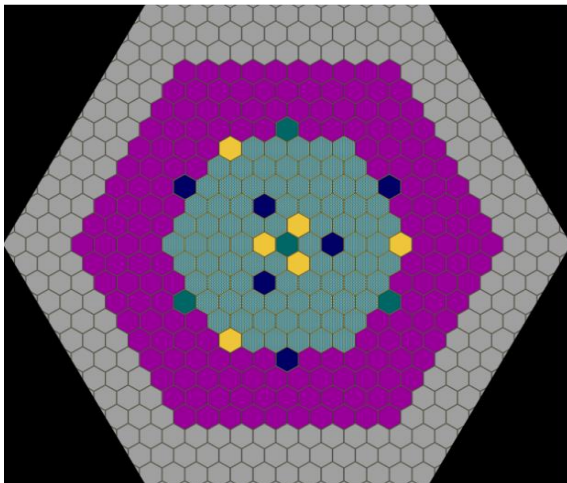

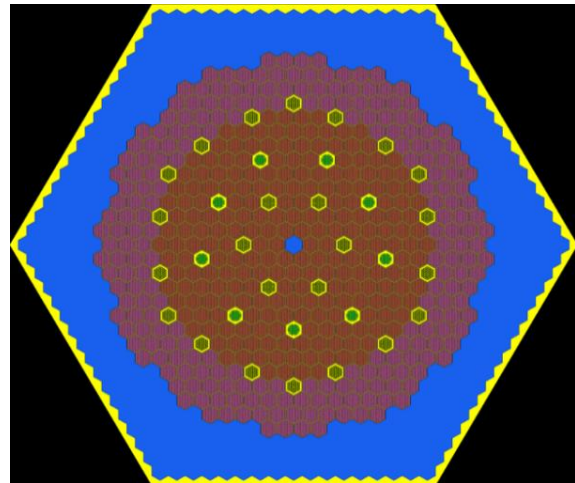FIG. 1. ALLEGRO core horizontal section.   FIG. 2. SFR core horizontal section.

The number of simulated neutrons is the main computational parameter. In case of ALLEGRO, 150.000 neutrons per cycle were started, the number of active cycles was 2.000 and the number of inactive cycles to reach fission source convergence was 50. The standard deviation of the effective multiplication factor was around 11 pcm. In case of SFR, only 50.000 neutrons per cycle were started, and the other parameters were the same as in case of ALLEGRO. The standard deviation of the obtained reactivity was around 14 pcm.

Calculations with different cross section libraries produce different effective multiplication factors and reactivity coefficients. The results in this study were obtained by using the ENDF/B-VII.1 library. The cross sections were given for 300K, 600K, 900K, 1200K, 1500K

and 1800K. Between these temperatures Serpent calculates cross sections with its own Doppler broadening routine. Unresolved resonance probability tables were taken into account. Concerning the other options, default values were used.

Effective multiplication factors were calculated with standard deviations and reactivity coefficients were derived from them.

2.2. ATHLET model

The thermal hydraulic computer code ATHLET (Analysis of Thermal Hydraulics of LEaks and Transients) is being developed by the GRS (Gesellschaft für Anlagen- und Reaktorsicherheit) for the analysis of operational conditions, abnormal transients and all kinds of leaks and breaks in nuclear power plants, primarily for light water reactors. In addition, the code is applicable to simulate plants and facilities with heavy water, helium, sodium or lead working fluids, but these features need to be further developed and validated [7].

In this work, only one average channel of the ALLEGRO and the SFR cores were modelled. This channel contains one fuel pin with its cladding and the associated coolant. The geometrical parameters were taken from benchmarks [2] [3].

The nuclear heat generation was simulated with the ATHLET point kinetics model. It requires reactivity contributions as a function of different temperatures, such as fuel and coolant temperatures or as a function of any user defined or system variable. The code also needs neutron kinetics parameters such as delayed neutron fractions and prompt neutron lifetime. Reactivity coefficients and kinetics parameters were taken from the Serpent calculations.

Most parameters related to heat transfer and heat conductance were taken from ATHLET by means of built-in correlations. Fuel and cladding density, specific heat capacity and thermal conductibility data had to be specified in the input as a function of temperature. As ATHLET uses fix geometry, densities were temperature independent. Steel and MOX specific heat correlation and thermal conductibility correlations were taken from literature [8]. Axial heat conduction was not modelled, only radial and the channel was divided into five axial regions.

Transient simulations were performed for both cores, which is presented in Section 3.2. The evolving temperatures of the fuel, the cladding and the coolant were calculated for both transients so as the reactivity contributions from each effect.

3. Results

To perform transient calculations, temperature dependent reactivity coefficients are needed. Space-independent fuel thermal expansion, Doppler, cladding thermal expansion, wrapper thermal expansion and coolant thermal expansion reactivity coefficients were calculated.

3.1. Reactivity coefficients

In the Serpent model the geometry and the densities were changed according to thermal expansion. In order to characterize and demonstrate the impact of the different physical phenomena, the fuel matrix temperature change (see Doppler effect) and the fuel thermal expansion were separately investigated and shown in this section. The obtained effective multiplication factors were converted to reactivity values and plotted as a function of temperature. Doppler data points were plotted as a function of logarithm of the pellet

temperature. Zero reactivity belongs to the nominal state of the core. FIG. 3. and FIG. 4. show the impact of the Doppler-effect and the pellet thermal expansion on the reactivity.
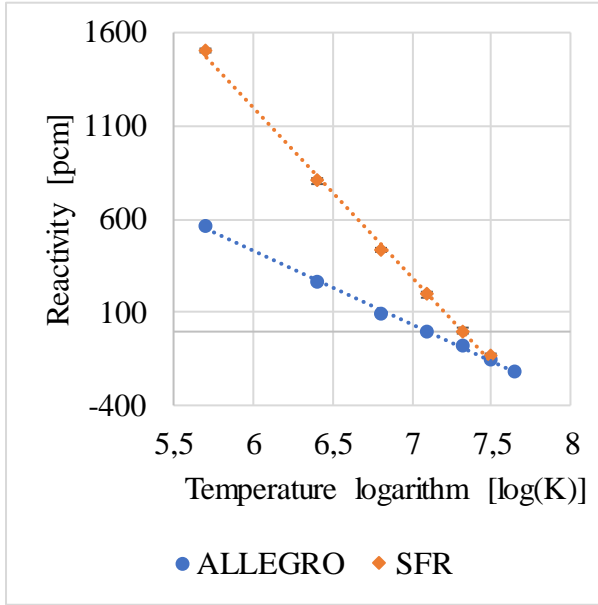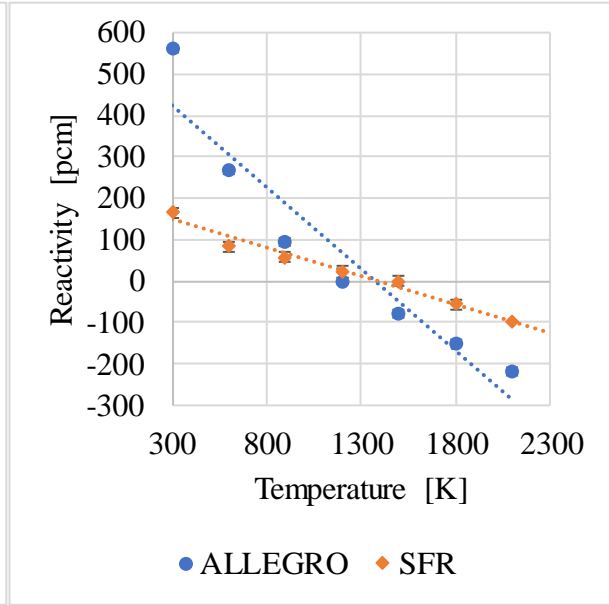

FIG. 3. Doppler coefficient diagram.   *FIG. 4. Fuel expansion diagram.*

The thermal expansion effects of the coolant, the wrapper and the cladding on the reactivity are shown in FIG. 5. and FIG. 6. respectively for ALLEGRO and SFR.
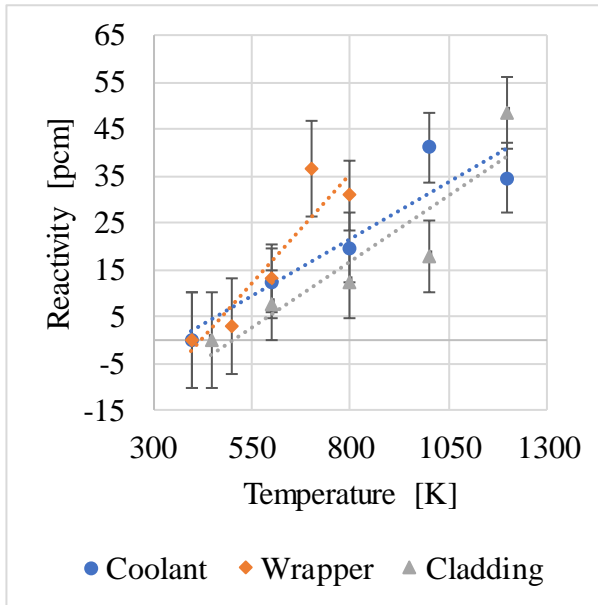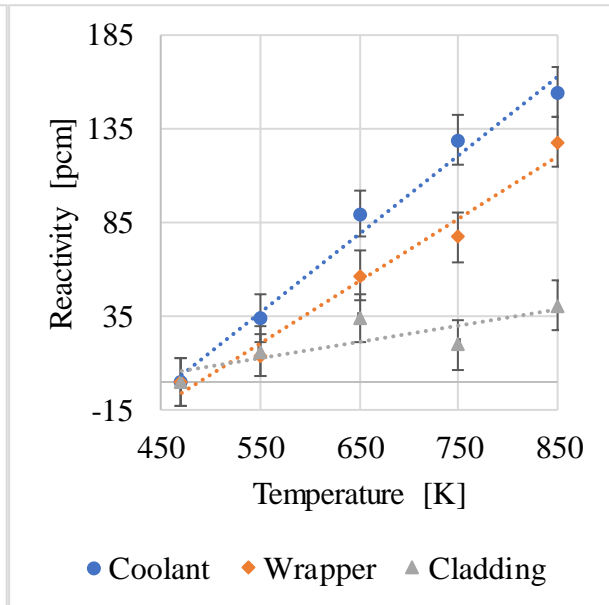

FIG. 5. ALLEGRO expansion coefficients.   *FIG. 6. SFR expansion coefficients.*

Reactivity values can be expressed approximately by simple formulas as equation (1) where ρ_D stands for the Doppler diagram and ρ_x stands for all the other diagrams. A, B, C_x and D_x are the fitted parameters. B is frequently called as the Doppler Constant.

$$\rho_D = A + B \cdot \ln(T) \, ; \, \rho_x = C_x + D_x \cdot T \tag{1}$$

Derivatives of (1) according to temperature results reactivity coefficients shown by equation (2). Doppler coefficient (α_D) is temperature dependent, while the others (α_x) are independent. TABLE I. summarizes the reactivity coefficients on nominal temperatures.

$$\alpha_D = \frac{\partial \rho_D}{\partial T} = \frac{B}{T}; \ \alpha_x = \frac{\partial \rho_x}{\partial T} = D_x \tag{2}$$

TABLE I: ALLEGRO AND SFR REACTIVITY COEFFICIENTS AT NOMINAL TEMPERATURE

Coefficients	ALLEGRO [pcm/K]	SFR [pcm/K]
Doppler (α_D)	$-0{,}346 \pm 0{,}007$ (1,9%)	$-0{,}610 \pm 0{,}015$ (2,4%)
Fuel expansion (α_F)	$-0{,}343 \pm 0{,}025$ (7,3%)	$-0{,}137 \pm 0{,}0073$ (5,3%)
Coolant (α_C)	$0{,}0480 \pm 0{,}0123$ (25,6%)	$0{,}420 \pm 0{,}032$ (7,6%)
Cladding (α_{Cl})	$0{,}0584 \pm 0{,}0156$ (26,7%)	$0{,}336 \pm 0{,}030$ (8,9%)
Wrapper (α_W)	$0{,}0898 \pm 0{,}0219$ (24,4%)	$0{,}087 \pm 0{,}033$ (37,9%)

Standard deviations of the coefficients come from the standard deviation of the Monte Carlo simulation and the error of the linear fit. Standard deviation of the Doppler coefficients and the fuel expansion coefficients are below 10%, as well as the coolant and the cladding expansion coefficients in case of the SFR. Reactivity coefficients for less significant effects have much higher standard deviation due to the high relative deviation of the Monte Carlo calculations. Increasing calculation time can improve the accuracy.

Increase of fuel pellet temperature follows reactivity decrease which partly comes from the Doppler broadening of the resonance capture cross sections of the fertile material. This effect results in an increase in the probability of resonance absorption thus reactivity decreases. In fast spectrum reactors, the Doppler coefficient is about one order of magnitude lower than in thermal reactors (VVER-440: -2,82 pcm/K). The amplitude of resonances decreases with energy increase. In fast spectrum reactors, the flux is shifted to higher energies than in thermal reactors. Consequently, higher energy resonance capture cross sections with lower amplitude play larger role in Doppler broadening. This explains the difference between the Doppler coefficients in fast and thermal reactors.

Pellet thermal expansion also has a significant effect on the reactivity in case of fast spectrum reactors, therefore it can not be neglected compared to Doppler broadening. Radial expansion effects reactivity through c*ollision e*scape probability, which gives the probability of one neutron escaping from a pellet without any collision. This escape probability can be given by equation (3) using the Wigner rational approximation [9].

$$P_0(E) = \frac{1}{1 + \sum_i n_{0,i} \frac{1}{(1+x)^3} \sigma_{t,i}(E) l_0 (1+x)} = \frac{1}{1 + \frac{1}{(1+x)^2} \sum_i n_{0,i} \sigma_{t,i}(E) l_0} \tag{3}$$

Summation goes over all isotopes, $n_{0,i}$ is the core density of isotope i on nominal temperature, $\sigma_{t,i}(E)$ is the total microscopic cross section of isotope i, l_0 is the average chord length in the pellet and x is the relative change in length due to thermal expansion. As the temperature increases (x increases), the collision escape probability also increases.

In fast reactors, high energy fission neutrons cause the main part of the fissions. As the escape probability of fast neutrons increases, neutron thermalization and absorption in the coolant also increases, which leads to decrease in reactivity. By contrast, in thermal reactors,

thermalization is advantageous considering the fission. These two reactions for thermal systems have opposite effect on reactivity as the escape probability increases. In addition, axial expansion of the active core leads to reactivity decrease due to density decrease. Thus, the overall pellet thermal expansion coefficient is negative for both fast and thermal reactors, but negligible in case of thermal systems (VVER-440: -0,098 pcm/K) compared to the Doppler coefficient.

In the ALLEGRO and the SFR, the coolant expansion reactivity coefficient is positive. This is a result of four different effects. First of all, the coolant can reflect a neutron back to the pellet. Secondly, the coolant can absorb a neutron. In addition, neutrons can thermalize which leads to loss in the number of fast neutrons. Lastly, neutrons can leave the system through the coolant. As the temperature increases in the coolant, reaction rates of the above-mentioned reactions decrease, due to the increase of the main free path. The overall effect could be positive or negative on reactivity and it depends on the coolant material and the neutron spectrum. The coolant expansion reactivity coefficient is much smaller in absolute terms for the ALLEGRO than for the SFR. This is the result of the approximately 16 times less nuclei in the coolant per fission core in ALLEGRO than in SFR and the smaller neutron cross section for helium as compared to sodium. In thermal reactors, thermalization has positive effect on the reactivity, thus as the temperature increases, the reactivity decreases.

Thermal expansion of cladding and wrapper leads to decrease in the amount of coolant, thus have reactivity coefficients with the same sign as the coolant expansion coefficient.

3.2. Transient calculations

Two types of transient simulations were performed. First an unprotected loss of flow (ULOF), second an unprotected transient over power (UTOP). By the end of the ULOF transient, the coolant mass flow rate decreases to 10% of the nominal value according to FIG. 7. At the beginning of the UTOP, 350 pcm external reactivity was inserted into the system in 10 seconds, shown in FIG. 8. Both transients started at the fifth second of the simulations.
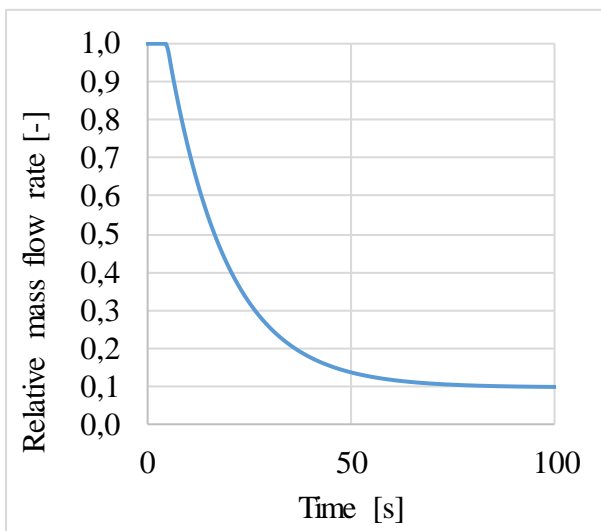
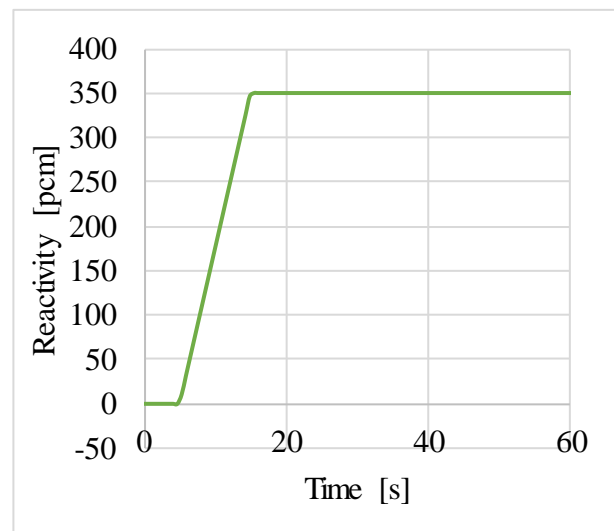FIG. 7. ULOF relative mass flow rate.   FIG. 8. UTOP reactivity insertion.

Reactivity contributions from the temperature changes of the fuel pellet, the coolant, the cladding and the wrapper were determined for the transients and shown on the reactivity balance diagrams. The maximum values of the time dependent fuel pellet, cladding and coolant temperatures were also calculated.

In case of the ALLEGRO ULOF, the fuel temperature increases despite the total reactivity decreases, as FIG. 9. and FIG. 10. show. The coolant temperature increases due to the decrease of the flow rate, thus the temperature difference between the pellet and the coolant decreases. Smaller temperature difference causes less effective heat removal so the temperature of the pellet increases which leads to reactivity and power decrease. Finally, new steady state mass flow rate and temperatures are reached. The difference between the pellet and the coolant temperature is smaller than at the beginning of the transient according to smaller power. Maximum pellet and cladding temperatures are 1130 °C and 1053 °C, respectively.
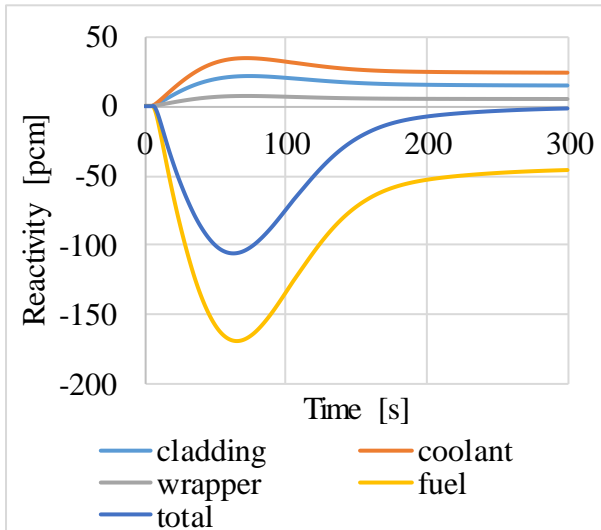
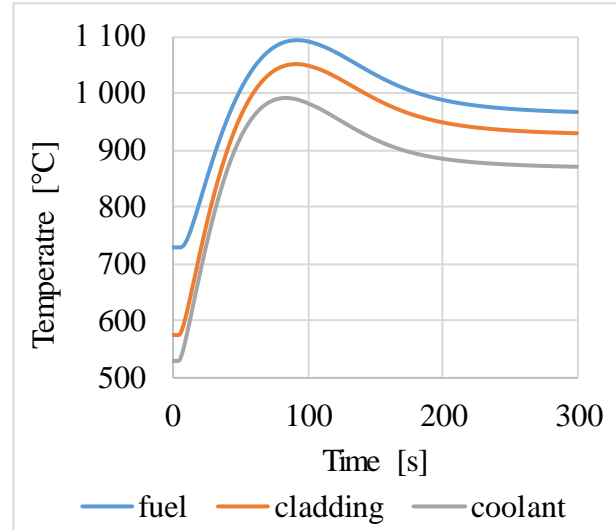FIG. 9. ALLEGRO ULOF reactivity balance.   FIG. 10. ALLEGRO ULOF max. temperatures.

In the beginning of ALLEGRO UTOP, the total reactivity increases, thus the power also increases due to the inserted reactivity which leads to temperature increase, shown in FIG. 11. and FIG. 12. Negative reactivity feedback occurs due to fuel pellet warming, which stops the further temperature increase and the power stabilizes at a higher value than the initial. The temperature difference between the pellet and the coolant increases in accordance with the increasing power. The maximum pellet and cladding temperatures are 1625 °C and 878 °C, respectively.
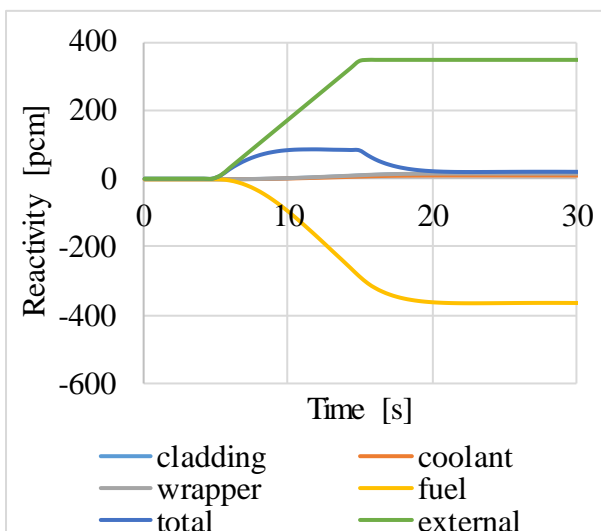
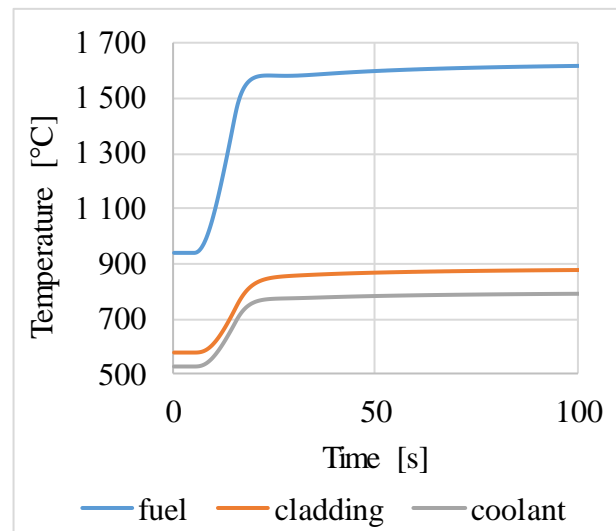FIG. 11.   ALLEGRO UTOP reactivity balance.   FIG. 12. ALLEGRO UTOP max. temperatures.

SFR ULOF (FIG. 13.) and ALLEGRO ULOF (FIG. 9.) have different characters. In case of SFR ULOF, the power increases at the beginning of the transient, due to the higher coolant and cladding reactivity coefficient. Reactivity contributions from the temperature increase of the fuel pellet and the coolant plus the cladding together are almost the same. At the end of the transient simulation, the reactivity contribution from the wrapper expansion is nearly the same as the total reactivity, which means even the smallest reactivity coefficient has impact on the direction of the power change. The simulation lasted 28 seconds, since the temperature of the coolant (FIG. 14.) reached the boiling point of sodium (873 °C) and ATHLET can not handle the two-phase sodium. It is important to mention that although the power increases during the transient, the main reason for the sodium boiling is the decreasing coolant mass flow rate.
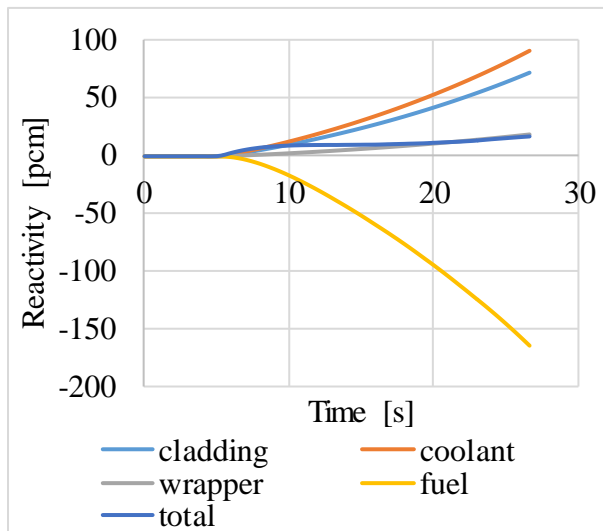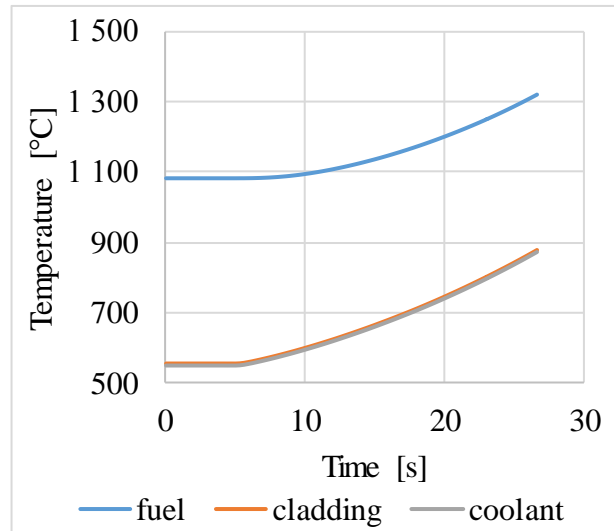

FIG. 13. SFR ULOF reactivity balance.

FIG. 14. SFR ULOF max. temperatures.

SFR UTOP produces similar diagrams (FIG. 15. and FIG. 16.) to ALLEGRO UTOP. It is important to note that the pellet temperature maximum (2804°C) is above the melting point.
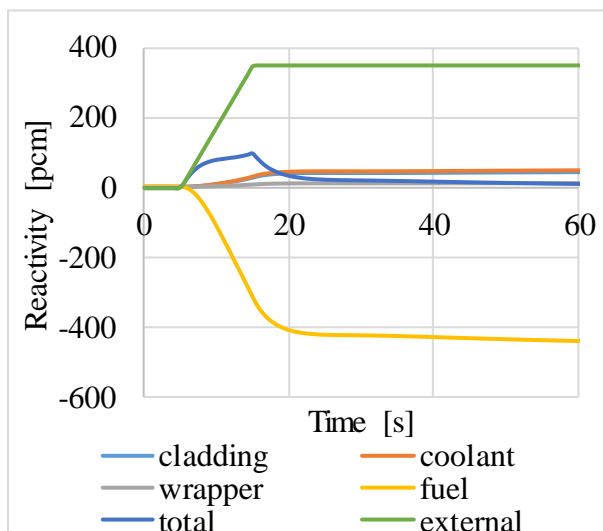

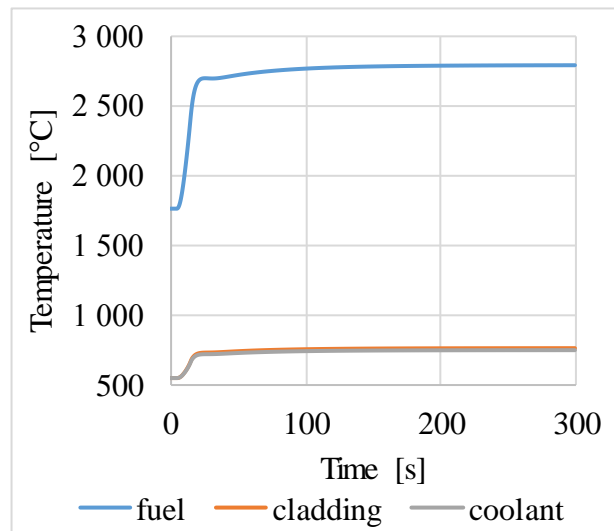FIG. 15. SFR UTOP reactivity balance.

FIG. 16. SFR UTOP max. temperatures.

3.3. The importance of the reactivity coefficients for transients

The importance of the reactivity coefficients was determined by using perturbed coefficients for the simulation. The fuel pellet, the cladding, the coolant and the wrapper reactivity coefficients were modified one by one by +20% and the temperature maximums were compared to the results featured in Section 3.2. On the following diagrams, the temperature differences from the nominal values are shown in case of the fuel pellet. The cladding and coolant temperature diagrams have very similar characteristics.

FIG. 17. shows that the Doppler and the fuel expansion coefficients have the most significant impact on the pellet temperature for both transients as these are the highest values in TABLE I. The other coefficients are also not negligible, these have important effects especially in case of the ULOF where the coolant and the structural element expansion coefficients have higher influence compared to the dominant fuel temperature related effects. The extent of the fuel temperature maximum change is determined by the combination of the reactivity coefficients and the temperature changes during the transients. The larger the coefficient and the temperature change during the transient, the higher the maximum temperature change in absolute terms.
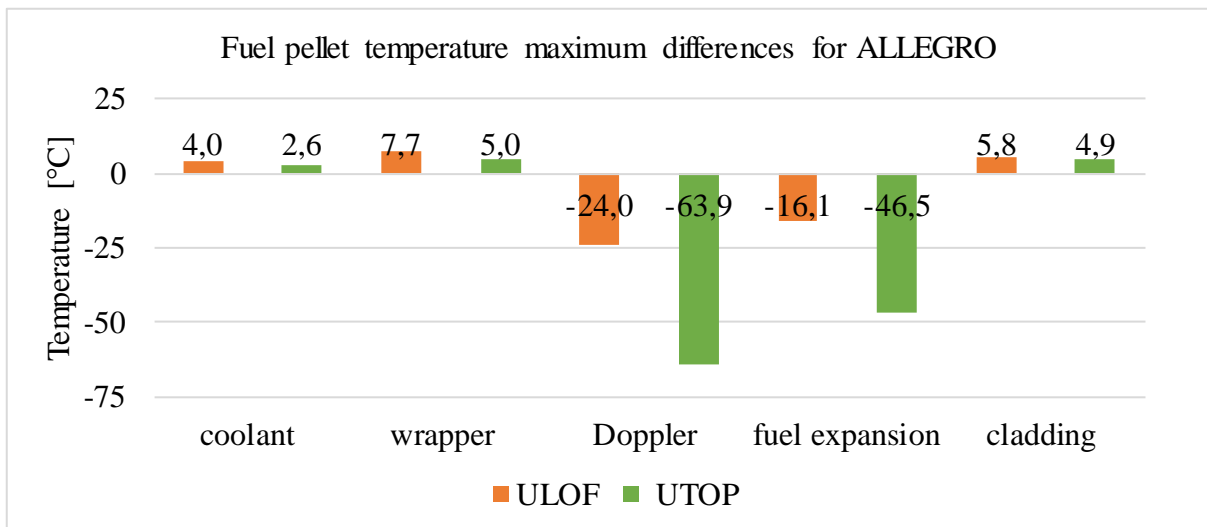

FIG. 17. Fuel pellet temperature. max. changes due to modified reactivity coefficients for ALLEGRO.

In case of SFR (FIG. 18.), the coolant and the cladding expansion effect become comparable with the fuel temperature effects, especially at the ULOF. The most significant effect remains the Doppler, but the fuel expansion effect becomes less important which is shown by TABLE I. too. The wrapper expansion has minimal impact on the obtained time dependent fuel temperature maximums.
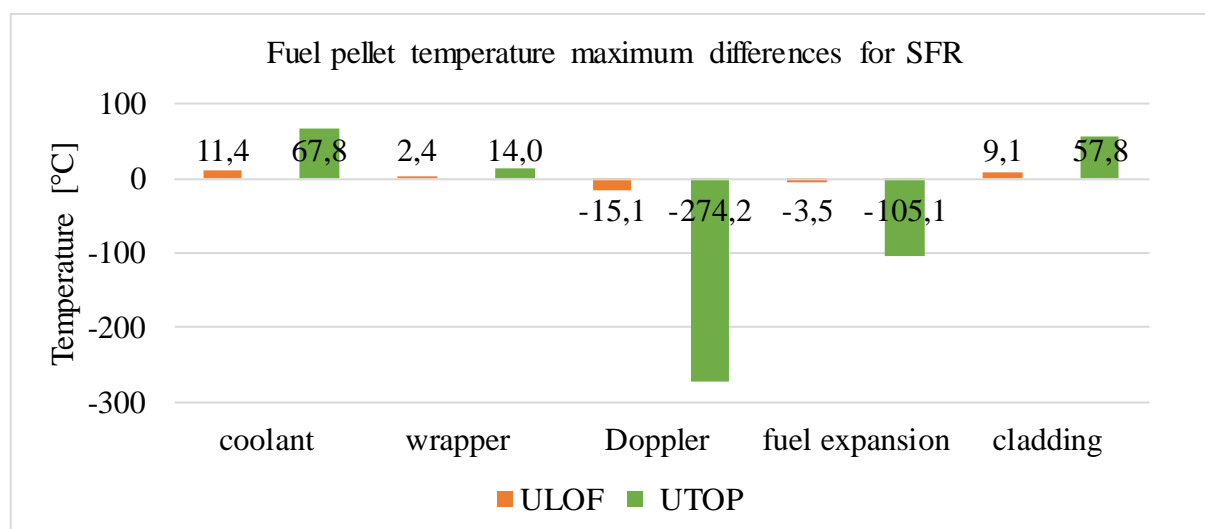
FIG. 18. Fuel pellet temperature. max. changes due to modified reactivity coefficients for SFR.

4. Conclusions

Advanced three-dimensional dynamic modeling of the unprotected transients of fast spectrum systems needs node-wise group constants. These group constants need to be parameterized according to temperature and thermal expansion effects. To evaluate the importance of the various feedback effects, several approximations needed. The present study shows transient calculations made by using point kinetic approach with 1D thermal hydraulic feedback.

Spatially-independent reactivity coefficients related to the active core were determined for the ALLEGRO gas-cooled demonstrator and for a sodium-cooled fast reactor - specified in an OECD NEA cooperation - with the Serpent Monte Carlo code. Using the ATHLET thermal hydraulic code with its point kinetics module, transient simulations were performed for two types of unprotected transients (ULOF and UTOP) with temperature dependent Doppler and constant coolant, fuel, cladding and wrapper expansion coefficients. The impact of the reactivity coefficients on the fuel temperature maximums were given. The Doppler effect proved to be the most important for both reactors, followed by the fuel expansion effect. Coolant and cladding expansions have more significant impacts in case of ULOF than in case of UTOP. Considering the SFR, positive overall reactivity feedback can occur due to the coolant and the cladding reactivity effects.

Acknowledgement

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