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Source and Reactivity Perturbations in Accelerator Driven Systems with Conventional MOX and Advanced Fertile Free Fuels

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Comparative safety analyses and investigations have been performed for a small scale ADS with conventional MOX fuel and an 800 MWth power class ADT with advanced fertile free fuel, both cooled by Pb/Bi. The analyses cover perturbations of the source, as e.g. unprotected transient over current (UTOC) and beam interruptions as well as perturbations on the core side, protected/unprotected transient over power (P/UTOP), induced by reactivity additions and unprotected loss of flow (ULOF) accidents. It shows that the small scale ADS has a very good safety performance, while for the 800 MWth ADT with ZrO_2 matrix based fuel some safety problems are identified, mainly related to the large positive void feedback. Further design and safety optimizations are under consideration.

KEYWORDS: ADS, ADT, safety analysis, MOX fuel, inert matrix fertile free fuel.

1. Introduction

Accelerator Driven Systems (ADS), which combine a sub-critical reactor with a high energy proton accelerator via a spallation target, are developed with the goal of efficient incineration/transmutation of minor actinides (MAs). Currently the feasibility of an ADS is investigated within the 5th Framework Programme (FP) of the European Union, the so-called Preliminary Design Studies of an Experimental Accelerator-Driven System (PDS-XADS) [1]. This work is devoted both to heavy metal cooled (Pb/Bi) and gas (He) cooled options. The power level of this demonstrator is chosen with 80 MWth, k_{eff} is 0.97 at BOL and the core contains conventional fast reactor fuel (MOX). In parallel, the 5th FP FUTURE [2] investigates accelerator driven transmuters of the 800 MWth power class with advanced fertile free CERCER and CERMET fuels. Inert matrices with high thermal conductivities are essential for theses fuels, because of the low thermal conductivities of the MAs. The main goal for designing this ADT was to investigate the feasibility of utilization of these advanced fuels. Details can be found in [3]. One of the important issues was the demonstration of an adequate safety level for cores with these advanced dedicated fuels. As already shown in [4] the utilization of such fertile free fuels could lead to some safety problems.

These new fuels significantly differ both in their thermal-physical/mechanical data and behavior from conventional fast reactor fuels. In addition, these fuels, because of their lack of U238 and the large MA content have a significant impact on the core safety parameters, represented by Doppler, void worth, clad worth, kinetics data etc. Different core designs for these transmuters have been developed mainly using ZrO_2, MgO and Mo-92 as matrices for the Pu/Am/Cm fuels. All these fuel/matrix combinations will be investigated step by step. Preliminary analyses showed that the most promising matrices from the safety point of view are those with MgO and Mo-92. To obtain a complete picture, the impact of ZrO_2 matrix based fuels on core safety is investigated.

In this paper comparative safety analyses and investigations have been performed for the PDS-XADS with MOX fuel and the FUTURE-ADT with a fuel embedded in a ZrO_2-matrix, both cooled by Pb/Bi.

The main differences between both ADS refer both to the power class (size) and fuel utilized.

The current analyses cover perturbations of the target/source side and transients triggered on the core/nuclear system side. In this first round of investigations the following transients have been investigated:

- UTOC : unprotected transient over current
- BI : beam interruption
- UTOP : unprotected transient over power
- PTOP : protected transient over power
- ULOF : unprotected loss of flow

Investigations of these advanced composite fuels reveal that especially for severe transients new phenomena and scenarios have to be expected and modeled. Severe accidents with fuel melting and loss of the core geometry are not investigated, because the phenomenology under such conditions can not be modeled adequately with the fuel and pin models in the current codes. The new phenomena that might be expected under such conditions are discussed in [5], as e.g. fuel/matrix separation because of the different melting points of the fuel/matrix system, or the high He production caused by Cm decay. The static neutronic analyses were performed by the ERANOS code system [6]. The transient analyses here are mainly performed with the SIMMER-III code, a 2D multiphase, multi-component, three velocity-field code coupled with space–time kinetics, using transport theory for the neutron flux-shape calculation [7, 8].

2. Core Design and Main Parameters

The design of the PDS-XADS including neutronics, thermohydraulics etc. has been performed in detail within the PDS-XADS project [1, 9]. On the other side, in FUTURE project a more simple core design was made for the purpose to investigate the feasibility of an ADT with new fuels. The PDS-XADS core midplane and FUTURE-ADT cross sections are shown in Figures 1 and 2. The main geometric, thermal-hydraulic and neutronic data are given for PDS-XADS and FUTURE-ZrO_2-Matrix Fuel ADT in Table 1, 2 and 3, respectively. For the FUTURE-ADT core cross section, the target area is given in yellow, surrounded by 3 enrichment zones and reflectors.

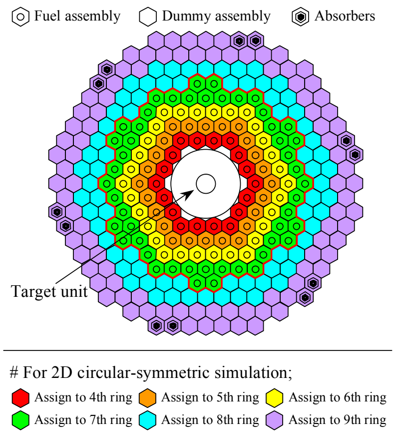


Fig. 1 Core cross section of the PDS-XADS.

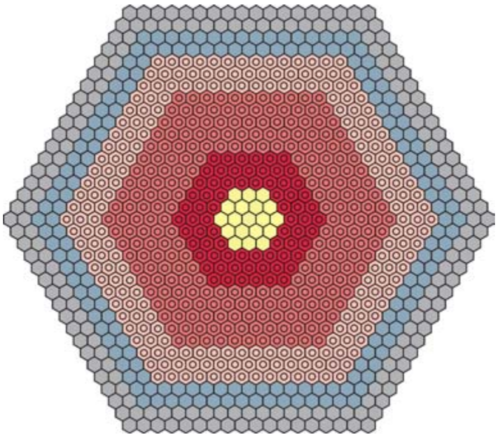


Fig. 2 Core cross section of the FUTURE-ADT.

Table 1. Geometric parameters in the PDS-XADS and FUTURE-ADT designs

Parameter	PDS-XADS	FUTURE ZrO_2
Core active height	0.87 m	1.00 m
Number of pins per SA	90	91
Number of fuel SAs	120	528
Sub-asssembly pitch	137.6 mm	112 mm
Fuel pellet inner diameter	1.80 mm	0 mm
Fuel pellet outer diameter	7.14 mm	5.85 mm
Clad inner diameter	7.37 mm	6.00 mm
Clad outer diameter	8.50 mm	6.80 mm
Wrapper thickness	2.00 mm	2.00 mm
P/D	1.57647	1.6

Table 2 Thermal hydraulic parameters in the PDS-XADS and FUTURE-ADT designs

Parameter	PDS-XADS	FUTURE ZrO_2
Total thermal power	80 MW	800 MW
Peak linear power	153 W/cm	276 W/cm
Mean velocity of coolant	0.42 m/s	1.0 m/s
Inlet coolant temperature	573 K	573 K
Outlet coolant temperature	673 K	723 K
Peak clad temperature	753 K	858 K
Peak fuel temperature	1169 K	2170 K

Table 3 Neutronic safety parameters (calculated by SIMMER) in the PDS-XADS and FUTURE-ADT designs

Parameter	PDS-XADS	FUTURE ZrO_2
Enrichment Zone	1	3
Enrichment	23.25 at%	38, 43, 53 vol%
K-eff at BOL	0.9655	0.9706
Beta-eff	314 pcm	191 pcm
Neutron generation time Λ	$1.43\text{x}10^{-6}$ s	$5.39\text{ x}10^{-7}$ sec
Decay constant λ^{-1}	11.36 sec	13.16 sec
Core void worth	-707 pcm	7184 pcm
Doppler constant	-580 pcm	-19 pcm

The neutronic safety parameters shown here are calculated by SIMMER and correspond to the results obtained by other groups in the PDS-XADS and FUTURE projects. Most significant deviations of the ADT from ADS are that the ADT has very small negative Doppler feedback and a very large positive core void worth. The significant void worth introduces a positive reactivity feedback mechanism from thermal coolant expansion. A stabilizing Doppler feedback is not available. Axial thermal expansion of the fuel pins and radial thermal expansion of the core subassemblies and grid-plate will lead to a negative feedback, but they have not been included in the analysis. Currently only an insufficient data base is available on these effects, but they will be taken into account in future analyses.

The positive void worth of the ADT is a result of the fuel composition and the larger size of the ZrO_2 core. In Figure 3 the void worth depending on the p/d ratio is given for ZrO_2, MgO and Mo-92 based fuels with a Pu/Am ratio of 40/60 and adjusted matrix fraction. As can be seen, for the CERMET fuel cores the lowest void values are predicted, mainly caused by higher thermal conductivities, allowing higher linear ratings and reduced core sizes. For the PDS-XADS and the FUTURE-ADT void worths of each fuel subassembly ring are shown in Figures 4 and 5, respectively.

The fuel thermal conductivity has a large impact on the fuel central temperature. Figure 6 shows thermal conductivities of ZrO_2 matrix fuel, including experimental values and MOX fuel. The curve for the MOX fuel is based on the standard European Fast Reactor (EFR) recommendation with O/M=2 and 5 % porosity [10]. The curve for FUTURE ZrO_2 matrix fuel is a linear volume weighting of thermal conductivities of ZrO_2 [11] and EFR fuel with O/M=1.88 and 10 % porosity, where the volume ratio of matrix and fuel is 62/38. The experimental data are chosen from [12] for the Ca-stabilized ZrO_2 inert matrix UO_2 fuel with a composition of 72.9 wt% ZrO_2 , 8.1 wt% CaO and 19 wt% UO_2 and 10.1% porosity.

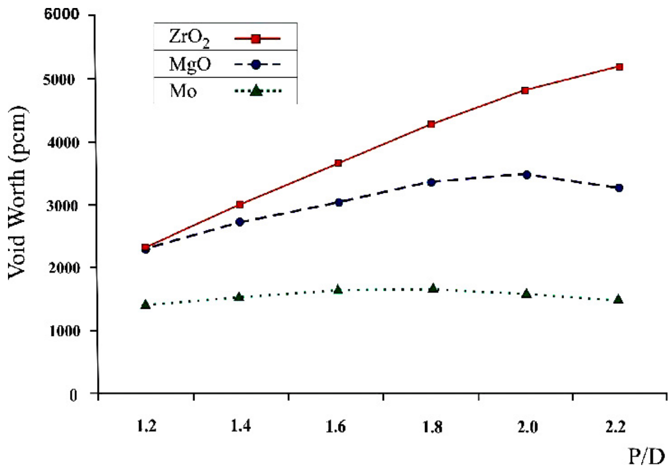
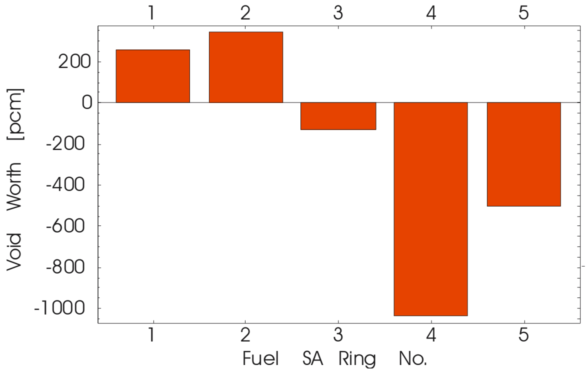


Fig. 3 Examples of void worth values for single zone cores and various matrices in dependency on the P/D ratio [2].



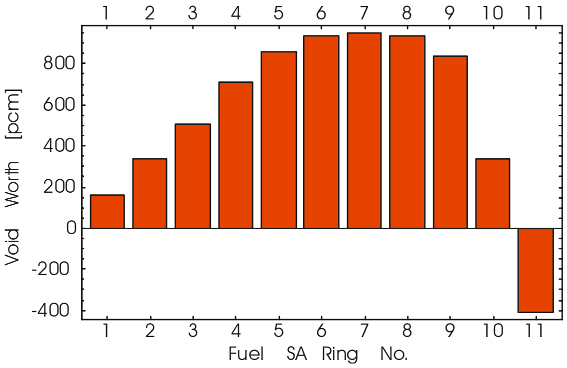


Fig. 4 Void worth distribution for the individual fuel SA rings of the PDS-XADS.

Fig. 5 Void worth of individual fuel SA rings for the FUTURE-ZrO_2-matrix fuel ADT.

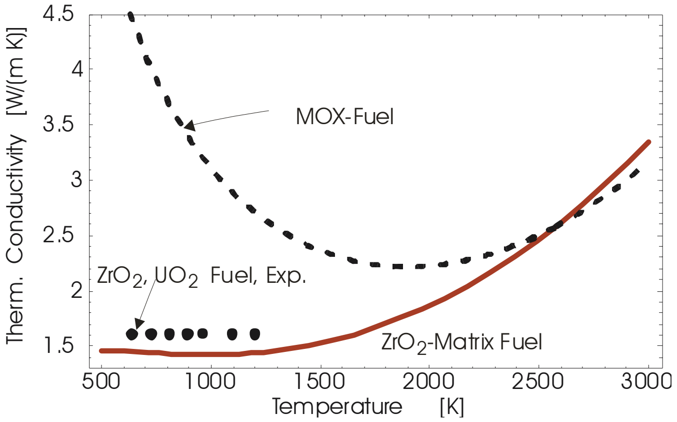


Fig. 6 Fuel thermal conductivities of PDS-XADS MOX fuel and FUTURE ZrO_2 matrix fuel with 62 vol% ZrO_2 and 10 % porosity and experimental data for ZrO_2-matrix UO_2 fuel [12] with 72.9 wt% ZrO_2 and 10.1% porosity.

3. Results of Transient Analyses

For the small scale PDS-XADS with good safety coefficients (negative void worth, large Doppler) the analyses reveal a benign behavior under design basis conditions (DBC) and strong resistance against severe transients [9]. Even under hypothetical conditions of core degradation and melting (DEC-design extension conditions), defined with ad-hoc assumptions, no severe accident scenario develops [13]. Such core melt scenarios have been modeled with SIMMER [7, 8] for MOX fuel and HLM coolant conditions.

For the FUTURE-ADT with deteriorated safety parameters the work has been started to get a first picture of its behavior [5]. A problem is the lack of many high temperature fuel data, lack of knowledge about the phenomenological behavior under melt conditions and lack of irradiation data. As described before, for transients within the design basis the fertile free cores show virtually no feedback from Doppler, but might reveal a positive feedback from coolant expansion.

3.1 UTOC : Unprotected Transient Over Current

Power and reactivity traces of a beam over current transient, where the beam strength is increased by 100% for 10 seconds, for the small scale MOX-ADS and the ADT are displayed in Figures 7 and 8, respectively. It is observed that the fuel center temperatures at the hottest cell reach melting conditions in the ADT. In contrast, for the small MOX-ADS, the fuel temperatures stay 1440 K below the melting point.

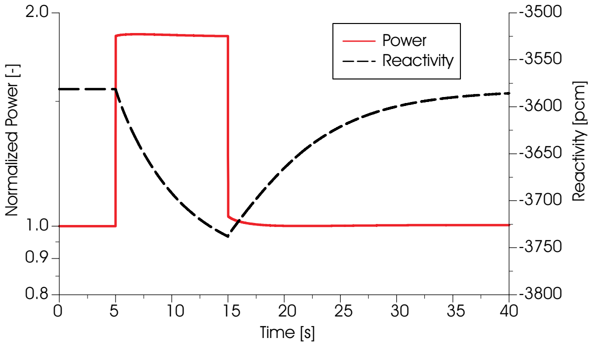


Fig. 7 100% beam over current in the small scale PDS-XADS with conventional fast reactor fuel.

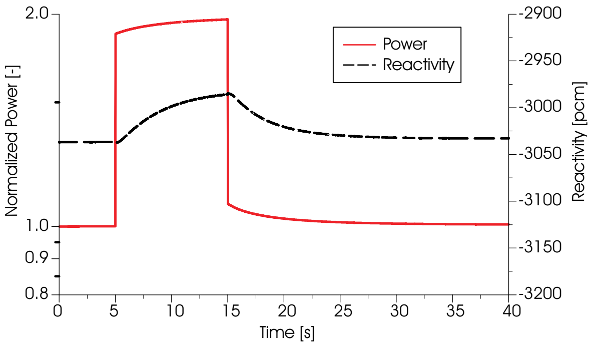
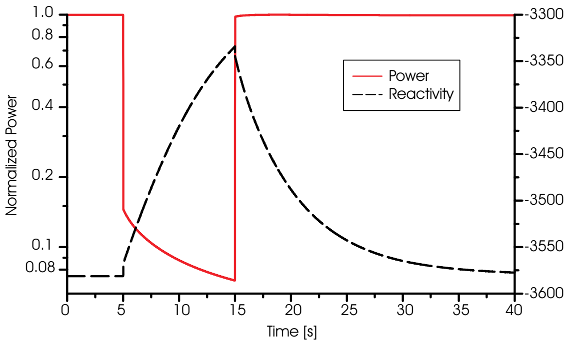


Fig. 8 100% beam over current in the 800 MWth ADT with fertile free fuel.

3.2 BI : Beam Trip/Interruption

Power and reactivity traces of a beam trip transient, where the beam is interrupted for 10 seconds, for the small scale ADS and the ADT are displayed in Figures 9 and 10, showing the difference in the reactivity development. The XADS has a significant negative feedback, while the ADT has a slightly positive feedback. As described, the core expansion effects have not been taken into account. The comparison of the fuel center temperature at the hottest cell that is normalized by its initial value is presented in Figure 11. Since the coolant inlet temperatures are the same for both reactors and the ADT has a higher fuel center temperature, the normalized fuel center temperature decreases more in the ADT than in the XADS. In addition, for the XADS thermal conductivity is increasing in case of a power reduction, whereas for the FUTURE-ZrO_2 fuel conductivity is decreasing under such conditions.



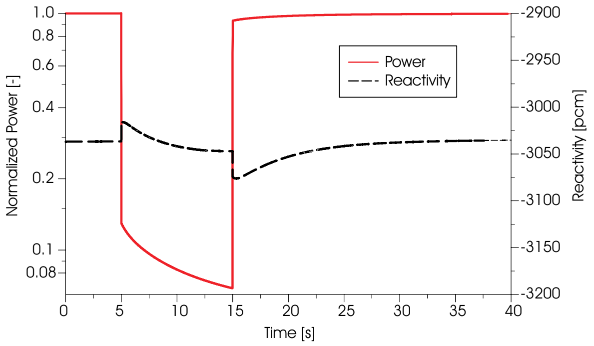


Fig. 9 Beam-trip (beam interruption) transient in the small scale XADS with conventional fast reactor fuel.

Fig. 10 Beam-trip (beam interruption) transient in the 800 MWth ADT with fertile free fuel.

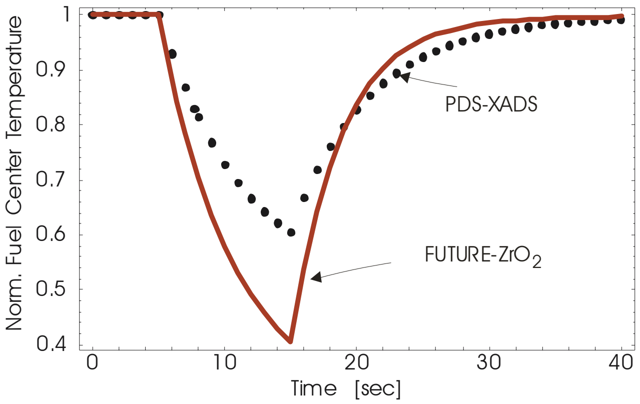


Fig. 11 Normalized fuel center temperatures of hottest cells at the beam-trip transients in the PDS-XADS and the ADT.

3.3 UTOP : Unprotected Transient Over Power

Power and reactivity traces of a UTOP transient, where the reactivity is increased by 314 pcm (see Table 3) within 0.5 second, for the small scale ADS and the ADT are displayed in Figures 12 and 13, respectively. A scenario which could introduce positive reactivity is the blow-down of fission gases and helium after local pin failure and the local voiding processes. This blow-down scenario has already been studied with SIMMER [8]. An additional UTOP case has been calculated for the ADT, where the reactivity increase is 2000 pcm. In the highly rated pins fuel melting conditions are reached under such conditions.

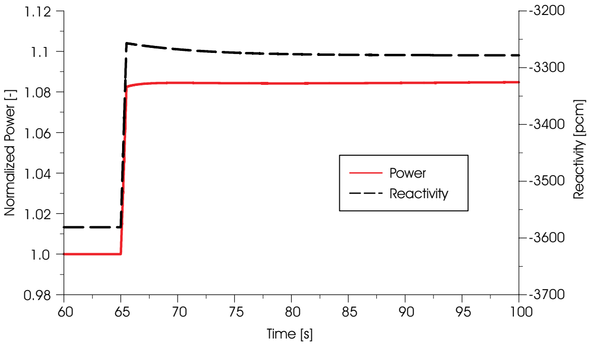


Fig. 12 Unprotected transient of over power at a reactivity increase by 314 pcm (1 $) in the 80 MWth XADS with MOX fuel.

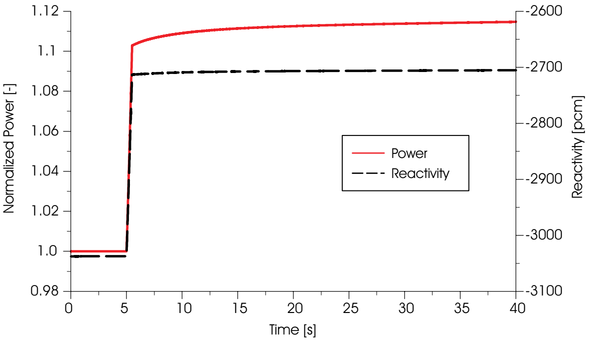


Fig. 13 Unprotected transient of over power at a reactivity increase by 314 pcm in the 800 MWth ADT with fertile free fuel.

3.4 PTOP : Protected Transient Over Power

The 10 $ reactivity increase, but under the protected condition, where the beam is shut off at the time the reactivity begins to increase, is also investigated. As expected the power drops to decay heat levels and all temperatures are reduced correspondingly. Power and reactivity traces of this PTOP transient are shown in Figure 14.

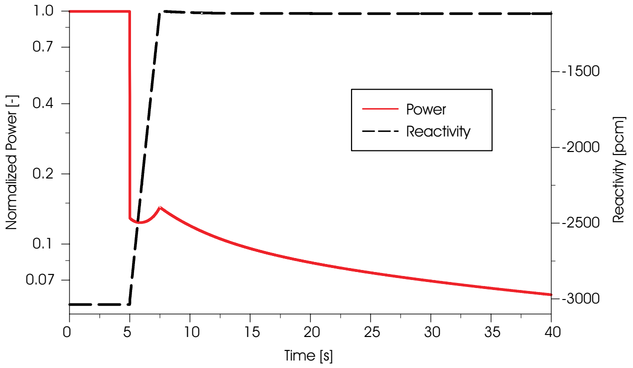


Fig. 14 Protected transient of over power at a reactivity increase by 10 $ in the 800 MWth ADT with fertile free fuel.

3.5 ULOF : Unprotected Loss of Flow

ULOF conditions mean a complete loss of forced coolant circulation in both the PDS-XADS and ADT. For the PDS-XADS this corresponds to a coast down of the gas-lift pumps, whereas for the ADT a conventional pump run-down is simulated. The coolant inlet temperatures are kept at steady state, as for the FUTURE-ADT up to now no primary/secondary side is defined.

The transient of the coolant flow rate and the normalized power for the PDS-XADS are shown in Fig. 15. After seizure of the gas-lift pumps a natural convection flow takes over. Since the reactivity feedback caused by Doppler effect and coolant thermal expansion is negative, the power levels off slightly below nominal.

The highest cladding temperature at the top position of the core reaches about 910 K that is much lower than the cladding melting point (1700 K). Coolant temperatures go up to 870 K. This result supports the high safety potential of the current XADS design.

As mentioned before, for the FUTURE ADT design a forced convection cooling is envisaged. The pump coast down has been arbitrarily assumed with a pump characteristic, which would result in a flow-halving time of 5 s in a sodium cooled fast reactor. Further, beam-on-conditions and constant coolant inlet temperatures are modeled. No axial structural expansion has been modeled in this first set of investigations. The calculations show that natural convection finally leads, after a flow-dip, to a coolant velocity of about 40% of nominal. A significant difference to the PDS-XADS is however the positive feedback from coolant expansion. Thus the core-power levels off above nominal power. The power and reactivity trace are given in Fig. 16. The highest coolant temperatures in this calculation reach 1160 K, peak clad temperature is around 1250 K and the peak fuel temperature increases to 2350 K. In this ULOF calculation no clad or fuel melting is reached, however the coolant temperatures go beyond the limit set for corrosion prevention.

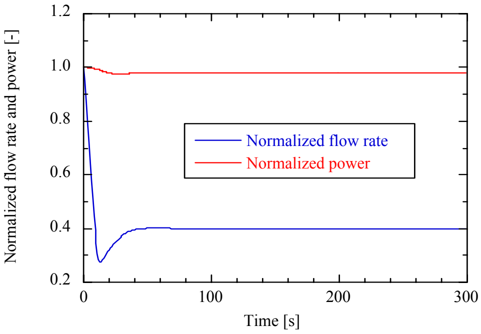


Fig. 15 Coolant flow rate and power in the ULOF case of the small scale PDS-XADS.

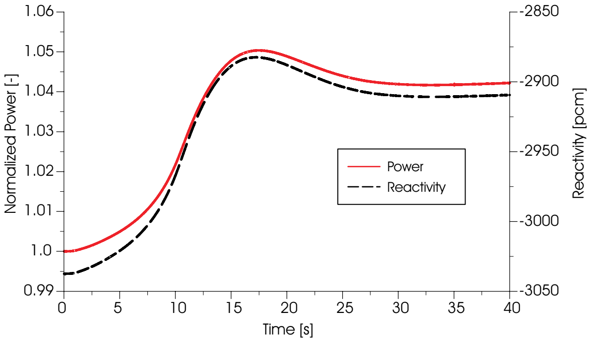


Fig. 16 Power and reactivity traces in the ULOF case of the FUTURE-ADT.

3.6 DEC Behavior

First qualitative analyses of the DEC behavior show the importance of the clad worth of these cores, as steel melting advances any Pb/Bi boiling and leads to un-clad pin-stubs, which disrupt and may lead to sweep-out scenarios and reduction of reactivity, depending on the timing and amount of clad/fuel removal. Voiding can take place and add reactivity via the blow-down of He and fission gases from the fission gas plena. It can also be noted that the change of the reactivity level alters the flux and power shape, possibly leading to higher energy deposition into the peripheral regions of the core [14]. The application of space-time kinetics seems to be important to cover these effects which might impact the propagation potential of an accident. Fuel break-up and sweep-out effects have been simulated and results have been presented in [13]. More detailed analyses of the DEC phenomena are planned in the future.

4. Conclusion

The transient behavior of the 80 MWth PDS-XADS with conventional fast reactor fuel and good safety parameters (no MA content in the fuel, low power rating)) is compared with an 800 MWth ADT with advanced fertile free fuels with high MA load. Specifically the option with a ZrO_2 matrix is investigated. The analyses show that the small Pb/Bi cooled ADS has a very good safety performance. Analyses for the ADT with ZrO_2 matrix based fuel and strong positive feedback potentials reveal some safety problems. These are mainly related to the thermal conductivity of the fuel and the high positive void worth of the core. The ZrO_2 fuel has a very low power to melt ratio of approximately 400 W/cm linear power. UTOC's and UTOP's might lead to local melting conditions. In the ULOF case the natural convection potential of Pb/Bi can prevent immediate core damage. However the coolant temperatures increase up to 1160 K which is far beyond the permissible temperature limits for corrosion control and prevention. From the view of safety, it can be stated, that the ZrO_2 based dedicated fuel is not an optimal choice for an ADT, mainly because of its thermal-physical conditions. The safety parameters of the ADT, especially the void worth, could be improved by reducing the core-size. Further calculations are currently going on, reaching also into the DEC range with fuel melting and pin disruption. Additional code development is under way, which reveals the urgent need for a broader experimental basis related to the high temperature range of these fuels.

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