Analysis of the impacts of homogeneous minor actinides loading in low void effect sodium fast reactor cores

T. Kooyman, L. Buiron, G. Rimpault

Annals of Nuclear Energy 124 (2019) 572–578

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Analysis of the impacts of homogeneous minor actinides loading in low void effect sodium fast reactor cores

T. Kooyman *, L. Buiron, G. Rimpault

CEA, DEN, DER, SPRC, CEA Cadarache, Saint Paul lez Durance 13108 CEDEX, France

ARTICLE INFO

Article history:
Received 23 July 2018
Received in revised form 17 October 2018
Accepted 21 October 2018
Available online 25 October 2018

Keywords:
Fast reactors
Minor actinides transmutation
Unprotected transients

ABSTRACT

Minor actinides transmutation is a solution to decrease the long-term radiotoxicity of nuclear waste and limit their short-term decay heat. In the homogenous approach, minor actinides are mixed in the fuel and loaded in the core in order to turn them into fission products. This leads to a neutron spectrum hardening in the core, which has a negative impact on the core integral feedback coefficients such as the Doppler Effect or the sodium void worth. Analysis of these impacts was used in the past to establish limit on maximal minor actinides loading in a reactor core. Low-void cores (CFV in French) have been recently developed by CEA to achieve negative sodium void worth by adding axial heterogeneities in the core layout in the form of an upper sodium plenum and an inner fertile blanket. In this paper, the impacts of minor actinides loading in such a core are analyzed and a comparison is carried out with earlier homogeneous core designs. In a first time, the impacts on integral feedbacks coefficients are evaluated, and in a second time, the perturbations of the core behavior during selected representative transients are analyzed. It is shown that even if the impacts on integral coefficients are similar between the two core designs, the low-void core behavior during loss-of-flow transient is not negatively impacted by minor actinides loading. For reactivity insertion transient, the two core designs behave similarly. It can be concluded that considering heterogeneous cores, the use of integral coefficients is insufficient to characterize the impact of minor actinides loading on the core for loss-of-flow transient. However, the impacts of minor actinides loading on the Doppler integral feedback coefficient can be used as reliable estimator for the modification of the core behavior during a reactivity insertion transient.

1. Introduction

In a closed fuel cycle where spent fuel is multi-recycled and plutonium reused as fuel for fast reactors, minor actinides become the main contributors to the long term radiotoxicity of the spent fuel and to the short term heat load of the nuclear waste packages. Consequently, a reduction in the total mass of minor actinides being discarded as waste during fuel reprocessing would lead to a decrease in the final fuel radiotoxicity and would increase the packing ratio of a deep geological repository, since spacing of the final waste packages depends on the heat load of the waste packages (Chabert et al., 2012; Salvatores et al., 1995).

Minor actinides are elements produced by successive captures on uranium and plutonium isotopes yielding neptunium, americium and curium. Neptunium is mainly produced by successive captures on ^{235}U in thermal reactors while americium and curium are mostly found in fast or thermal reactors loaded with MOX fuel as they are produced either by decay of ^{241}Pu for ^{241}Am ($T_{1/2}$ = 14.4 years) or capture on ^{242}Pu for ^{243}Am. Curium is produced by captures on americium isotopes. As americium is the main contributor to mid term (≈10,000 years) radiotoxicity and the most abundant minor actinide in a closed fuel cycle, this work will focus on americium transmutation only. Neptunium being longer-lived than americium ($T_{1/2}$ = 2.14e6 years), its impact on long-term radiotoxicity is lower while curium transmutation is currently ruled out due to the very high decay heat and neutron source of several curium isotopes such as ^{242}Cm and ^{244}Cm (Pillon et al., 2003).

Minor actinides transmutation is the process of turning these heavy nuclides into fission products by nuclear bombardment. The neutron source of the process can either be a critical reactor or an Accelerator Driven system (Tommasi et al., 2001). This paper will focus on transmutation in fast reactors. Indeed, these reactors are more suited to transmutation than thermal reactors as they exhibit more favorable fission-to-capture ratios, which means that the transmutation process will be overall more efficient in a fast spectrum with a lower impact on the core neutron balance (NEA,

* Corresponding author.
E-mail address: timothee.kooyman@cea.fr (T. Kooyman).

https://doi.org/10.1016/j.anucene.2018.10.044
0306-4549/

2013). Additionally, it is necessary to achieve closure of the fuel cycle to remove the plutonium contribution to the waste long-term radiotoxicity prior to consider minor actinides transmutation, as otherwise, the plutonium contribution dominates the waste radiotoxicity by one order of magnitude.

Two main approaches have been discussed to implement minor actinides transmutation in fast reactors: the heterogeneous and the homogeneous one. In the heterogeneous approach, minor actinides are loaded in dedicated targets located at the core periphery. As the minor actinides are located in a low flux and importance zone, their impacts on the core neutron spectrum are limited and the overall core behavior during a transient is not impacted. However, the neutron flux being lower at the core periphery, the transmutation performances are lower. This is usually compensated by higher loading of minor actinides in the blankets, which has negative impacts on the fuel cycle as the higher loaded mass leads to a higher decay heat and neutron source of the targets assemblies both at manufacturing and reprocessing stage (Chabert et al., 2015; NEA, 2012).

This paper will focus on the homogeneous approach, in which minor actinides are directly mixed with the reactor fuel. As such, they are loaded directly at the core center and "see" a higher neutron flux, which has positive impacts on the transmutation performances. However, this has two main drawbacks. The first one is the fact that it leads to a contamination of the entire fuel cycle with minor actinides, which are strong decay heat (^{241}Am, ^{244}Cm, ^{238}Pu) and neutron source emitters (^{244}Cm).

The second drawback is the modification of the core feedback coefficients due to a spectrum hardening. Indeed, the higher capture cross section in the epithermal range of americium and neptunium isotopes, which represents the most produced minor actinides, leads to a decrease of the neutron population in this energy range (Wallenius, 2012). This limits the efficiency of the Doppler broadening of ^{238}U low energy resonances and thus decreases the whole Doppler feedback coefficient.

Furthermore, it also has a negative impact on the core voiding behavior, as the fission threshold of ^{241}Am is lower than the threshold of ^{238}U (Wallenius, 2012). Consequently, when sodium is removed from the core, the resultant spectrum hardening leads to a higher reactivity increase. Finally, a decrease in the effective delayed neutron fractions is also observed due to the ^{241}Am loading as heavier actinides tends to exhibit a lower delayed neutron fraction and as the less energetic delayed neutrons are captured by americium isotopes.

These negative impacts on the Doppler feedback and sodium void worth have been used to compute limitations on the maximal allowable minor actinides content in fast reactors, which depend on the core design, size and power, as such as in (Palmiotti et al., 2011; Tommasi, 1995) or (NEA, 2012). Limits of 2 to 5% have been considered based on such analysis and more recently it was concluded in (Palmiotti et al., 2011) that no upper limit in minor actinides loading could be obtained by considering only these parameters as no threshold could be obtained regarding the core transient behavior degradation. Nevertheless, increased sodium void worth obtained by additional axial heterogeneities was pursued to design cores dedicated to minor actinides transmutation in (Gabrielli et al., 2015) or (Kawashima et al., 2013) .

Departing from earlier homogeneous designs such as the EFR (Lefèvre et al., 1992) or the SFR V2B (Sciora et al., 2009) with a unique assembly design and enrichment zoning, CEA recently developed a new heterogeneous core design with axial heterogeneities (Sciora et al., 2009). This core exhibits a negative sodium void worth, which strongly improves its behavior during loss-of-flow transients (Varaine et al., 2012). The axial design of the CFV core is detailed in the next part of this paper. Considering the fact that an increased sodium void worth is a positive feature for minor actinides loading, the CFV core thus appears as a good candidate for transmutation of americium. However, given the results obtained in (Palmiotti et al., 2011), an analysis based purely on the Doppler and sodium void worth feedback appears as inconclusive.

Considering this, an approach based on the evaluation of the modification of the core response to various transients was implemented here. Unprotected loss-of-flow transients in the primary or secondary circuit and slow reactivity insertion are hypothetical situations which are representative of the core response to a real transient (Massara et al., 2005), and as such, the changes in the core response depending on the minor actinides content is an indicator of its resiliency to minor actinides loading.

The aim of this paper is to show that considering only the Doppler and sodium void feedback coefficients is sufficient to analyze minor actinides loading in homogeneous core designs but leads to erroneous conclusions in the case of newly designed cores with axial heterogeneities. Furthermore, it is shown that it is necessary to carry out a transient analysis with detailed feedback profiles to correctly evaluate the impact of minor actinides loading on axially heterogeneous cores.

Two 3600 MWth core designs developed at CEA, one homogeneous and one with axial heterogeneities, will be compared throughout this work. In a first part, the two cores compared here will be described along with the calculations tools which were used. In a second part, an analysis based on the two feedbacks coefficients will be carried out, and this analysis will be compared with the results of a simplified transient analysis of the cores behavior in a third part.

2. Core description & calculations tools

Two cores will be compared in this work, one with a homogeneous design and on with an axially heterogeneous assembly. The first one is the SFR V2b (Sciora et al., 2009) core designed by CEA, EDF and AREVA around 2009 to achieve a low sodium volume fraction in the assembly and thus a reduced sodium void worth. The corresponding design is shown below in Fig. 1. Such a core is deemed homogeneous as all the assemblies in the core have a similar design. Radial blankets are sometimes added to the core, either to tune the breeding gain of the core or to load minor actinides bearing blankets. These will not be considered here.

The second type of core which will be studied here is the so-called CFV core ("Coeur à faible vidange" in French or Low void effect core) (Sciora et al., 2011). This core has been designed by CEA to achieve a negative sodium void worth at the end of irradiation, mainly by increasing the axial neutron leakage during sodium voiding. This design is shown in Fig. 2.

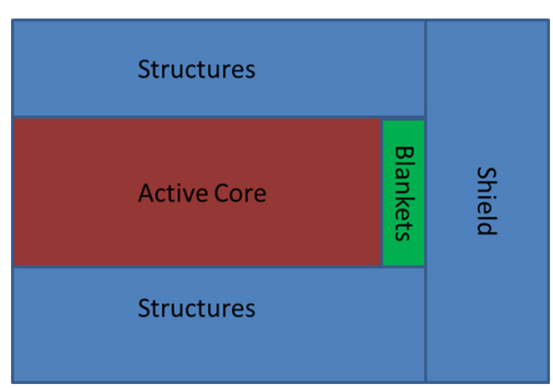

Fig. 1. Homogeneous core layout of the SFR V2b.

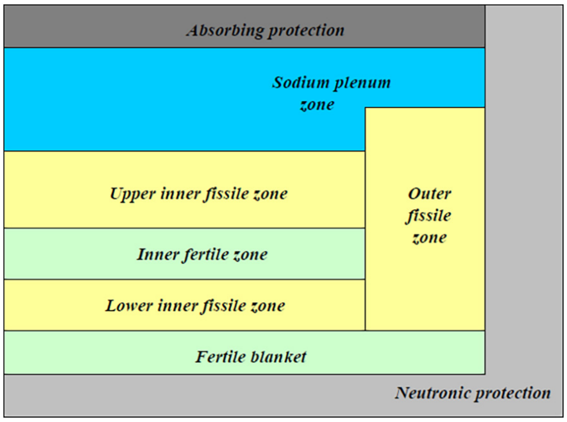

Fig. 2. Heterogeneous core Layout of the CFV Core.

A sodium plenum was added to this core in order to increase neutron leakage in the upper part of the core. In case of voiding, this part of the core will be voided first due to its higher temperature and thus significantly increase axial neutron leakage. This effect is reinforced by the use of an upper absorbing neutron shielding which prevents neutron from backscattering into the core in voided conditions. During normal operations, the sodium plenum zone acts as a neutron reflector.

Axial neutron leakage is also enhanced by the addition of an inner fertile zone which increases the flux level in the upper part of the core and thus the importance of the neutrons in this region. During voiding, this importance decreases sharply thus contributing negatively to the reactivity. Finally, the outer core part was designed slightly taller than the inner core, which increases the core interface with the sodium plenum without increasing core radius.

The core calculations will be carried out using the ERANOS deterministic code for fast reactor (Rimpault, 2002) with the JEFF 3.1 nuclear data library (NEA/OECD, 2006). A 2-D RZ description of the core will be considered with calculations carried out using the diffusion approximation. Sodium void worth will be calculated by voiding the entirety of the fissile and fertile layer along with the upper gas expansion plenum and sodium plenum. The so-called K_d Doppler factor was computed using the formula given in Eq. (1). The geometrical data of both cores are given below in.

$$\Delta\rho_{Doppler} = K_d \ln\left(\frac{T_f}{T_i}\right) \quad (1)$$

Eq. (1): Definition of the K_d factor. $\Delta\rho$ is the reactivity insertion due to the Doppler feedback during a fuel temperature increase between T_i and T_f. The initial and final temperatures were respectively taken here at 1500 K and 2500 K Table 1.

Regarding the transients calculations, three transients will be evaluated:

Table 1
Geometrical data of the two cores considered.

Parameter	Unit	SFR	CFV
Core power	MWTh	3600	3600
Inner core height	cm	100	80
Inner axial blanket	cm	0	20
Outer core height	cm	100	100
Number of pins	/	271	331
Assembly flat to flat	cm	21,08	21,28
Pin diameter	mm	9,43	8,45
Clad thickness	mm	0,5	0,5
Gap thickness	mm	0,15	0,15

- An Unprotected Loss of Flow (ULOF), which corresponds to a stop of the primary pumps without insertion of the control rods.
- An Unprotected Loss of Heat Sink (ULOHS), which corresponds to a stop of the secondary pumps while the primary pumps are still running, effectively removing the core heat sink, without insertion of the control rods.
- An Unprotected Transient OverPower (UTOP), which corresponds to reactivity insertion in the core. We will consider here a slow insertion of reactivity due to the malfunction of a control rod drive mechanism and the consequent extraction of a control rod without insertion of the others.

These transients have been chosen as they are considered conservative, in a sense that they represent hypothetical highly damaging situations and are thus a good measure of the core behavior during any similar transients (Varaine et al., 2012). The calculations were carried out using the MAT4DYN dynamic code, which is a mono-channel code with point kinetics developed at CEA at the beginnings of the 2000s (Massara, 2002). A constant exchange coefficient was taken for the gap conductance at 5000 W/m^2/°C, assuming contact between fuel and cladding.

The description of the power, Doppler and sodium thermal expansion axial profiles was simplified to calculate the core transient behavior. An axial power profile from the inner 60 cm of the core was extracted and the average power per region (inner fuel, lower axial blanket, inner axial blanket) was computed. The power profile was then flattened over the assembly height so as to keep the same total power but averaged per medium. However, in the mesh corresponding to the higher fuel temperature (usually slightly above the top of the inner axial blanket), the power was adapted so that the ratio of the maximal power to the average of the fissile part was conserved. This was done to keep the information about the fuel maximum temperature, which is primordial for UTOP behavior. A graphical description of the process done is shown below in Fig. 3. This approach was previously used in (Fabbris et al., 2016) in combination with the more detailed CATHARE code (Emonot et al., 2011) and it was shown to introduce limited errors on the temperature profile in the core (below 5 °C). Doppler and sodium thermal expansion profiles were similarly averaged over each medium, with the sodium and plenum sodium thermal expansion being added in an extra mesh on top of the fissile stack with zero power generation. The impacts of these approximations were found to be below 1% for the temperature estimator.

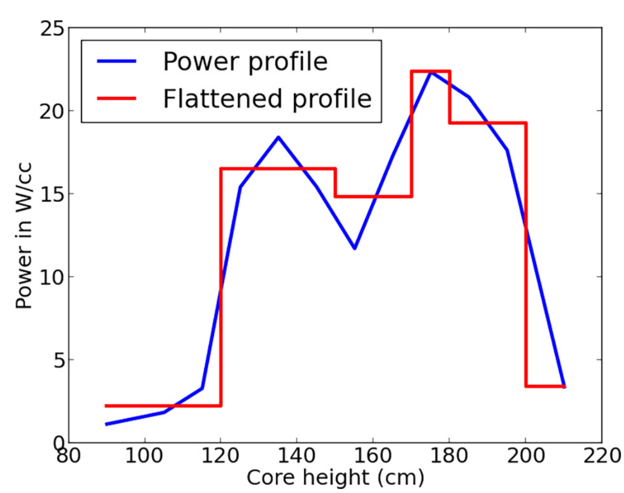

Fig. 3. Comparison of the real power profile and the flattened profile considered for this study.

3. Comparison of integral feedbacks coefficients

For both cores, the Doppler feedback and total sodium void worth were calculated without minor actinides and with 5% of americium. The americium isotopic vector used contained 75% of ^{241}Am and 25% of ^{243}Am. The delayed neutron fraction was also computed. The results are given below in Table 2. As discussed in the introduction, it can be observed that in both cases, all the three parameters are negatively impacted. Consequently, it could be concluded here that in both cases modifications of the core design would be required to accommodate for the higher sodium void worth and Doppler feedback associated with minor actinides loading. Various approaches have been discussed in the past, with the main goal being a reduction of the linear power density in the core which can be achieved either by lowering the core power (Zhang and Wallenius, 2014) or by modifying the assembly design so as to increase the length of the fissile elements.

4. Comparison of transient behavior

To refine the analysis, the core behavior during three transients was computed. In addition to the sodium thermal expansion (ρ_{void}) and Doppler feedback ($\rho_{Doppler}$), additional feedback coefficients were considered, namely:

- Fuel axial expansion, which decreases the fuel density in the core thereby inserting negative reactivity. This coefficient further decreases when minor actinides are added to the core due to the spectrum hardening. This feedback is denominated ρ_{Dilat} in the next figures. Fuel radial expansion was neglected here.
- Cladding thermal expansion, which decreases cladding density thereby inserting positive reactivity. The reactivity inserted increases with the minor actinides loading. This feedback is denominated ρ_{Clad} in the next figures. Cladding radial expansion was neglected here.
- Grid radial expansion, which decreases the core compactness due to the dilatation of the supporting structure. This leads to a negative reactivity insertion which further decreases when minor actinides are added. This feedback is denominated ρ_{Grid} in the next figures. The expansion coefficients of 316L austenitic steel was used to compute diagrid expansion. Even though martensitic steel offers better irradiation tolerance, it is assumed that the diagrid is far enough from the flux to be manufactured using austenitic steel, which is less expensive.
- Control rod differential dilatation, which effect depends on the transient. This effect is complicated to model as it depends on the time constants for core, control rods and control rod drive mechanisms dilatation. Based on the data calculated for the SFR V2B, a differential reactivity insertion of ±2 pcm/mm was considered for both cases. This feedback is denominated ρ_{Rod_Dilat} in the next figures.

Table 2
Comparison of the main feedback coefficients for a homogeneous and a heterogeneous core at the end of an equilibrium cycle.

Sodium void worth (pcm)	0% Am	5% Am
V2B	1919	2055
CFV	−524	−297
Kd (pcm)	0% Am	5% Am
V2B	−767	−561
CFV	−957	−794
β_{eff} (pcm)	0% Am	5% Am
V2B	364	338
CFV	353	333

The variations of these coefficients for a limited minor actinides loading (below 5 at%) are relatively limited and much lower than the variations of the sodium thermal expansion and Doppler feedback. The values used for these parameters are given below in Table 3. It can be seen that the addition of minor actinides has a very limited impact on these parameters. The ρ_{ext} parameter describes the external reactivity inserted and is used in the UTOP case to represent the rod extraction.

4.1. ULOF

For the ULOF transient, a pump coast down of 100% of nominal flow to 10% of the nominal with a time to half-flow of 24 s was considered. This takes into account the inertia of the primary pumps and the natural convection or pony motors operating and maintaining a stable final flow. The maximum sodium temperature was taken as the estimator of interest for this calculation. As it can be seen in Table 4, the addition of americium has a strong negative impact on this estimator for the V2B case while it has nearly no impact on the CFV case. It should nevertheless be mentioned that in both cases, the maximum temperature is above sodium boiling and therefore non physical, since MAT4DYN does not model sodium boiling.

However, information can still be extracted from an analysis of the core behavior here.

The difference between the two cores can be explained by looking at the reactivity evolution during the transient. This is shown in Figs. 4 and 5. For the V2B case, the Doppler feedback is negative at the beginning of the transient as the fuel heats up while the sodium thermal expansion feedbacks insert positive reactivity. These two phenomena are the main contributors to the reactivity evolution during the transient. Consequently, if americium is added to the fuel, the increase in the Doppler feedback will limit the amount of negative reactivity inserted while the increase in the total sodium void worth will lead to an higher positive reactivity insertion. Consequently, the total reactivity inserted in the core during the transient increases which explains the negative effect observed when loading minor actinides in a homogeneous core.

On the other hand, it can be observed that for the CFV core, the Doppler contribution is positive after around twenty seconds. This is explained by the fact that the initial voiding of the upper part of the CFV core leads to a strong negative void reactivity insertion in the core, which decreases the core power and thus decreases the fuel temperature, inserting positive Doppler reactivity. Sodium thermal expansion inserts negative reactivity as the core is designed precisely for this purpose. Consequently, when minor actinides are loaded, we observe a compensation effect between the decrease in the Doppler feedback, which decreases the positive reactivity insertion during the transient, and the increase in the sodium thermal expansion, which decreases the negative reactivity

Table 3
Evolution of the minor feedback coefficients depending on the core and americium content.

pcm/K	V2B	CFV
Clad axial expansion		
0 %Am	0,09	0,08
5% Am	0,09	0,08
Fuel expansion		
0 %Am	−0,12	−0,14
5% Am	−0,13	−0,14
Diagrid expansion (Austenic steel)		
0 %Am	−0,77	−0,84
5% Am	−0,77	−0,84

Table 4
Comparison of the ULOF behavior of both cores with and without Americium.

ULOF max temperature (°C)	0% Am	5% Am
V2B	1332	1557
CFV	1027	1026

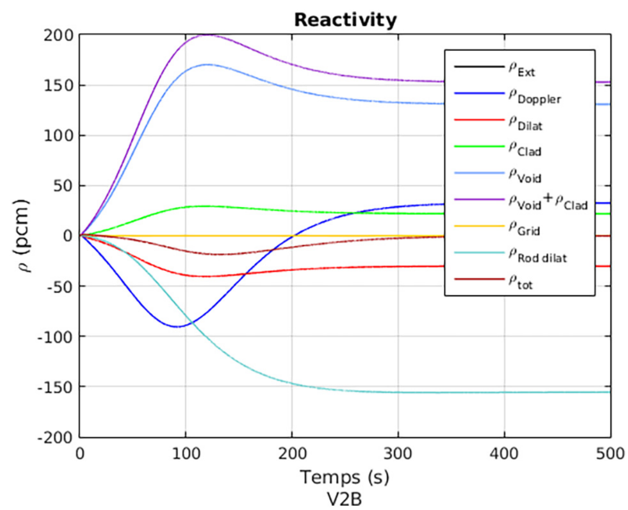

Fig. 4. Reactivity evolution of the V2B core during an ULOF without minor actinides.

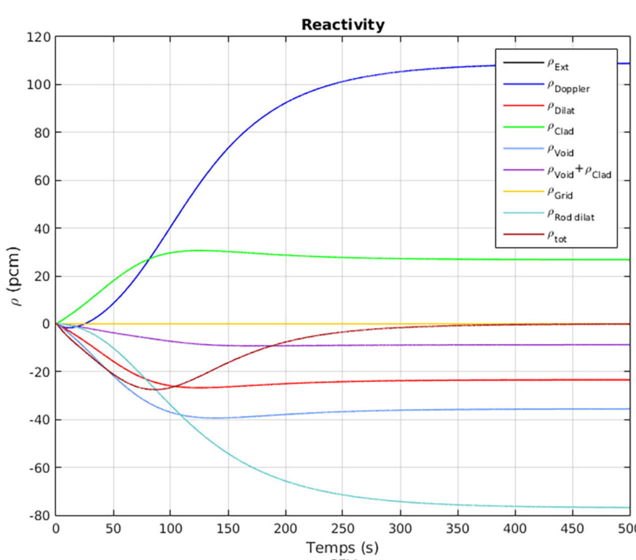

Fig. 5. Reactivity evolution of the CFV core during an ULOF without minor actinides.

inserted. It can be concluded that the general behavior of a CFV during an ULOF transient is not modified by the addition of minor actinides. This could not have been concluded by considering only the Doppler feedback and total sodium void worth. These results are consistent with the findings in (Fabbris et al., 2016). It can be observed in Table 5 that these results do not appear to depend on the transient considered.

These results were found to be strongly sensitive to the control rods differential dilatation, especially for the V2B case. As can be seen in Table 6, when the control rods differential insertion efficiency is decreased, the maximal sodium temperature during an ULOF increases in all the cases. However, this increase is significantly higher in the V2B case. This is most probably explained by the fact that the plenum negative sodium void worth will dampen the modification in the control rods differential efficiency in the CFV case, which is not the case for the V2B. This is a further indication of the role which is played by negative reactivity insertion in the upper part of the core during an ULOF transient. Further analysis of the impact of the upper parts of the core on its behavior during an ULOF is planned but requires more precise tools.

4.2. ULOHS

For the ULOHS, a linear decrease of the secondary pumping power was considered with a total cancellation of the flow after 40 s. The core behavior is shown below in Table 7. It can be observed that americium loading has a positive effect on the core behavior during an ULOHS, regardless of the core design considered. For this transient, the final sodium temperature was considered as the estimator of interest. Indeed, during an ULOHS, the core reaches the so-called "neutron shutdown" temperature in which the chain reaction stops by itself.

This can be explained by looking at the evolution of the core reactivity during the transient, as down in Figs. 6 and 7. Indeed, during an ULOHS, the entirety of the primary sodium is heating up due to the lack of heat sink, and thus there is no specific negative insertion of reactivity from the upper part of the core contrary to the ULOF case, but rather a global positive reactivity inserted due to the sodium heat, which is higher in the V2B than in the CFV case as it is linked with the total sodium void worth. For the ULOHS, the second main feedback is the grid thermal expansion, which is due to the increase in the sodium inlet temperature. This effect tends to separate the fuel assemblies and thus insert negative reactivity. Consequently, we observe a decrease in core power and in fuel temperature, which leads to a positive Doppler reactivity insertion during the transient. Adding minor actinides thus reduces the amount of positive reactivity inserted by the Doppler Effect, which quickens the core power decrease. This effect is true for both cores. It can thus be concluded that minor actinides addition has a positive impact on the core behavior during the transient. The speed of the transient was found to have no impact on the final sodium temperature which was used as the reference estimator here. Considering only the Doppler and total sodium void worth, this conclusion could also not have been reached.

4.3. UTOP

For the UTOP, a 150 pcm insertion in 250 s was considered. This was calculated based on a control rod drive mechanism malfunction with a rod extraction at the speed of 4 mm per second with a rod worth of 1.5 pcm per cm, with the rod being extracted from an insertion of 1 m in the core. The results are given in Table 8. It can be observed that in both cases the addition of americium has

Table 5
Comparison of the maximal sodium temperature for a CFV core depending on the ULOF transient considered.

Final flow/Half time	10%/24 s	5%/24 s	15%/24 s	10% / 12 s	5%/12 s
No Am	1027	1189	928	1082	1292
5% Am	1026	1185	927	1078	1283

Table 6
Evaluation of the impact of control differential reactivity insertion on the ULOF behavior.

Max Na Temperature during ULOF (°C)	V2B	CFV
Reference 2 pcm/mm		
No Am	1332	1027
Am	1557	1026
Decreased efficiency 1,8 pcm/mm		
No Am	1393	1037
Am	1964	1045
Increased efficiency 2,2 pcm/mm		
No Am	1282	1018
Am	1399	1009

Table 7
Comparison of the ULOHS behavior of both cores with and without americium.

ULOHS final sodium temperature (°C)	0% Am	5% Am
V2B	860	857
CFV	709	703

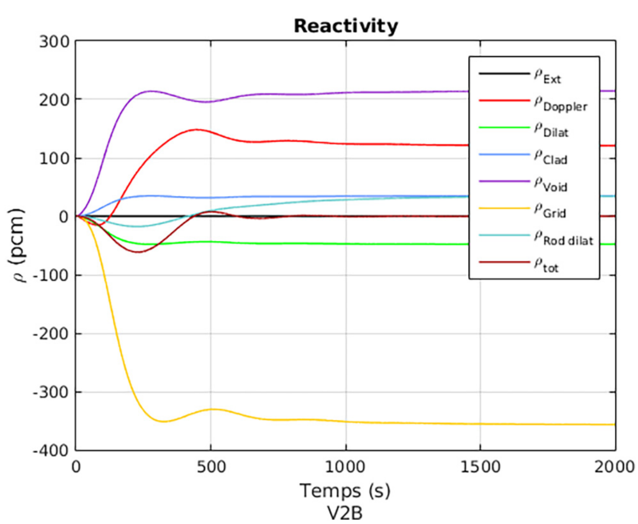

Fig. 6. Reactivity evolution of the V2B Core during an ULOHS without minor actinides.

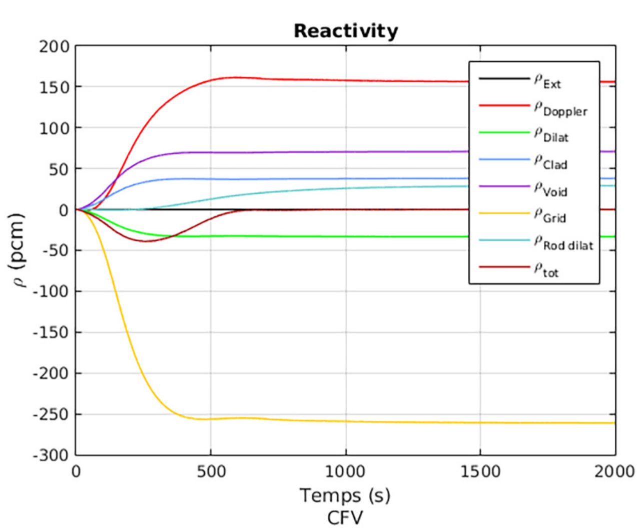

Fig. 7. Reactivity evolution of the CFV core during an ULOHS without minor actinides.

Table 8
Comparison of the UTOP Behavior of both cores with and without americium.

UTOP max fuel temperature (°C)	0% Am	5% Am
V2B	2180	2330
CFV	2390	2446

a negative impact on the core behavior during an UTOP. For this transient, the maximal fuel temperature was used as the estimator of interest.

This can be explained by looking at the reactivity evolution for both cases, as shown in Fig. 8 and Fig. 9, which is extremely similar. During a reactivity insertion, the Doppler feedback plays the main role as it is nearly instantaneous compared to the other feedback effects which depend on thermal exchanges between fuel, sodium and steel. Consequently, the incorporation of minor actinides in the fuel is going to decrease the Doppler feedback magnitude and thus

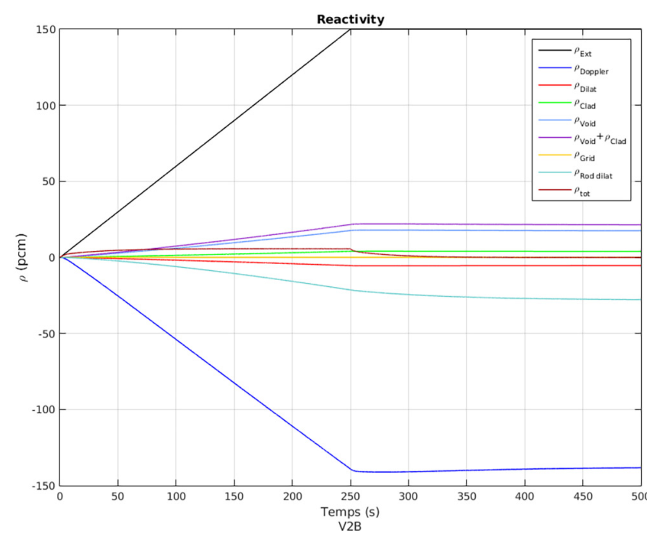

Fig. 8. Reactivity evolution of the V2B core during an UTOP without minor actinides.

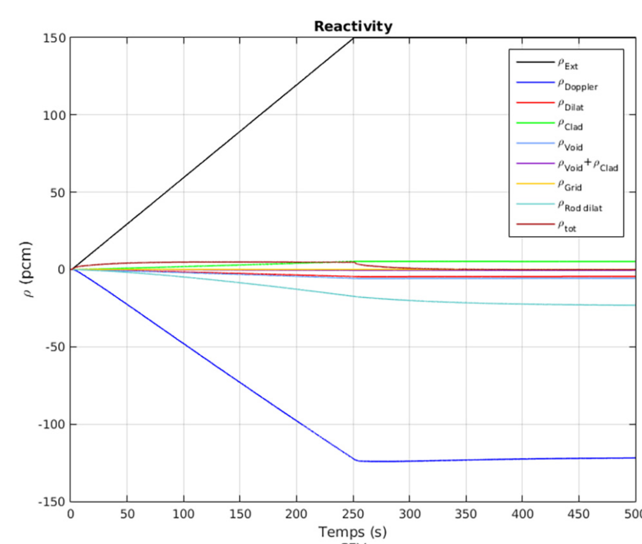

Fig. 9. Reactivity evolution of the CFV core during an UTOP without minor actinides.

require a higher temperature elevation to insert enough negative relativity to stabilize the core.

It should be noted here that the withdrawal of a control rod also leads to a localized modification of the core power map which cannot be taken into account with the tools used here. Consequently, the maximal fuel temperatures obtained here are corresponding solely to the point kinetics contribution to the fuel temperature increase without considering any change in the power distribution.

Considering the fact that the Doppler feedback is the main effect dominating the core response to a reactivity insertion, the impact of minor actinides loading on the UTOP behavior of a given core can be appreciated using the modification of the Doppler feedback coefficient only. In the situation described here, it should also be mentioned that the architecture of the control rod system is going to play a role in the core response to minor actinides loading.

5. Conclusions

The impact of minor actinides on two cores with different geometrical designs – one homogeneous and one axially heterogeneous – have been computed here using a simplified approach. Various conclusions have been reached, the first one being that for such heterogeneous cores, it is not possible to use only the variations on the Doppler feedback and total sodium void worth to evaluate the impact of minor actinides loading. Indeed, despite an increase in both the Doppler and sodium void worth, it was shown that for a primary circuit loss of flow, the heterogeneous core design considered here is nearly not impacted by the loading of minor actinides due to a compensation effect between the Doppler feedback and the sodium dilatation. It was also shown that minor actinides loading had a positive impact on the core behavior during a loss of secondary flow regardless of the core concept considered.

These results are promising as they hint at the fact that minor actinides loading in an industrial fast reactor with an heterogeneous core is not limited by the increase in Doppler and sodium void worth, but by additional considerations mainly linked to the core behavior during an UTOP and thus to the Doppler feedback and to technological choices related to the possibility of a reactivity insertion in the core. If a core design acceptable with regards to the ULOF and ULOHS transients can be obtained, it appears that such a core would remain acceptable when loaded with minor actinides for these two transients.

However, the analysis presented here is rather preliminary and should be validated using more detailed core calculations with 3D description of the core and transport calculations for the core calculation part, and with a complete system code such as SIMMER or CATHARE to finely evaluate the core behavior. Specific care is required regarding the treatment of the control rods systems, which requires a complete modelling of the core. Indeed, a constant control rod worth of 2 pcm/mm has been considered here for control rod differential insertion in the transient calculation, but this value actually depends on the control rod efficiency, which itself depends on the overall design of the rod system.

References

Chabert, C., Warin, D., Milot, J., Saturnin, A., Leudet, A., 2012. Impact of minor actinide transmutation options on interim storage and geological disposal. In: 12th IEMPT, Prague.

Chabert, C. et al., 2015. Considerations on the industrial feasibility of scenarios with the progressive deployment of Pu multirecycling in SFRs in the french nuclear power fleet. In: GLOBAL2015, Paris.

Emonot, P., Souyri, A., Gandrille, J., Barré, F., 2011. CATHARE-3: a new system code for thermal-hydraulics in the context of the NEPTUNE project. Nucl. Eng. Des. 241 (11), 4476–4481.

Fabbris, O., Dardour, S., Blaise, P., Ferrasse, J.-H., Saez, M., 2016. Surrogates based multi-criteria predesign methodology of sodium-cooled fast reactor cores - application to CFV-like cores. Nucl. Eng. Des. 305, 314–333.

Gabrielli, F., Rineiski, A., Vezzoni, B., Maschek, W., Fazio, C., Salvatores, M., 2015. ASTRID like fast reactor core for burning plutonium and minor actinides. Energy Procedia 71, 130–139.

Kawashima, K., Sugino, K., Ohki, S., Okubo, T., 2013. Design study of a low sodium void reactivity core to accomodate degraded TRU fuel. Nucl. Technol. 3 (185), 270–280.

Lefèvre, J., Mitchell, C., Hubert, G., 1992. European fast reactor design. Nucl. Eng. Des. 162, 133–143.

Massara, S., 2002. Etude et amélioration du comportement cinétique de coeurs rapides dédiés à la transmutation de déchets à vie longue. Université Louis Pasteur, Strasbourg.

Massara, S., Tommasi, J., Vanier, M., Köberl, O., 2005. Dynamics of critical dedicated cores for minor actinide transmutation. Nucl. Technol. 149 (2), 150–174.

NEA, 2012. Homogeneous versus heterogeneous recycling of transuranics in fast nuclear reactors. NEA, Paris.

NEA, 2013. Minor actinides burning in thermal reactors. Paris.

NEA/OECD, 2006. The JEFF-3.1 Nuclear Data Library. NEA, Paris.

Palmiotti, G., Salvatores, M., Assawaroongreungchot, M., 2011. Impact of the core minor actinide content on fast reactor reactivity coefficients. J. Nucl. Sci. Technol. 48 (4), 628–634.

Pillon, S., Somers, J., Grandjean, S., Lacquement, J., 2003. Aspects of fabrication of curium-based fuels and targets. J. Nucl. Mater. 320, 36–43.

Rimpault, G., 2002. The ERANOS code and data system for fast reactor neutronic analyses. In: PHYSOR 2002, Seoul.

Salvatores, M., Zaetta, A., Girard, C., Delpech, M., Slessarev, I., Tommasi, J., 1995. Nuclear waste transmutation. Appl. Radiat. Isot. 46 (6/7), 681–687.

Sciora, P., Buiron, L., Rimpault, G., Varaine, F., 2009. A break even oxide fuel core for an innovative French sodium-cooled fast reactor: neutronic studies results. In: GLOBAL 2009, Paris.

Sciora et al., 2011. Axially heterogeneous CFV design used for ASTRID. In: ICAPP 2011, Nice.

Tommasi, J., 1995. Long-lived, waste transmutation in reactors. Nucl. Technol. (111)

Tommasi, J., Bottollier-Curtet, H., Massara, S., Varaine, F., Delpech, M., 2001. Scenarios for waste management involving innovative systems (ADS). In: GLOBAL2001, Paris.

Varaine, F., Marsault, P., Chenaud, M.S., Bernardin, B., Conti, A., Sciora, P., Venard, C., Fontaine, B., Devictor, N., Martin, L., Scholer, A.C., Verrier, D., 2012. Pre-conceptual design study of ASTRID core. In: ICAPP2012, Chicago.

Wallenius, J., 2012. Physics of americium transmutation. Nucl. Eng. Technol. 44 (2), 199–206.

Zhang, Y., Wallenius, J., 2014. Upper limits to americium concentration in large sized sodium-cooled fast reactors loaded with metallic fuel. Ann. Nucl. Energy 70, 180–187.