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Minor actinide balance reduction in ESFR-SMART

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Abstract. New safety measures were proposed recently for ESFR, a design for a large European sodium-cooled fast reactor. The fissile height was reduced by 25% and 5% in the inner and outer cores, respectively; a lower fertile blanket was implemented. A unique fissile enrichment was chosen. Additional fuel subassemblies (FAs), passively operating safety rods and corium discharge tubes were introduced. In the current core, the sodium void effect is strongly reduced, that is favourable for reactor safety, but the Am and Cm balances, i.e. their mass variations under irradiation, remain positive. In the paper we investigate options for Am incineration in the core radial and lower fertile blankets by introducing there a mixture of U and Am oxides instead of U oxide and/or steel. With this mixture in the radial blanket instead of steel, the Am and total minor actinide balances approach negative and zero values, respectively. With this mixture instead of U oxide and steel in the lower blankets, these balances are negative; the sodium void effect is lower. The modified cores produce more Pu and Cm.

1. Introduction

A large 3600 MWth European Sodium Fast Reactor (ESFR) design proposed by CEA in 2008 for the EURATOM CP-ESFR (2008-2012) project [1] is studied since 2017 in the ESFR-SMART one [2], in particular regarding safety issues. After taking into account CP-ESFR core safety studies [3] and other ones [4, 5], a new ESFR-SMART core configuration with a sodium void reactivity effect (SVRE) below 1$, that is about 400 pcm, has been established recently [6]. The configuration includes a sodium plenum of 60 cm above the core, corium discharged tubes, fuel assemblies (FAs) with shorter fissile heights, and additional FAs; see figures 1, 2 with the core radial and FA axial layouts. The FA numbers in figure 1 describe the chosen six-batch reloading scheme. The cycle length is 350 days. Compared to CP-ESFR, the FA fissile core height is reduced by 25% and 5% in the inner and outer cores, respectively, but the total fissile and fertile height in each FA is the same as the fissile one initially: 100 cm. Both initial and current cores produce Am and Cm. In the following we consider introduction of Am, with the Am-241:Am-243 ratio of 3:1 [7], in the lower blankets by replacing steel and/or UOX in the lower/radial blankets/reflectors by a mixture of U oxide and Am oxide with the 80:20 ratio, in order to reduce the Am balance. For the radial blanket case, we consider replacement of subassemblies around the core, denoted as R1 in figure 1, by those similar to the outer core FAs, but with the mentioned mixture instead of fertile and fissile. We also consider a longer radial blanket: extended by 25 and 7 cm downwards and upwards, respectively.

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2. Numerical analyses

The fissile core contains MOX fuel of unique 18% (wt%) enrichment. At the beginning of life (BOL), the Pu238/Pu239/…Pu242/Am241 vector (at%) is 3.7/48.6/28.0/8.4/10.5/0.8, the Pu content is ca. 12 tons. With the ERANOS code [8] and JEFF 3.1.1 data, we performed calculations of actinide mass variations, between BOL and 2100 effective full power days (EFPDs) without fuel reloading, i.e., using a simplified procedure. We also computed reactivity effects at the end of equilibrium cycle (EOEC), which corresponds to 1225 EFPDs in the simplified procedure, see figures 3, 4 and table 1. The calculated Am and Cm balances after 2100 EFPDs of operation and SVRE (in the fissile core and plenum above, at EOEC) are given in table 1 for the current design and for the one with Am in the lower blanket. The introduction of Am affects the Pu, Am, and Cm balances and increases the neutron leakage that leads to a slightly lower SVRE of 118 pcm instead of 257 pcm. The Am balance is definitely negative after this introduction, but more Cm is produced from Am. Also the Pu balance increases, mainly due to decay of Cm-242 to Pu-238. The axial power profile is not affected strongly by adding Am to the lower blanket, see figure 5. With Am in the lower blanket, the minor actinide balance is reduced from ca. 300 kg to ca. -600 kg.

1 2 3 4 5 6	Outer fuel	288
1 2 3 4 5 6	Inner fuel	216
	CSD / DSD	24 / 12
R1 R2 R3	1st / 2nd /3rd reflector ring	66 / 96 / 102
S1	Spent Inner / Outer fuel storage	108
S2	Spent Inner / Outer fuel storage	144
	Corium discharge tubes	31

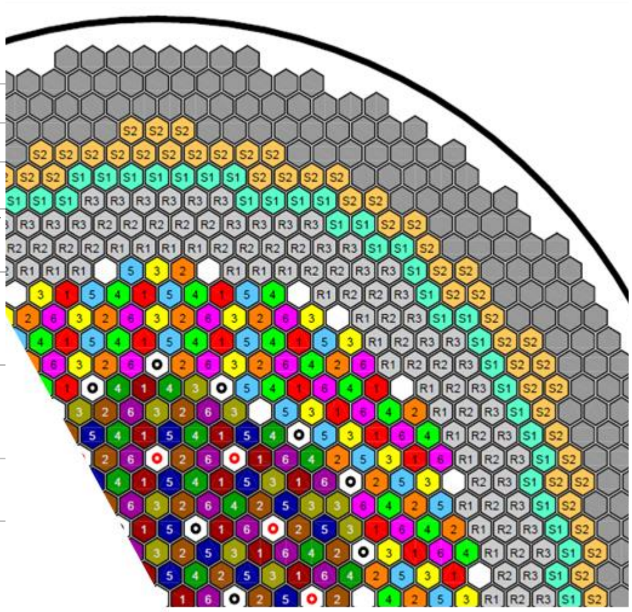

Figure 1. ESFR core layout in plane, the HEX pitch is 20.985 cm

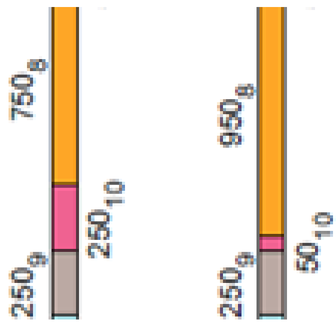

Figure 2. Inner/outer (left/right) FA axial layouts in the core and lower blanket, from bottom to the top: steel reflector of 250 mm (9), fertile blanket of 250/50 mm (10), fissile part of 750/950 mm (8).

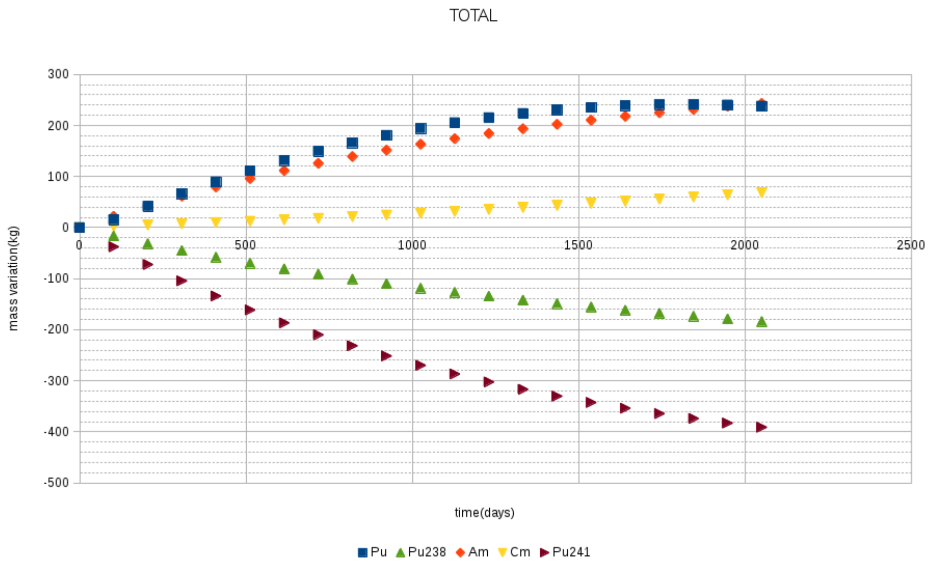

Figure 3. Mass variations of Pu, Am, Cm, Pu-238 and Pu-241 in ESFR-SMART under irradiation.

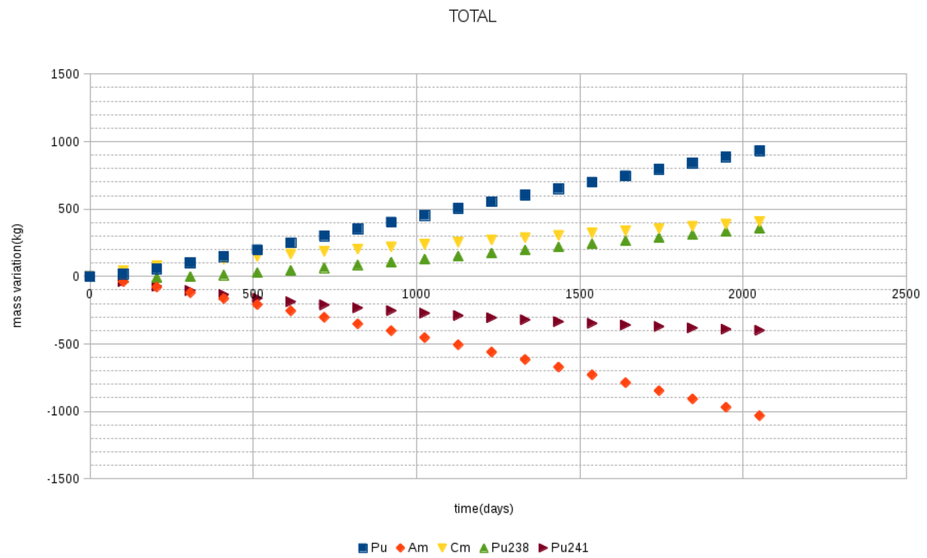

Figure 4. Mass variations of Pu, Am, Cm, Pu-238 and Pu-241 in ESFR-SMART with Am in the lower blanket under irradiation.

Table 1. Pu/Am/Cm balance after 2100 EFPDs, sodium void reactivity effect at EOEC.

Configuration	Pu/Am/Cm variation, kg	SVRE at EOEC, pcm
Current design	238/243/68	257
Am in the lower blanket	931/-1032/406	118

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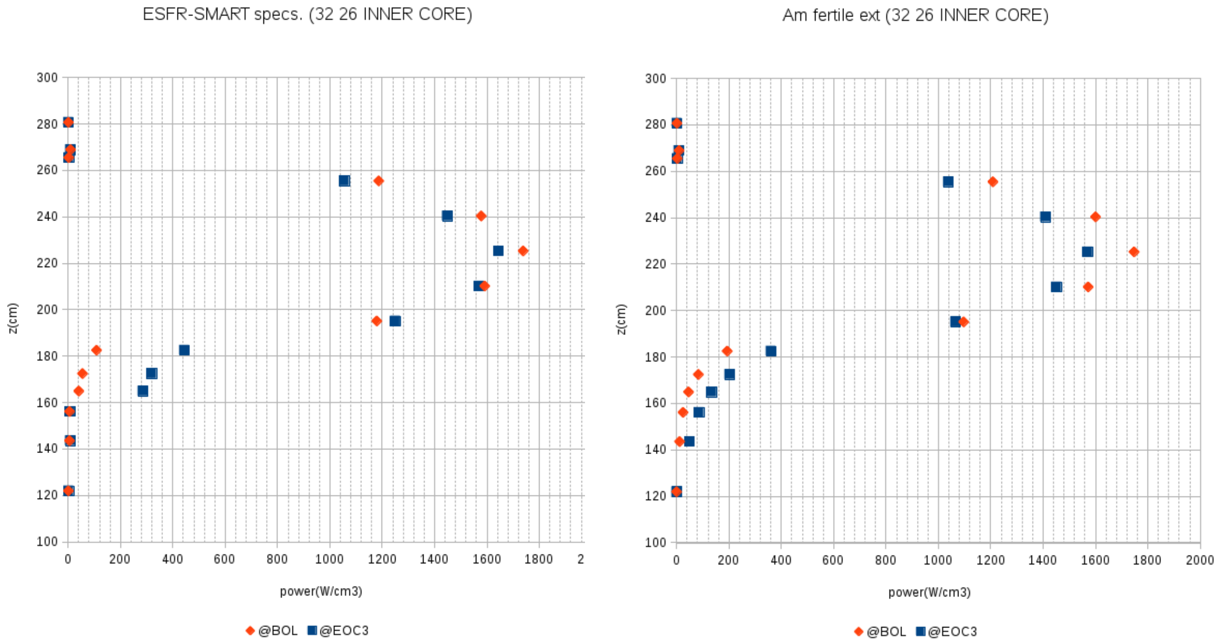

Figure 5. Power density axial distribution in an inner core fuel assembly at BOL and End Of Cycle 3 (EOC3) in ESFR-SMART: without Am (left) and with Am (right) in the lower blanket.

For adjusting the criticality reduction by about 200 pcm - in view of the increased leakage to the blanket with Am, which is a strong neutron absorber - the Pu enrichment should be changed by about 0.5%; that would partly compensate (by -165 kg, not taken into account in table 1) the Pu balance augmentation. The reactivity variation per cycle of 350 days is about -660 pcm for the enrichment of 18% and -775 pcm for the enrichment of 18.5%. This variation can be made closer to zero by introduction of a small fraction of Am, less than 2%, in the core that would not affect appreciably SVRE at EOEC and reduce the Am balance further; this option was studied in [3] and therefore not discussed here. Introductions of Am into the short/long radial blankets lead to smaller Pu/Am/Cm balance variations, resulting in 657/-128/165 kg and 727/-190/182 kg for the short and long radial blankets, respectively, and to minor variations in the radial power profile, see figures 6 and 7.

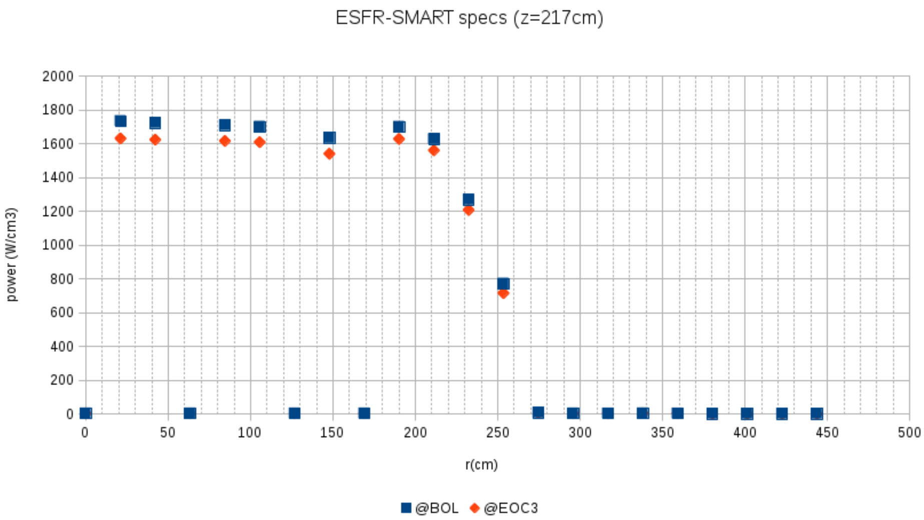

Figure 6. Power density radial distribution in ESFR-SMART: at BOL and End Of Cycle 3 (EOC3).

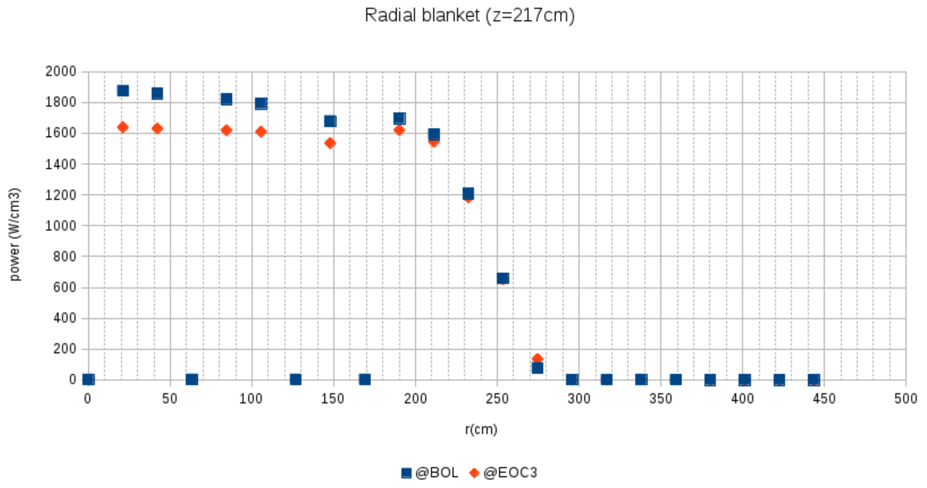

Figure 7. Power density radial distribution in ESFR-SMART with Am in the short radial blanket at BOL and End Of Cycle 3 (EOC3)

The related to radial blanket modifications SVRE reductions are very small, about 10 pcm. The Doppler constant is -715 pcm in the ESFR-SMART core; the absolute value of this constant is marginally smaller, by less than 20 pcm, for all considered blanket modifications. The influence of Am introduction on the kinetics parameters and transient core behavior has not been studied yet.

3. Conclusions

The sodium void reactivity effect is strongly reduced to a value below 1$, that is about 400 pcm, in the new ESFR-SMART core based on the earlier design of CP-ESFR, but the Am and minor actinide balances remain positive. Reductions of the Am and total minor actinide balances and a further slight reduction of the sodium void reactivity effect are expected to be favorable for fuel cycle and safety. These reductions can be achieved by admixing Am oxide to U oxide in the fertile blankets and by replacing steel in reflectors by a material containing Am, the most effective studied option being replacement of U oxide and steel by a mixture of U and Am oxides below the fissile core part. The sodium void effect reduction is due to augmentation of the neutron leakage from the core to the blanket with Am, which is a strong neutron absorber. Note, that the uncertainties of the calculated sodium void reactivity effect values are comparable to these values. But the computed variations of these values due to an introduction are assumed to be representative. Handling of fresh and spent fuel may become more complicated and costly after this introduction. The Pu and Cm balances are higher; options for their reduction may have to be considered. The obtained results will support future studies on ESFR application in different fuel cycles.

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