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ASTRID-like Fast Reactor Cores for Burning Plutonium and Minor Actinides

Fabrizio Gabrielli[a,*], Andrei Rineiski[a], Barbara Vezzoni[a], Werner Maschek[a], Concetta Fazio[a], Massimo Salvatores[b]

[a]*Karlsruhe Institute of Technology (KIT), Institute for Nuclear and Energy Technologies (IKET), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany*

[b]*CEA Cadarache, Saint Paul Lez Durance, France*

Abstract

A reduction of nuclear waste by transmutation of trans-uranium elements (TRUs), such as Pu and Minor Actinides (MAs) contained in Spent Nuclear Fuel (SNF), is a goal for future reactors. In general, countries with on-going nuclear scenarios would profit from MA mass stabilization, while transmutation of Pu and MAs from SNF could be desired in countries in nuclear phase-out. Both missions can be accomplished by employing fast reactors loaded with fuels containing different amounts of Pu and MAs in a closed (or partially closed) fuel cycle. In this paper, two 1200 MWth sodium-cooled fast reactor cores, based on the French ASTRID design, are proposed for burning TRUs (phase-out option) or only MAs (on-going option). Main attention is focused on the safety and on the transmutation performance. The coolant void effect, in the region including the core and the plenum above and the Doppler constant of both systems are negative also with irradiated fuel. The conversion ratios (CR) of the Pu and MA burners are in the ranges from 0.6 to 0.7 and from 0.5 to 0.6, respectively. These results show a large safety and transmutation potential of ASTRID type reactors.

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Keywords: Sodium fast reactors; Nuclear reactor safety; Nuclear fuel cycle; Transmutation

* Corresponding author. Tel.: +49-721-608-22491; fax: +49-721-608-23824.
E-mail address: fabrizio.gabrielli@kit.edu

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1. Introduction

Fast reactors may allow fulfilling a wide range of different goals such as breeding of fissile material or burning of all trans-uranium elements (TRUs) or mainly Minor Actinides (MAs). The introduction of critical fast reactor (FR) burners in Partitioning and Transmutation (P&T) strategies aims at minimizing the radioactive waste in the fuel cycle and reducing the burden on SNF disposal [1, 2]. The P&T technologies are developed to extract the TRUs, i.e. Plutonium and MAs, from the spent nuclear fuel (SNF) discharged from LWRs and later FRs (Partitioning) and to "transform" this material (Transmutation) into fission products in dedicated FR burner facilities. This approach may be employed within different fuel cycle strategies: countries with on-going scenarios (continuous use of nuclear energy) aim at optimizing the fuel cycle by stabilizing the MAs mass while a strong reduction of the TRUs in the final repository is considered in the countries in phase-out. Both targets can be achieved, as shown in the following, by employing dedicated FRs loaded with different amounts of Pu and MAs in a closed (or partially closed) fuel cycle [1, 3].

In this work we propose two 1200 MWth sodium-cooled FR cores with a negative coolant void effect, in case both the core and the plenum above it are voided, for transmuting either all TRUs or mainly MAs, in view of their employment in phase out and on-going scenarios [4]. The core designs are based on the French ASTRID sodium-cooled FR core concept [5], including a large sodium plenum and two inner and outer radial core zones with different heights and Pu enrichments. The objective of the work is the assessment of two reactor systems with different MA to Pu ratios in the fuel for phase-out and/or on-going scenarios: the Pu burner allows a drastic reduction of the Pu mass in the cycle, while the MA amount stays almost unchanged; the MA burner allows reducing the MA mass in the cycle, while Pu is considered as a resource. Depending on the scenario either a combination of Pu and MA burners (or similar systems with an intermediate fuel composition) or MA burner only can be used. Having this in mind, the burning performance and the safety level, in particular related to the coolant void effect, of the two systems are investigated.

2. Assessment of the ASTRID-like models

The 3D (HEX-Z) ASTRID-like models for Pu and MAs burning have been assessed by means of the European Reactor Analysis Optimized System (ERANOS) code [6]. The 33 energy groups effective neutron-cross sections (XSs) have been processed with the European Cell Code (ECCO) [7], the JEFF3.1 nuclear data library [8] being employed, and neutron transport calculations have been performed by means of the VARIANT code [9, 10]. The models are based on the 1500 MWth French ASTRID CFV (Coeur à Faible effet de Vide, i.e. low sodium void core) concept developed by CEA with support of AREVA and EdF as described in [11, 12]. The ASTRID core layout in plane is shown in Figure 1 [11].

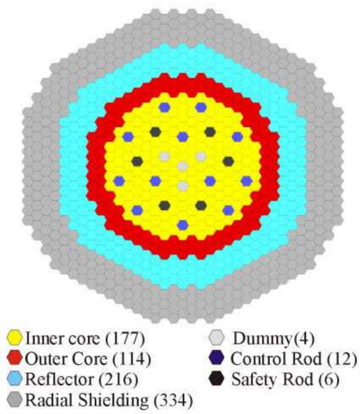

Fig. 1. Layout of the ASTRID core [11]. The number of SAs in each region is indicated.

An important parameter for assessing a FR burner transmutation performance is its conversion ratio (CR), defined here following [3] as the ratio of the TRU production (from U) rate to the TRU destruction rate (mainly due to TRU fission). Unlike ASTRID, that has been optimized for energy production and CR=1, the ASTRID-like transmuters herein proposed are assessed for achieving a low CR (0.5-0.7) without a significant power reduction as compared to ASTRID. This has been done by increasing the TRU content, while reducing the core height in order to compensate the reactivity increase (due to the increased Pu content) and the deterioration of safety parameters due to introduction of MAs into fuel. The fissile core height has been reduced by about 20%, and the thermal power has been reduced by 20% to 1200 MWth to get a similar power density as in the original ASTRID design. As a result, the active heights of the inner and outer core regions are 50 and 70 cm, respectively. The main geometrical characteristics of the ASTRID-like burners are given in Table 1 and the axial layout of such systems is shown in Figure 2. In order to reduce the CR value of the system, the internal fertile blanket has been removed and the height of the lower blanket has been reduced to 2 cm. Further, the depleted U in the lower blanket is homogeneously mixed with MAs (10 wt.%) to further improve the core safety and proliferation performance, following an earlier study performed for the European Sodium Fast Reactor (ESFR) project [14]. The introduction of MAs makes the spectral component of the sodium void effect more positive, the exclusion of the fertile blanket makes the leakage component less negative, while the decreased core height makes the leakage component of the void effect more negative, the total variation of the void effect being positive. As a result the void effect is slightly negative for the considered case, while it is strongly negative for the initial ASTRID design. The batch loading scheme of the burners has been modified as compared to ASTRID. The fuel elements in the ASTRID-like burners are assumed to stay in the reactor at operating conditions for 5 cycles of 365 effective full power days (EFPDs) plus 5 years of cooling.

Table 1. Main geometrical parameters of the ASTRID-like burners.

Parameter	ASTRID-like burners
Number fuel pins per SA	217
Outer pin diameter (mm) [13]	8.45
Pin pitch (cm)	1.08
Inner/outer fuel Sas	177/114
SA pitch (cm)	17.5
Inner/outer core height (cm)	50/70

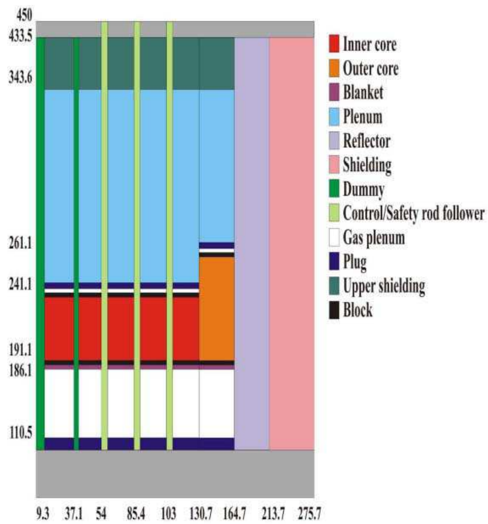

Fig. 2. Axial layout of the ASTRID-like core (dimensions in cm not in scale).

It is important to mention that the calculation results are of course affected by nuclear data uncertainties in particular when systems loaded with large amount of MA are considered. This is a well-known problem as shown in e.g [15]. Nevertheless sensitivity analyses of the results, in particular related to the coolant void effects, are beyond the scope of this work which aims at a preliminary assessment of the transmutation and safety potential of the ASTRID-like cores.

2.1. Transmutation Fuel

The ASTRID-like cores are homogeneously loaded with a mixed U-TRU oxide (MOX) fuel. Depending on their mission, the fuel of the two models is composed by different relative amounts of MAs and Pu. A low MA to Pu ratio (MA:PU=1:20) is employed in the Pu burner since such system is assessed for drastically reducing the TRU from spent fuel where Pu mass is the main component. On the contrary, a larger MA to Pu ratio (MA:PU=1:2) is used in the MA burner since such system aims significantly reducing the MA mass in the cycle, keeping Pu as a resource. In our investigations, we have considered the Pu and MA isotopic vectors corresponding to those in MOX SNF reprocessed after 30 years after irradiation in a PWR, i.e. with a burn-up of about 45 MWd/kg [16]. These vectors have been used in the past for design studies of the subcritical European Facility for Industrial Transmutation (EFIT) [16]. The Pu and MA ASTRID-like/EFIT vectors are compared in Tables 2 and 3 with those of German and French SNF in average under some assumptions (German SNF ca. 50 years after phase-out [17], French SNF from a 400 Twhe PWR park with a 60 GWd/t burn-up after 50 years cooling [18]). It can be seen that the EFIT vector is conservative because of the lowest fraction of fissile Pu isotopes. The fact that the EFIT vector is a reasonable assumption is also confirmed by fuel cycle studies described in [4].

Table 2. Isotope-wise composition (wt.%) of the Pu vectors employed at BOL in ASTRID-like burners, and evaluated for the German [17] and French [18] SNF.

Isotope	ASTRID-like	German SNF [17]	French SNF [18]
^{238}Pu	3.7	2.45	4.5
^{239}Pu	46.4	52.49	59.83
^{240}Pu	34.1	32.19	18.47
^{241}Pu	3.8	0.9	0.00
^{242}Pu	11.9	11.97	0.00

Table 3. Isotope-wise composition (wt.%) of the MAs vectors employed at BOL in ASTRID-like burners, and evaluated for the German [17] and French [18] SNF.

Isotope	ASTRID-like	German SNF [17]	French SNF [18]
^{241}Am	75.5	63.8	62.07
^{242m}Am	0.3	0.1	0.05
^{243}Am	16.1	10.7	8.62
^{237}Np	3.9	24.4	28.54
^{243}Cm	0.1	0.0	0.05
^{244}Cm	3.0	0.5	0.32
^{245}Cm	1.1	0.5	0.32
^{246}Cm	0.1	0.0	0.05

3. Transmutation performance

The core reactivity, reactivity effects, and variations in the fuel isotopic composition during reactor operation for the ASTRID-like Pu and MA burners have been evaluated by performing 3D (HEX-Z) transport calculations by means of the ERANOS code. The main characteristics of the ASTRID-like burners are shown in Table 4. The inner/outer TRU enrichments of the Pu (MA:Pu=1:20) and MA burners (MA:Pu=1:2) are 25/27 wt.% and 22.5/24.5 wt.%, respectively, in order to be critical after 3 irradiation cycles which is considered as an approximation for the End of Equilibrium Cycle (EOEC) for FR systems with a 5-batch scheme. The U, Pu, and MAs inventories at the Beginning of Life (BOL) are provided in Table 4 for each core region, including the lower axial blanket. The reactivity loss (pcm) per EFPD is higher for the Pu than for the MA burner because of the higher Pu content. Results show that the CR (5 years of cooling assumed) of the Pu burner is about 0.68 and almost no MAs are produced or destroyed, since CR(Pu)=CR(TRUs). The MA burner mainly transmutes MAs (CR(MAs)=0.55) while a small amount of Pu is burned (CR(Pu)=0.9).

Table 4. Main parameters of the ASTRID-like Pu and MA burners.

Parameter	Pu burner	MA burner
Fuel type	$(U\text{-}TRU)O_2$	$(U\text{-}TRU)O_2$
Power (MWth)	1200	1200
MA:Pu ratio	1:20	1:2
U inventory at BOL (tons)	$6.8^a/5.9^b/0.3^c/0.2^d$	$6.1^a/5.2^b/0.3^c/0.2^d$
MAs inventory at BOL (tons)	$0.12^a/0.12^b/0.03^c/0.02^d$	$1.1^a/1.1^b/0.03^c/0.02^d$
Pu inventory at BOL (tons)	$2.4^a/2.4^b/0.0^c/0.0^d$	$2.2^a/2.2^b/0.0^c/0.0^d$
TRU enrichment (wt.%)	25/27	22.5/24.5
Conversion Ratio	0.68(Pu)/0.68(TRUs)	0.9(Pu)/0.55(TRUs)
Cycle length (EFPD)	365	365
Average fuel residence time (days)	3650	3650
Average discharge burn-up (MWd/kg)	100/137	100/133
Reactivity loss (pcm/EFPD)	7.8	2.7

^{a}Inner Core ^{b}Outer Core ^{c}Inner axial blanket ^{d}Outer axial blanket

The element- and isotope- wise consumptions of TRUs in the full core (fuel and blankets) are shown in Table 5. Results for the Pu burner shows that the mainly burns Pu only. The Pu consumption (-13.2 kg/TWh) comes from ^{239}Pu, ^{240}Pu, and ^{242}Pu. The main contribution to the MAs consumption comes from ^{241}Am, while ^{243}Am and ^{244}Cm are mainly produced. For the MA burner, the total consumption of MAs is -15.4 kg/TWh, the largest contribution coming from ^{241}Am and ^{243}Am. A small amount of Np is burned while ^{244}Cm is produced. Concerning the Plutonium mass balance, the ^{238}Pu production is compensated by the ^{239}Pu and ^{240}Pu consumption.

Table 5. Isotope- and element-wise TRUs consumption (kg/TWh) in the ASTRID-like burners after 5 irradiation cycles and 5 years cooling.

Parameter	Pu burner	MA burner
^{238}Pu: ^{239}Pu: ^{240}Pu: ^{241}Pu: ^{242}Pu	-0.63:-8.21:-2.82:0.26:-1.83	5.87:-6.75:-2.09:-0.63:-0.15
Total Pu	-13.2	-3.7
^{241}Am: ^{242m}Am: ^{243}Am	-1.79:0.12:0.76	-15.04:0.70:-1.93
Total Am	-0.9	-16.3
^{237}Np: ^{238}Np: ^{239}Np	-0.09:0.17:0.05	-0.49:0.16:0.00
Total Np	0.1	-0.3
^{242}Cm: ^{244}Cm	0.18:0.54	0.00:1.06
Total Cm	0.8	1.2
Total elements	-13.2	-19.1

In order to evaluate the potential of the Pu and MA ASTRID-like burners as transmutation facilities, they have been employed in preliminary analyses of hypothetical phase-out and on-going scenarios [4]. As an example of phase-out scenario, it is assumed in [4] that the German TRU inventory from the LWR SNF (137 tons of Pu and 38 tons of MAs in 2075) should be burned in about 150 years [1, 3, 19]. Note that the last nuclear reactor in Germany is planned to be stopped in 2022, the Pu and MA inventories are stabilized later, mainly due the ^{241}Pu to ^{241}Am decay. The results in [4] show that a fleet of four to five Pu burners and two MA burners working for 150 years are able to fulfill this mission. As an example of on-going scenario, case studies done in the past [14] has been considered in [4]. The analyses show that the MA inventory is reduced with the same rate by using either three ASTRID-like MA burners or six larger ESFR-like units homogenously loaded with a smaller fraction of 5% of MA in the core [4]. The results therefore show that a combination of these ASTRID-like models can be used to burn TRUs unloaded from LWRs for any realistic scenario. In particular the Pu and MA burners could be used in phase-out scenarios for burning all TRUs, while the MA burner could be employed in on-going scenarios for stabilizing the MA mass with no significant consumption of Pu. Note that the TRU isotopic composition varies with time, so the employment of different systems or fuels may vary with time too.

4. Safety performance

The evaluation of the safety level of any nuclear reactor system requires the analysis of major possible accidental evolution patterns. As shown in [20], the reactivity effects induced by the different phenomena occurring during accidental transient may compensate each other. For example, a typical scenario for an ULOF in a critical sodium-cooled FR, is that several competing reactivity effects, e.g Doppler feedback and axial fuel expansion, limit a reactivity insertion coming from a coolant density reduction.

Having this in mind, the main safety-related parameters (including the Doppler constant and coolant void reactivity effect) of the ASTRID-like burners have been evaluated at BOL and at EOEC for the 3D (HEX-Z) models by means of the ERANOS code. The effective delayed neutron fraction (β_{eff}) and the mean neutron generation time (Λ) of the Pu burner at BOL are 331 pcm and 0.66 μs, respectively. The larger amount of MAs in the MA burner (MA:PU=1:2) leads to a smaller value of these parameters (β_{eff}=275 pcm, Λ=0.42 μs). The results show no significant degradation of the kinetics parameters during irradiation: the βeff at EOEC of the Pu and MA burners is 328 pcm and 272 pcm, respectively, and Λ is 0.63 μs and 0.47 μs, respectively.

The results of the original ASTRID core [21] at BOL and of a preliminary safety assessment for the Pu and MA burners at BOL and at EOEC3 are shown in Table 6. The Doppler constant (K_D) of the Pu burner is about twice as high as one in the MA burner because of the larger amount of MAs loaded in the fuel. It is important to observe that K_D does not deteriorate during irradiation in both systems.

Also the Sodium Void Reactivity Effect (SVRE) and the extended SVRE have been evaluated. With SVRE, we refer to the voiding of the total active height for the inner and outer fuel zones. The void is considered only inside the SAs wrappers, i.e. sodium between SAs is not removed. With extended SVRE, in addition to the active height, we refer to the voiding in the above structures. Also in this case, the void is considered inside the SAs wrappers only. For calculations, the self-shielded neutron XSs for the sodium plenum have been processed by assuming a bulk of homogeneous mixture of stainless steel and coolant. The use of such approximation in the analyses of the ESFR core did show to provide similar results to MCNP for what concerns the coolant void effect in the plenum [22]. The analysis of the coolant void effect shows a potentially high safety level of the ASTRID-like cores. The SVRE and the extended SVRE are shown in Table 6 in dollar units (1\$=β_{eff}).

Table 6. Doppler and void reactivity effects for the original ASTRID design at BOL [21] and for the ASTRID-like Pu and MA burners at BOL and EOEC3.

	Original ASTRID [21]	Pu burner		MA burner	
Parameter	BOL	BOL	EOEC3	BOL	EOEC3
K_D (pcm)	~-870	-571	-540	-275	-272
SVRE ($)	+2.2	+3.1	+4.0	+5.9	+6.1
Extended SVRE ($)	-2.9	-3.4	-2.6	-0.3	-0.6

If the core is voided, the coolant void worths at BOL for the Pu and MA burners are ~3$ and ~6$, respectively, and increase by about 1$ at EOEC in the Pu burner. If the upper plenum is also voided, the total void worth is negative for the Pu and MA burners at BOL (~-3.4$ and ~-0.3$) and at EOEC (~-2.6$ and ~-0.5$). As expected, the introduction of MAs in the ASTRID-like burners deteriorates the safety parameters compared with the original ASTRID.

Nevertheless, such comparison is not fair because of the quite different fuel compositions employed. In order to have a more suitable comparison, the safety parameters of the ASTRID-like burners at BOL are compared in Table 7 with the results for the modified configurations of BN-600 [18] and ESFR (called CONF-2) [22] MOX cores loaded with MAs.

Table 7. Doppler and void reactivity effects at BOL for the ASTRID-like burners, the BN-600 core [18], and the ESFR CONF-2 [22] core.

Parameter	Pu burner	MA burner	BN-600 [18]	ESFR CONF-2 [22]
K_D (pcm)	-571	-275	-384	-712
SVRE ($)	+3.1	+5.9	+5.2	+5.0
Extended SVRE ($)	-3.4	-0.3	+4.4	+2.9

The TRU content in the BN-600 core model described in [18] vary from about 26% to 30 % with about 6% to 7% of MAs. Several measures have been adopted to reduce the Na void effect in BN-600, namely a reduction of the fissile core height, the incorporation of a Na plenum above the core, and the elimination of the upper axial and internal fertile blanket. The TRU content inner and outer core of the ESFR CONF-2 is 14.76 % and 17.15 %, respectively, and 4 % of Am (76%:24%, ^{241}Am:^{243}Am) is homogeneously loaded in the core. As shown in [22], core structure modifications have been employed in order to reduce the SVRE. The results in Table 7 for the BN-600 refer to average values computed in the framework of a benchmark exercise [18], the first-order perturbation theory being employed. Results for ESFR CONF-2 [22] refer to 3D (HEX-Z) direct transport calculations performed by means of the ERANOS code, the JEFF-3.1 nuclear data library being employed. Results provide a coherent picture of the safety margins of the ASTRID-like burners. The KD parameter for the Pu burner lies between the BN-600 and ESFR CONF-2 values, because of the intermediate TRU enrichment (25%/27%) and MA content (5%). As expected, the Doppler effect in the MA burner is lower compared with the TRU burner because of the larger MA content. Results in Table 7 show that the void reactivity effects for the ASTRID-like burners are more favorable compared with BN-600 and ESFR CONF-2. The reason is due to fuel composition and core geometry. Since the active core height of the ASTRID-like burners (see Table 1) is lower than in BN-600 (87.4 cm) and ESFR CONF-2 (100 cm), the SVRE and extended SVRE for the Pu ASTRID-like burner is lower than those for BN-600 and ESFR CONF-2. Results in Table 7 also show that the effect of the upper plenum voiding in the ASTRID-like burners (~-6 $) is stronger than those in BN-600 (-0.8 $) and ESFR CONF-2 (-2.1 $). In addition to the core height, also the plenum height plays a role: the BN-600 (23 cm) plenum is smaller compared to ESFR CONF-2 (60 cm [22]) and ASTRID-like (95 cm and 76 cm in the inner and outer core, respectively) cases.

A detailed investigation of the spatial distribution of the coolant void reactivity has been also performed. Figure 3 shows the average coolant void worth per fuel SA (pcm) in each fuel ring at BOL in the ASTRID-like burners (inner core up to ring number 8) if only the core is voided. The results are typical for FR systems, namely higher values in the core center and lower at the periphery.

The spatial distributions of the coolant void reactivity has been evaluated by performing 3D (HEX-Z) exact perturbation calculations by using the KIN3D [23] extension of the VARIANT code. Results have been then obtained by using a SAS4A Interface to Reactor Data Evaluated Using the Nuclear Code System ERANOS (SIRENE) [24]. The calculation cells have the same volume. The coolant void reactivity in each calculation cell for the MA burner at BOL is shown in Figure 4 for the corresponding axial layout. The purple zones in Figure 4 refer to the regions where no coolant density perturbation has been considered, namely the control and safety rods, the diluent SAs, and the gas plena. Results show a quite homogeneous distribution of the reactivity contributions which are positive mainly in the inner and outer core center (red and orange regions) peaking to about 4 pcm. Due to neutrons escaping from the core, the reactivity contributions are negative in the lower part of the outer core region (gray) as well as in the upper part of the core (green region). The most negative contributions (dark blue and black regions) appear near the step between the inner and outer core regions because of the largest neutron leakage there. Similar results have been observed for the Pu burner. Preliminary analyses have been performed concerning the evaluation of other parameters, such as flux shape tilt and control rod worth, the results being encouraging.

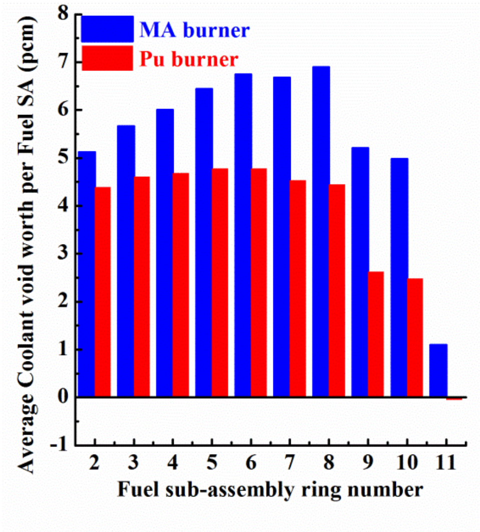

Fig. 3. Average coolant void worth (pcm) per fuel SA in the ASTRID-like burners.

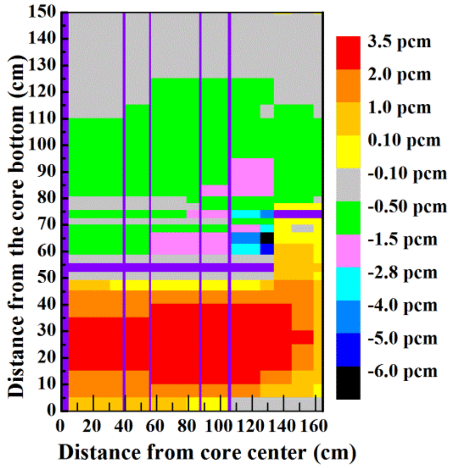

Fig. 4. Axial layout of the cell-wise coolant void reactivity effect (pcm) in the MA burner model.

5. Conclusions

Two ASTRID-like core models for burning Pu and MAs have been assessed for on-going and phase-out nuclear scenarios. With this aim, the transmutation performance and safety-related parameters of these models has been investigated. The results of this and other studies [3, 4] show that an employment of these systems together with fuel reprocessing and fabrication facilities can drastically reduce the TRU mass and the burden on a nuclear waste repository. Alternatively, systems of single type can be used at each time in a TRU burning scenario, provided that proper choices of the MA to Pu ratios and TRU fractions in MOX, intermediate to those for ASTRID-like burners, are used. The safety performance of the two systems seems to be reasonable and the safety parameters do not significantly deteriorate during irradiation. The Doppler constant is negative as well as the coolant void effect. The analyses of the spatial distribution of the coolant void reactivity do not show possibility for a large positive reactivity increase due to sodium boiling onset after a hypothetical accident. More investigations are necessary to optimize the core as concerns the power profile and the potential flux tilting effects in the close to pancake-type geometry. Moreover, the TRU composition and Control Rod efficiency should be further investigated. The paper provides a basis for performing scenario analyses which should confirm the trend observed with the neutronic calculations.

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