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ANALYSIS OF TRANSITION SCENARIO FROM A PWR TO A SFR FLEET SIMULATED WITH THE CLASS CODE

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One evolution envisaged in France for electronuclear fleets considers the deployment of ASTRID-like Sodium Fast Reactor (SFR). Fuel cycle prospective studies involving this SFR integrated into a Pressurized Water Reactor (PWR) fleet is one way to evaluate such strategies. This paper presents two scenario analysis exploring effects on in-cycle plutonium quantity and quality of ASTRID-like reactor parameters and cycle parameters such as SFR spent fuel reprocessing. On one hand, under specific conditions, cycle strategies impact ASTRID-like behavior, however, on the other hand, the fuel cycle is also strongly dependent on ASTRID-like operation.

I. INTRODUCTION AND MOTIVATIONS

The transition from a Pressurized Water Reactor (PWR) fleet to a Generation IV Sodium Fast Reactor (SFR) fleet is one of the potential strategies explored in many countries^{1,2}. Depending on possible futures for the global electronuclear industry, the evolution of nuclear energy production could lead to strain access to natural resources like natural uranium. Thus, plutonium multi-recycling in dedicated reactors, like Generation IV SFRs, may become necessary leading potentially to a closed fuel cycle.

However, just like the global nuclear energy evolution, the need of a transition to a full SFR fleet is unsettled. In this context, a waiting strategy involving the integration of few SFRs into a PWR fleet should be investigated. Strategy evaluations based on scenario studies are one way to assess these questionings. This paper discusses scenarios involving the integration of some SFRs into a full PWR fleet to see if a small proportion of SFRs in the cycle may be a game changer in the plutonium handling for PWR to SFR transitions.

All the scenarios are simulated with the dynamic fuel cycle simulation tool CLASS^{3,4}. These scenarios describe transitions from a whole PWR fleet loaded with UOX and MOX fuels to a potential mix containing SFRs. Part II of this paper briefly describes the reactors deployed and the CLASS code. After that, transition parameters are presented in part III. SFRs' impacts on in-cycle plutonium

quantity and quality are first studied without SFR spent fuel reprocessing, in part IV.A, then considering it, in part IV.B. Finally, this work presents an analysis of some steady-state specific characteristics for a mix PWR and SFR fleet in part V.

II. CLASS: METHODS AND SYSTEMS CONSIDERED

The CLASS code is used for electronuclear scenario analyses. It simulates an entire fuel cycle from reactors' fuel fabrication to final storage after irradiations. In CLASS, special attention is cared for reactor irradiation modeling. The main challenges, while considering fuel reprocessing, are the dynamic fuel fabrication and irradiation adapted to available material over time and reactor's characteristics. Indeed, during the fuel fabrication, fuel enrichment should be adjusted from available radioactive materials in storages according to reactors' type specificities. In fact, spent fuel compositions vary at each reprocessing as they depend on the fuel history. Then, fuel irradiation should be simulated for each determined fresh fuel composition. Most of the time, as traditional reactor simulations are time consuming, these steps need, in CLASS, dedicated models using Artificial Neural Network^{6,7} for each reactors' type. In fact, once they are built, these predictors are capable of quasi-instantaneous physic value estimations.

All scenarios presented in this paper integrate three types of reactors: PWR loaded with UOX fuel, PWR and SFR loaded with MOX fuel.

II.A. PWR Modeling

PWRs are representative of typical 900 MWe French PWRs. They are described as macro-reactors into the simulations: there is only one unit for each PWR type representing all independent reactor units. An average homogeneous fuel is built for each macro-PWR cycle. Thus, PWR fuel-loading models determine one fuel enrichment to achieve a targeted reactivity at Beginning Of Cycle (BOC). For each fuel to be tested the

multiplication factor (k_{eff}) predictor is used⁴. Then, PWR irradiation models use mean cross-section predictors to solve the Bateman equations and calculate compositions evolution.

II.B. ASTRID-like reactor presentation

Generation IV SFRs considered in this paper are based on the 600 MWe French “low void effect” ASTRID-V1 concept⁵ developed by the CEA and its industrial partners. As it can be operated as a plutonium breeder, break-even or burner, this reactor concept has gathered attention for its flexibility. The ASTRID concept is adapted to potential strategy changes. In this study, only the ASTRID-like break-even design is used.

To reach a negative void coefficient during irradiation, this design is highly heterogeneous. In fact, it is radially composed of an internal and an external core with two plutonium contents and several fissile and fertile fuel zones are axially visible. The ASTRID-like break-even design is shown on Fig 1.

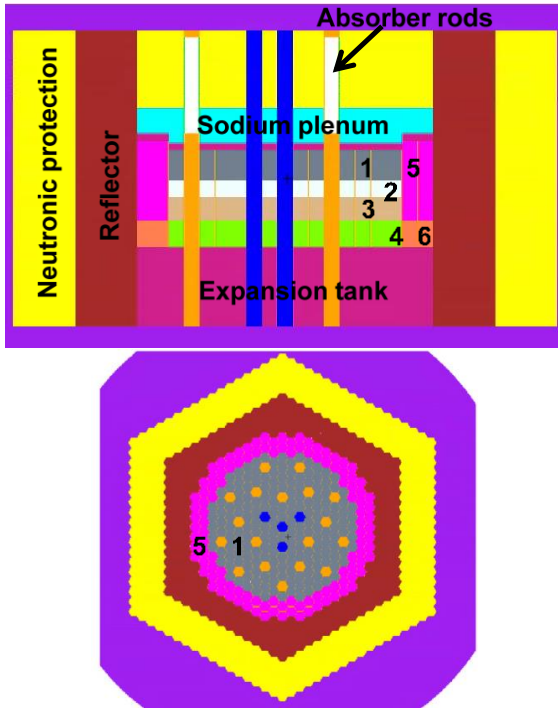


Fig 1. Axial (on the top) and radial (on the bottom) layouts of ASTRID-like break-even core

Six fuel zones can be defined in the ASTRID-like design. The three fertile fresh fuel compositions (Zone 2, 4, 6) are always depleted uranium containing 0.2% of ^{235}U . Then, this SFR manages a wide variation of plutonium isotopic compositions into its three fissile fuel zones (Zone 1, 3, 5).

II.C. ASTRID-like reactor modeling

1000 ASTRID-like fresh fuel compositions have been sampled by the Latin Hypercube Method⁹ inside the ranges presented in TABLE I. These ranges cover the possible fresh SFR’s fuels that may appear during scenarios by reprocessing UOX and MOX spent fuels with different histories.

TABLE I. Ranges used for fresh fuel considered in the break-even ASTRID-like study

	Min / Max (%)		Min / Max (%)
^{238}Pu	1 / 8	^{242}Pu	5 / 17
^{239}Pu	3 / 74	^{241}Am	0 / 15
^{240}Pu	20 / 40	$T_{\text{Pu}}^{\text{int}}$	15 / 40
^{241}Pu	0 / 17	$T_{\text{Pu}}^{\text{ext}}$	15 / 40

Full core depletion simulations up to 115 GwD/t have been computed for the 1000 compositions with the VESTA¹⁰ code, VESTA using Monte-Carlo calculations performed here by the MCNP code. These depletion simulations show that the six fuel zones have very different behaviors, which can change during irradiation, as depicted in Fig 2 for one example. This is due to the initial compositions loaded and the fuel interactions in reactor.

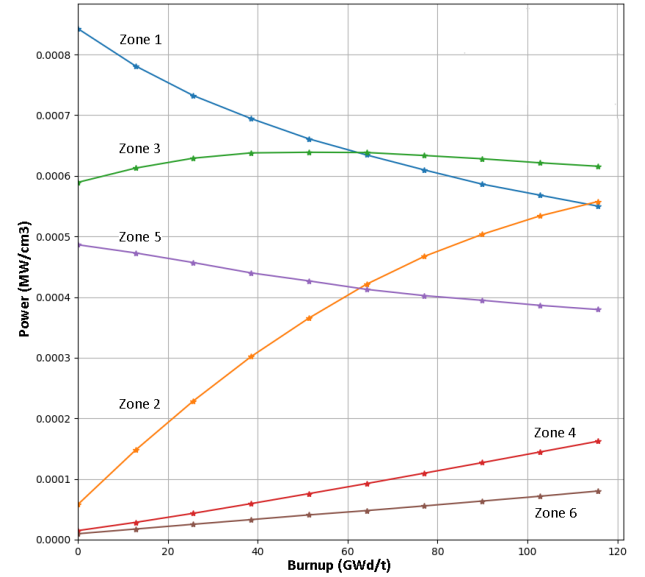


Fig 2. Evolution of the fuel zone’s powers during irradiation for one composition

Besides, the analysis of the internal (zones 1 and 3) and the external (zone 5) fissile powers (P_{int} and P_{ext}) at BOC as a function of the ratio between the internal and the external plutonium contents at BOC ($T_{\text{Pu}}^{\text{int}}$ and $T_{\text{Pu}}^{\text{ext}}$) as expressed in Eq. (1), shows that for a specific ratio P_{int} and P_{ext} are fixed and unique at BOC, as depicted in Fig 3.

$$x_T = \frac{T_{\text{Pu}}^{\text{int}}}{T_{\text{Pu}}^{\text{ext}}} \quad (1)$$

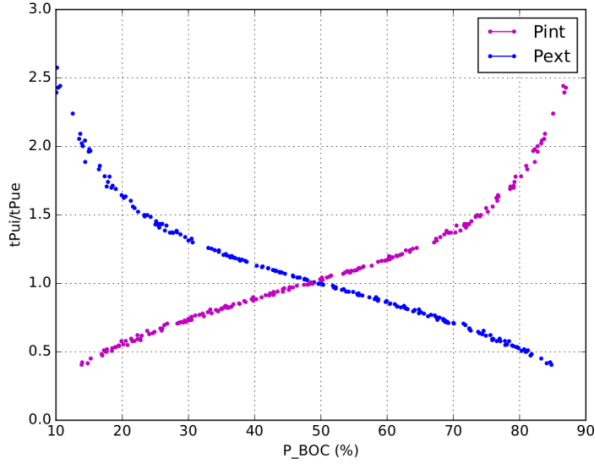


Fig 3. Evolution of fissile powers at 0 GWd/t for different ratio of plutonium contents

Hence, to reliably simulate ASTRID-like reactor in scenarios new multi-zone fuel irradiation and fuel fabrication models have been implemented in the CLASS code. The multi-zone irradiation model⁸ for ASTRID-like reactors uses cross-section and flux predictors to solve the Bateman equations per fuel zone. Those predictors are Artificial Neural Networks generated on the database composed of the 1000 depletion simulations already mentioned. Induced deviations by these predictors on global inventory estimation compared to depletion simulation stays under 3% for the main actinides.

The fuel loading model is more complicated than in Leniau *at al.*⁴ for PWR, which considers a mean fuel for the core. Thus, existing models determine only one plutonium content. For the new SFR model, two plutonium contents have to be determined, and then two criteria are needed. The first one remains the criticality (as for PWR): a targeted k_{eff} at BOC is defined. The second one corresponds to the power distribution inside the reactor defined as a targeted zone power at BOC defining x_T .

The mean plutonium content (T_{Pu}^{moy}) can be expressed as described in Eq. (2), with M^{int} , M^{ext} , M^{tot} respectively the internal, the external, the total fissile masses and M_{Pu}^{tot} the total plutonium mass in all fissile fuel zones. M^{int} , M^{ext} , M^{tot} are fixed by the reactor design, they are known values. The formulas used to calculate T_{Pu}^{int} , T_{Pu}^{ext} and the internal and external masses of plutonium (M_{Pu}^{int} and M_{Pu}^{ext}) are respectively presented in Eq. (3), (4), (5) and (6).

$$T_{Pu}^{moy} = \frac{T_{Pu}^{int} \cdot M^{int} + T_{Pu}^{ext} \cdot M^{ext}}{M^{int} + M^{ext}} = \frac{M_{Pu}^{tot}}{M^{tot}} \quad (2)$$

$$T_{Pu}^{ext} = T_{Pu}^{moy} \cdot \frac{M^{int} + M^{ext}}{x_T \cdot M^{int} + M^{ext}} \quad (3)$$

$$T_{Pu}^{int} = x_T \cdot T_{Pu}^{ext} \quad (4)$$

$$M_{Pu}^{ext} = M_{Pu}^{tot} \cdot \frac{1}{1 + \frac{M^{int}}{M^{ext}} \cdot x_T} \quad (5)$$

$$M_{Pu}^{int} = M_{Pu}^{tot} \cdot \frac{\frac{M^{int}}{M^{ext}} \cdot x_T}{1 + \frac{M^{int}}{M^{ext}} \cdot x_T} \quad (6)$$

In the multi-zone fuel fabrication model, the initial T_{Pu}^{moy} is taken equal to a chosen value, for example 40%, see TABLE I. It allows the determination of fissile fuel compositions to be tested. The model then calls an Artificial Neural Network to predict the k_{eff} , at BOC, associated with that fuel. The prediction is then compared with the target value and T_{Pu}^{moy} is accordingly adjusted. These steps are iterated until a chosen tolerance criterion is met.

The k_{eff} predictor has been generated on the database built from the 1000 depletion calculations. Its accuracy has been verified on 200 independent full core depletion simulations, up to 115 GWd/t, made with the VESTA code; resulting values are taken as a reference in accuracy estimation. The 200 corresponding fresh compositions have also been sampled by the Latin Hypercube Method⁹ inside the ranges presented in TABLE I. For the 200 k_{eff} values the predictor induced deviations (D_k) are calculated with the formula (7).

$$D_k = \frac{k_{eff}^{pred} - k_{eff}^{VESTA}}{k_{eff}^{VESTA}} \quad (7)$$

Fig 4 presents the predictor-induced deviations on k_{eff} at BOC. The mean value is close to zero meaning that no systematic bias is introduced. Then, the standard deviation of the distribution is 132 pcm. This value is one order of magnitude higher than the statistical uncertainty of this ASTRID-like design, which is 15 pcm at BOC and limited to 30 pcm during irradiation. This statistical uncertainty has been calculated here for the reference ASTRID composition, presented in (Ref.8), for 50 different random seeds. However, an induced error of 132 pcm is judged acceptable for a fuel-loading model used in scenario study.

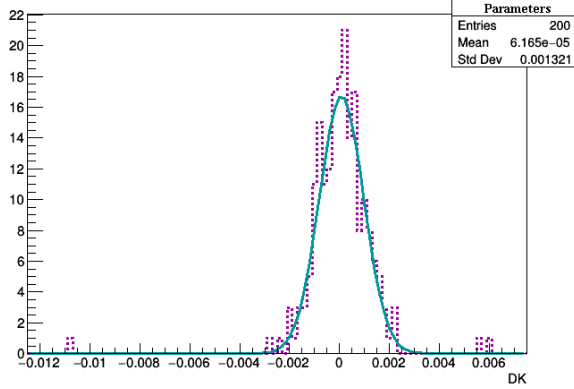


Fig 4. Predictor induced deviations on k_{eff} at 0 GWd/t in magenta and associated Gaussian fit in turquoise

III. SCENARIO DEFINITION

This paper presents the analysis of two scenario families describing over 120 years a transition from a full PWR fleet loaded with UOX or MOX fuels to a potential mix containing SFRs. It aims at understanding the impact of the introduction of ASTRID-like SFRs on in-cycle plutonium in mix fleet containing PWRs and SFRs. For each scenario family, different variables are sampled; however, to simplify the simulations some parameters are fixed:

- all fresh fuels are built in different fabrication plants (FP) in 2 years and PWR spent fuels are cooled 5 years in pools,
- UOX fuel is built from an infinite stock of natural uranium,
- MOX fresh fuels are mainly built from UOX spent fuel with a LIFO strategy *i.e.* Last fuel arrived In stock First fuel Out,
- all reactors load factors are taken equal to 1,
- macro-PWRs heavy metal mass is proportional to 72.3 t, its power is proportional to 2785 MW_{th}. The proportionality constant depends on the number of single units replaced that is to say , N_{UOX} and N_{MOX} , defined in the next paragraph,
- each SFRs heavy metal mass is equal to 39 t, its power is 1490 MW_{th},
- PWR-MOXs burnup is set equal to 45 GWd/t and SFRs burnup is fixed at 100 GWd/t.

The first family keeps the total power equal to an arbitrary value of 100 GW_{th} with a deployment of SFRs after 70 years as illustrated in Fig 5.

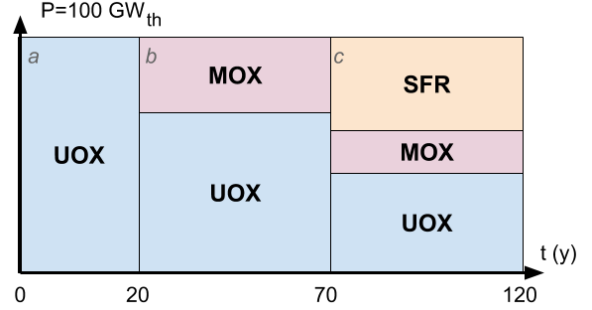


Fig 5. Schematic representation of the fleet evolution in the first scenario family

During the 20 first years, phase a, the power is only produced by PWR loaded with UOX fuel. Thus, N_{UOX}^a , the number of PWR-UOX represented by the UOX macro-PWR, corresponds to the ratio between total fleet power and PWRs power as expressed in Eq. (8). Phase b lasts 50 years; the fleet is then a PWR mix. N_{UOX}^b and N_{MOX}^b are calculated with the formula (9) with F_{MOX}^b the fraction of total power produced by PWR-MOX in phase b. SFR are instantaneously deployed as phase c starts, this phase also lasts 50 years. As SFR are single reactors, N_{SFR}^c used the floor function on the SFR fraction, F_{SFR}^c , representing the fraction of total power produced by SFR as shown in Eq. (10). It induces the calculation of a corrected SFR fraction, F'_{SFR}^c . From this corrected fraction, N_{UOX}^c and N_{MOX}^c are respectively calculated with Eq. (12) and Eq. (11) assuring that the ratio between PWR-UOX fraction and PWR-MOX fraction remains constant. The fraction of total power produced by PWR-MOX in phase c is called in F_{MOX}^c .

$$N_{UOX}^a = \frac{P}{P_{UOX}} \quad (8)$$

$$N_{MOX}^b = \frac{P \cdot F_{MOX}^b}{P_{MOX}}, N_{UOX}^b = \frac{P \cdot (1 - F_{MOX}^b)}{P_{UOX}} \quad (9)$$

$$N_{SFR}^c = \left\lfloor \frac{P \cdot F_{SFR}^c}{P_{SFR}} \right\rfloor, F'_{SFR}^c = \frac{N_{SFR}^c \cdot P_{SFR}}{P} \quad (10)$$

$$N_{MOX}^c = \frac{P \cdot F_{MOX}^b \cdot (1 - F'_{SFR}^c)}{P_{MOX}} \quad (11)$$

$$N_{UOX}^c = \frac{P \cdot (1 - F_{MOX}^b) \cdot (1 - F'_{SFR}^c)}{P_{UOX}} \quad (12)$$

This first scenario family purpose is to analyze the impact of SFR integration into a PWR fleet on plutonium in-cycle composition and quantity. Two cases are distinguishable: either SFR spent fuels are not reprocessed as shown on Fig 6, either they are, as illustrated on Fig 7.

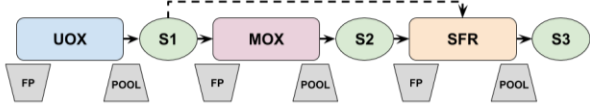


Fig 6. Schematic representation of fuel cycle facilities for the mix fleet without SFR fuel reprocessing, case A



Fig 7. Schematic representation of fuel cycle facilities for the mix fleet with SFR fuel reprocessing, case B

In both case, different variables are sampled by the Latin Hypercube Method⁹. Thiollière *at al.* shows that plutonium inventory is mainly driven by the PWR-UOX burnup (BU_{UOX}) and F_{MOX} in a PWR fleet¹¹. Thus, no other PWR operational parameters are sampled. Operation parameters related to SFRs considered as variable, and then sampled, are:

- F_{SFR}^c implying a variation up to 20 SFRs,
- S_{SFR}^{in} corresponding to the fuel fabrication origin: either PWR-MOX spent fuels stocked in S2 or PWR-UOX spent fuels stocked in S1 and PWR-MOX spent fuels stocked in S2. Thus, SFR fresh fuel is built either only using PWR-MOX spent fuel or using both PWR-UOX and PWR-MOX spent fuels chosen according to the stock management strategy,
- SM_{SFR} the stock management strategy, either LIFO or FIFO i.e. Last or First fuel arrived In stock First fuel Out.

In case B, two variables are added to the sampling:

- TC_{SFR} the SFR spent fuel cooling time,
- S_{SFR}^{out} the SFR spent fuels destination. They can be dumped either in the PWR-MOX spent fuel stock S2 or in the PWR-UOX spent fuel stock S1. In that last case, PWR-MOX fresh fuel are built from PWR-UOX and SFR spent fuels.

Variables and associated ranges are presented in TABLE II. In case A, 988 sets of variables are determined, while in case B, 2000 scenarios are simulated.

TABLE II. Variables sampled in the first scenario family

Variables	Case A	Case B
BU_{UOX} (GWd/t)	[30 ; 65]	[30 ; 65]
F_{MOX}^b (%)	[5 ; 15]	[5 ; 15]
F_{SFR}^c (%)	[0 ; 30]	[0 ; 30]
SM_{SFR}	LIFO – FIFO	LIFO – FIFO
TC_{SFR} (y)	/	[5 ; 10]
S_{SFR}^{in}	S2 – (S1,S2)	S2 – (S1,S2)
S_{SFR}^{out}	/	S1 – S2

IV. IMPACT OF SFR INCLUSION IN PWR FLEET

The following part presents the main results for the first scenario family, case A and B. Outputs of interest are first plutonium quantities managed by SFRs and their impact on plutonium quality and then in-cycle plutonium quantity and quality.

IV.A. Mix fleet without SFR fuel reprocessing

Case A analyses effects induced by SFR integration into a PWR fleet without considering SFR spent fuels reprocessing. First, we focus on ASTRID-like SFR intrinsic behavior regarding plutonium.

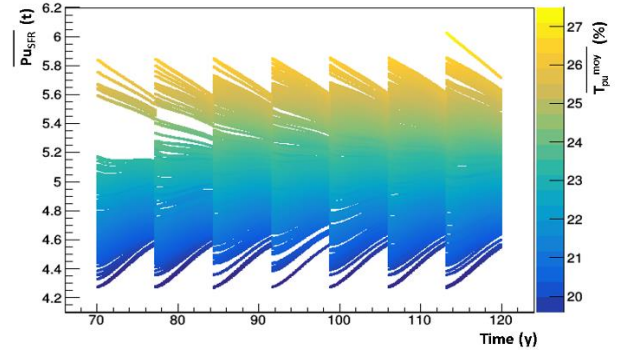


Fig 8. Evolution of plutonium quantity in SFR, colored by the fresh fuel mean plutonium content

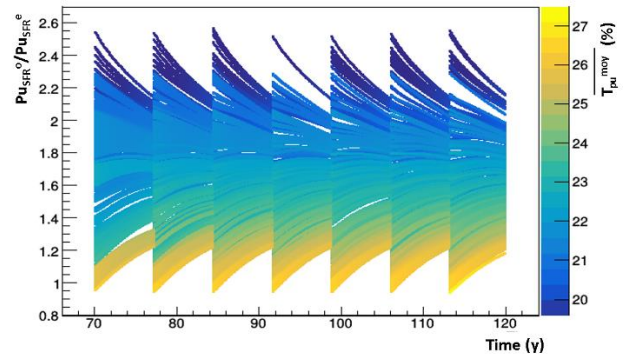


Fig 9. Evolution of plutonium quality in SFR, colored by the fresh fuel mean plutonium content

Fig 8 depicts the variation over time of the plutonium quantity in each SFR. The mean plutonium quantity loaded in SFRs varies between 4 and 6 tons. T_{Pu}^{moy} , represented by the coloration, fluctuates between 20 and 27 %. As a comparison, initial plutonium quantity for ASTRID reference composition, presented in (Ref.5), is 5 tons, and the mean plutonium content is 21.77 %. According to T_{Pu}^{moy} , the SFR behavior changes from plutonium burner, maximum of -300 kg per cycle, to plutonium breeder, maximum of +300 kg per cycle. Knowing that ASTRID-like break-even design produces around 14.4 GWh_e and that one cycle lasts around 7 years, burning and breeding ratios can reach ± 8 g per GWh_e. Breeder behavior is related to low T_{Pu}^{moy} and *vice versa*.

Fig 9 illustrates the variation over time of the plutonium quality, calculated as the ratio between odd plutonium isotope (^{239}Pu , ^{241}Pu) and even plutonium isotope (^{238}Pu , ^{240}Pu , ^{242}Pu) masses. The colorization represents again $T_{\text{Pu}}^{\text{moy}}$. This figure shows that $T_{\text{Pu}}^{\text{moy}}$ is correlated to the ratio between odd and even initial masses: when this latest is close to one, meaning that initial fresh fuel quality is low due to an important proportion of fertile isotopes, the mean plutonium enrichment has to be high enough to reach criticality. In that case, irradiation improves the plutonium quality. In the contrary, for low initial $T_{\text{Pu}}^{\text{moy}}$, reached with high fissile proportion in the initial fresh fuel, the plutonium quality decreases inside the reactor, during irradiation. Thus, the plutonium quality per cycle tends to converge to a standard quality.

S_{SFR} and $S_{\text{SFR}}^{\text{in}}$ are two fuel cycle variables that strongly impact the plutonium quality for ASTRID-like fresh fuel. Fig 10, derived from Fig 8 considers only the stock of PWR-MOX spent fuels to provide plutonium to the SFR fuel fabrication plant.

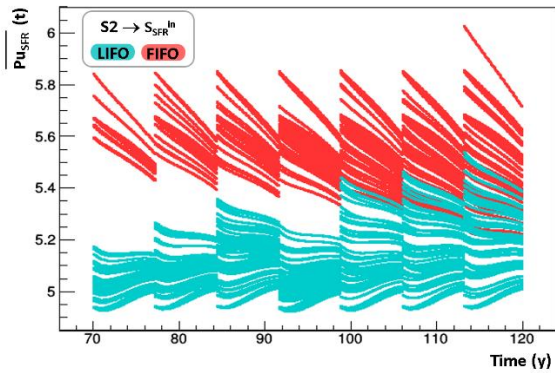


Fig 10. Evolution of plutonium quantity in SFR, when S2 only feeds the SFR fuel fabrication plant

Cyan lines correspond to LIFO strategy, while coral-colored lines are associated with FIFO strategy. The LIFO strategy leads to a reactor close from a plutonium break-even behavior, but FIFO strategy, as older plutonium is used to build SFR fresh fuels, implies an increase of initial plutonium masse loaded leading to a burner behavior. This phenomenon tends to disappear over time while S2 is emptied and all the oldest PWR-MOX spent fuel is used after few ASTRID-like cycles.

The fuel cycle has a strong effect on ASTRID-like SFR behavior, even if this impact dims when stock composition evolves. Then, the total plutonium quantity variation due to ASTRID-like SFRs integration into the fleet may be investigated.

Fig 11 represents the evolution of in-cycle plutonium quantity *i.e.* in reactors, stocks, pools and fabrications plants, depending on BU_{UOX} . A slight slope reduction is visible after PWR-MOX integration and then with SFR integration. In fact, as the total power is kept

constant, PWR-MOX, plutonium burner, and SFR, supposed to be break-even, replace PWR-UOX that are plutonium breeder. As in a PWR fleet¹¹, BU_{UOX} is driving the in-cycle plutonium quantity.

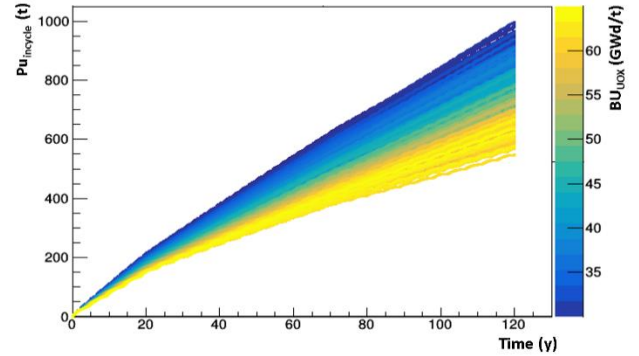


Fig 11. Evolution of in-cycle plutonium quantity depending on PWR-UOX burnup

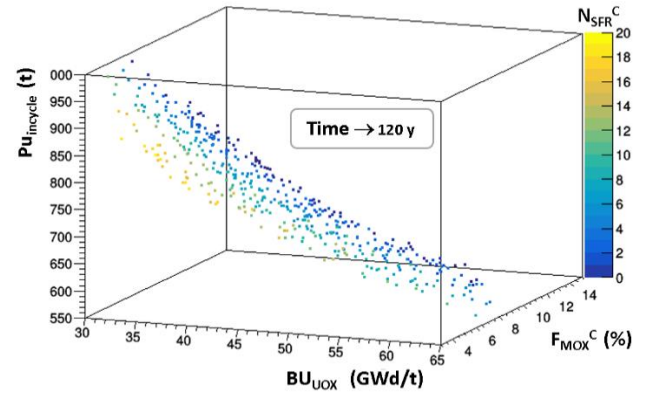


Fig 12. In-cycle plutonium quantity function of BU_{UOX} , $F_{\text{MOX}}^{\text{c}}$ and $N_{\text{SFR}}^{\text{c}}$ at 120 years

Fig 12 shows a selection of in-cycle plutonium quantity at 120 years according to BU_{UOX} , $F_{\text{MOX}}^{\text{c}}$ and $N_{\text{SFR}}^{\text{c}}$. At end of cycle, minimum plutonium in-cycle quantity reaches 500 t and maximal one stays below 1000 t. The behavior of a full PWR fleet is recovered when the number of SFRs tends to zero. It can be observed that the more SFRs there are, the less plutonium amount is accumulated. Causes are multiple and combined. The reduction of the PWR-UOX fraction has a strong impact. Nevertheless, SFR may operate as plutonium breeder when S1 is also used to build SFR fresh fuel with a LIFO strategy. This plutonium breeding is not sufficient to compensate PWR-UOX fraction reduction. Moreover, when S1 is used to build ASTRID-like fresh fuel, it impacts PWR-MOX behavior.

Fig 13 depicts the variation of $T_{\text{Pu}}^{\text{MOX}}$ over time when S1 and S2 feeds the SFR fabrication plant with LIFO strategy in cyan and with FIFO strategy in coral. This figure shows that in case of LIFO strategy for SFR, the quality of PWR-UOX spent fuel available for the PWR-MOX fuel fabrication plant decreases. Hence, the

burning ratio of PWR-MOX rises. In fact, when ASTRID-like SFRs use plutonium from PWR-UOX spent fuel, the plutonium quality available for PWR-MOX fresh fuel decreases. Consequently, the plutonium content for PWR-MOX fuel is higher. Therefore, either the PWR-MOX and SFR behavior are coupled, or effects are balanced.

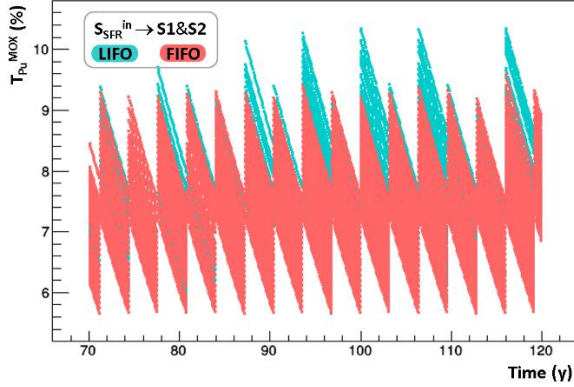


Fig 13. Evolution of PWR-MOX plutonium content, when S1 and S2 feeds the SFR fuel fabrication plant

Finally, as PWR-MOX and ASTRID-like SFR impacts on plutonium quantity are very bound, we can yet compare their effect on plutonium quality shown in Fig 14. It illustrates the evolution of the ratio between odd and even isotopes of plutonium in S1: PWR-UOX spent fuel, S2: PWR-MOX spent fuel and in S3: SFR spent fuel. Reprocessing PWR-MOX spent fuel into SFR distinctly improves plutonium fissile isotope content but this stays below PWR-UOX quality. Knowing that, the impact on plutonium quantity and quality of SFR spent fuel reprocessing is analyzed in case B.

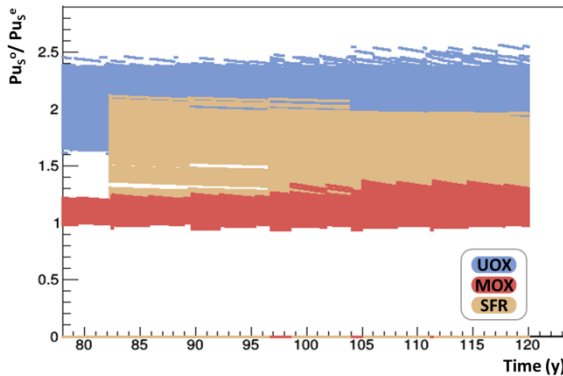


Fig 14. Evolution of plutonium quality in stocks: S1 in blue, S2 in red, S3 in brown

IV.B. Mix fleet with SFR fuel reprocessing

Case B differs from case A by reprocessing SFR spent fuels either in S1 with PWR-UOX spent fuel or in

S2 with PWR-MOX spent fuel. As the plutonium content of SFR spent fuel reaches 20%, the cooling time, TC_{SFR} , is sampled between 5 and 10 years. Our work shows that this last variable has no visible effect on in-cycle plutonium quality and quantity managed by the fleet and in the different reactors independently.

ASTRID-like SFR behavior is not impacted by its fuel reprocessing. In fact, effects due to the use of SFR spent fuel to build fresh one are negligible. Variations of plutonium quantity, quality and plutonium contents are similar as results obtained in case A. Moreover, SFR management of plutonium is still impacted by fuel cycle parameters as SM_{SFR} and S_{SFR}^{in} . For instance, the evolution of plutonium quantity in SFR, when S2 only feeds the SFR fuel fabrication plant and , is comparable with Fig 10.

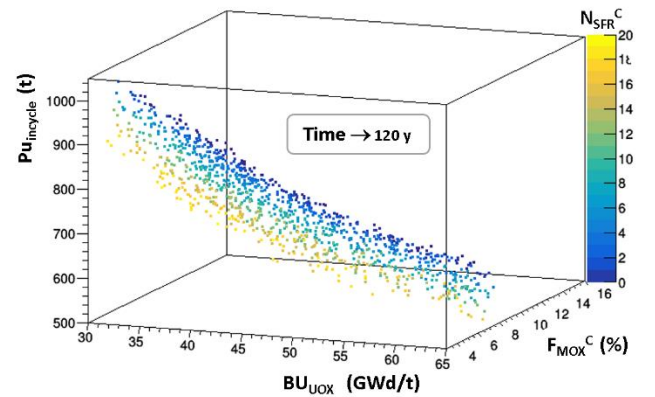


Fig 15. In-cycle plutonium quantity function of BU_{UOX} , F_{MOX}^c and N_{SFR}^c at 120 years

Likewise, the shape of the graph representing in-cycle plutonium evolution over time and BU_{UOX} is equivalent in case A and case B. At end of cycle, plutonium in-cycle quantity varies between 500 and 1000 t. Fig 15 shows a cut of in-cycle plutonium quantity at 120 years according to BU_{UOX} , F_{MOX}^c and N_{SFR}^c . Like previously, this quantity considered plutonium in all cycle facilities. BU_{UOX} , F_{MOX}^c and N_{SFR}^c are the three main parameters driving the in-cycle plutonium quantity for a mix fleet containing PWR-UOX, PWR-MOX and SFR when considering the total power and the ratio between PWR-UOX and PWR-MOX fractions constant.

SFR fuel management options have strong impact on the all fuel cycle scale, mainly on PWR-MOX behavior. As we saw in case A results, stocks feeding SFR fabrication plant, variable S_{SFR}^{in} , can under certain conditions change plutonium content in fresh fuel loaded into PWR-MOX. For example, when S1 and S2 give spent fuels to build SFR fresh fuel with a LIFO strategy, while SFR spent fuel is reprocessed in S2, T_{Pu}^{MOX} raises compared to FIFO strategy as depicted on Fig 16. In that situation, the burning ratio of PWR-MOX increases. Then, stock used to dump SFR spent fuel also changes PWR-MOX behavior. As shown on Fig 17, if SFR spent

fuels are dumped in S1, with PWR-UOX spent fuels, it induces an important increase of T_{Pu}^{MOX} . Some plutonium contents exceed 12%, a usual limit. This is mainly due to the lower plutonium quality in SFR spent fuel than in PWR-UOX spent fuel.

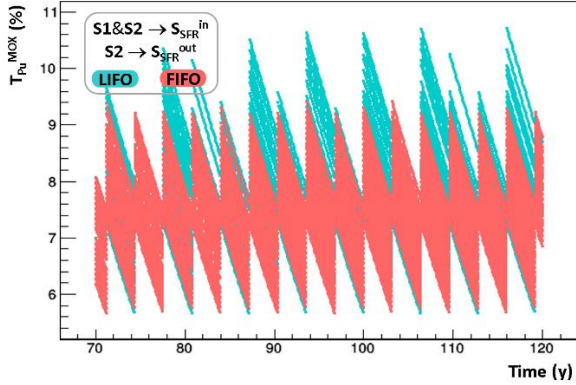


Fig 16. Evolution of PWR-MOX plutonium content, when S1 and S2 feeds the SFR fuel fabrication plant and SFR spent fuel is mixed in S2

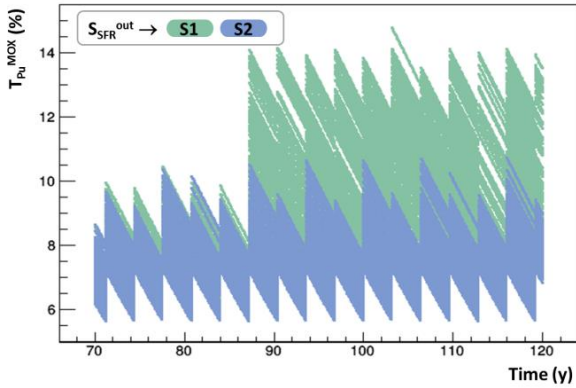


Fig 17. Evolution of PWR-MOX plutonium content depending SFR spent fuel dumping stock

These scenarios analysis is bounded by two major constraints. In fact, the total power of the fleet is kept equal to 100 GW_{th} and the ratio between PWR-UOX and PWR-MOX fractions remains constant between phase b and phase c. Knowing that, it appears that ASTRID-like SFRs can reprocess all spent fuels in the mix fleet and its fuel composition under irradiation tends to a mean plutonium quantity and quality. However, ASTRID-like fuel management can have strong cycle effects and particularly highly influence the PWR-MOX optimal operation.

The waiting strategy involving the integration of few SFR into a PWR fleet may have several purposes such as plutonium inventory stabilization upstream future decisions on fleet evolutions or fuel cycle closure to limit the natural uranium consumption. Hence, the following

part focuses on the viability of some possible steady-state scenarios.

V. STEADY-STATE SCENARIOS

From the analysis of the previous scenario families, some conclusion can be drawn about steady-state nuclear fleet. On one hand, the issue of in-cycle plutonium stabilization with a mix fleet containing PWR-UOX, PWR-MOX and SFR is investigated. On the other hand, full closed fuel cycle transitions from PWR to SFR fleet are studied.

V.A. In-cycle plutonium stabilization

In-cycle plutonium stabilization may be sought as an objective for future nuclear strategy. It means that the total plutonium, sum of the plutonium present in reactors, in the spent fuel, in fuel fabrication units and in the cooling pools, remains constant over time. A UOX loaded PWR produces plutonium whereas MOX loaded PWR tends to burn it. If a mix PWR fleet composed of UOX and MOX fuel produces plutonium, SFR should behave as plutonium burner to reach plutonium equilibrium. On the contrary, if the PWR stratum is incinerating plutonium, steady-state implies that some plutonium is produced in the SFR stratum to fulfill the gap.

The previous section shows that ASTRID-like SFR trends to improve plutonium quality compared to PWR-MOX spent fuel as shown in Fig 14. Plutonium quality from PWR-MOX spent fuel is too low to allow plutonium breeding in ASTRID-like reactors with no extra plutonium. Actually, our calculations show that the maximum breeding capabilities of ASTRID-like SFRs are reached when plutonium for fresh fuel fabrication comes from PWR-UOX spent fuel, with a LIFO strategy. Besides, when SFR spent fuels are reprocessed in PWR-MOX, it increases the PWR-MOX burning ratio. In that case, the PWR stratum produces plutonium in overall (PWR-UOX+PWR-MOX). Consequently, a double stratum composed with ASTRID-like SFR and PWR-MOX seems unlikely with a relatively low number of SFR, meaning smaller than 30% of the fleet. However, one prospect would be to separate SFR spent fuels to adapt fuel reprocessing. In fact, the plutonium quality in the fertile blanket spent fuel, ratio between odd and even isotopes around 10 after irradiation, is much higher than in the fissile zones, ratio around 1,5 at end of cycle. Thus, fuels from fertile blankets could be unloaded in S2 to allow plutonium breeding in SFRs while the rest of the spent fuels could be unloaded in S1 to increase PWR-MOX burning ratio. However, the cycle management would be much more complicated.

The second possibility is a PWR fleet producing plutonium. With an appropriate fuel management, ASTRID-like SFR may behave as a plutonium burner.

The incineration rate should compensate the production of plutonium in the first PWR stratum.

As an example, a 900 MWe PWR stratum made of PWR-UOX (burnup of 45 GWd/t) and PWR-MOX (burnup of 45 GWd/t) where all the PWR-UOX spent fuels are reprocessed to build PWR-MOX fresh fuels, leads to a PWR-MOX fraction of approximately 11%. PWR cycle length is around 3 years. One equivalent PWR produces then approximately 20 g per GWh. SFR fraction in the fleet should be calculated to burn this plutonium quantity.

In order to have ASTRID-like SFR working as plutonium burner without cycle equilibrium disruption, last section showed that the SFR fabrication plant should be fed with PWR-MOX spent fuel through a FIFO strategy and that SFR pool should dump SFR spent fuel with the PWR-MOX spent fuel. The leading fuel cycle considered is illustrated on Fig 18.

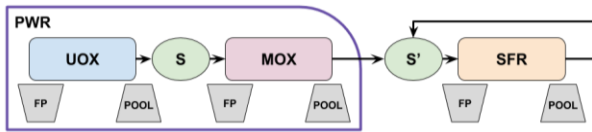


Fig 18. Schematic representation of fuel cycle facilities for the in-cycle plutonium stabilization

In such condition, the maximum burning SFR ratio reaches ~200 kg per cycle corresponding to 5.4 g per GWh_e. Thus, the equilibrium between plutonium production in PWR and plutonium reduction in SFR leads to approximately 80% of energy produced by SFRs and 20% by PWRs. For a total power of 100 GW_{th} it means 54 SFRs for 7 PWRs. This SFR fraction is not compatible with the hypothesis of the deployment of few SFRs. Besides, ASTRID-like SFR increases the plutonium quality while it burns it. Thus, cycles after cycles, with a large majority of SFRs, the burning ratio may decrease and the optimal equilibrium may change. Hence, in-cycle plutonium stabilization in such conditions is not possible.

Actually, the fact that plutonium stabilization is not possible in the framework of this study can be seen in Fig 11, which clearly shows that no plutonium stabilization is observed in our calculations.

V.B. Closed fuel cycle

Last paragraph shows that plutonium stabilization may be obtained with a 100% SFR fleet multi-recycling plutonium. To operate the transition and to close the fuel cycle, PWR loaded with UOX and MOX fuel should be stopped.

Thus, a last scenario family is studied here, based on the case B of the section IV. The same design of experiment as presented in TABLE II is used. However, PWRs stop after 70 years of simulation as SFRs start, implying an important total fleet power reduction, as

illustrates on Fig 19. N_{UOX}^c and N_{MOX}^c are set to zero. 2000 new scenarios are simulated.

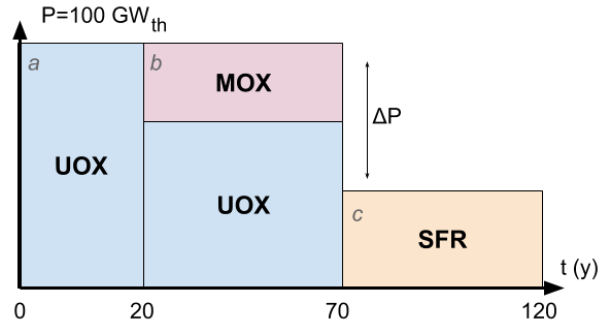


Fig 19. Schematic representation of the fleet evolution in the second scenario family

The aim of this study is to see if solutions exist with no plutonium shortage during the transition regarding the fuel cycle strategy. As ASTRID-like behavior may differ regarding the plutonium composition and where it comes from, the plutonium needed for ASTRID-like SFR operation may be time dependent.

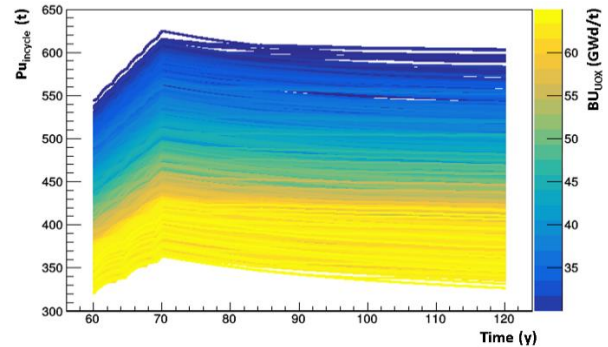


Fig 20. In-cycle plutonium quantity evolutions after 60 years as a function of PWR-UOX burnup

Fig 20 shows the evolution of in-cycle plutonium quantity in all the simulated scenarios with the fleet represented in Fig 19. At 70 years, when SFRs start, the plutonium quantity is mainly dependent on PWR-UOX burnup and on PWR-MOX fraction. After SFRs start up, Fig 20 does not show any difference in the fleet behavior. No matter where the plutonium for SFR operation comes from, the hierarchy of the different curves remains identical. Plutonium burning or breeding in ASTRID-like reactors seems of no importance at the fleet level. In addition no transition in the plutonium evolution behavior seems to appear. Fig 21 shows the evolution of plutonium managed in fabrication plants, pools and stocks after 60 years. With 20 SFRs or 1 SFR, plutonium quantity remains constant after PWR shutdown. Thus, plutonium multi-recycling in ASTRID-like break-even design is possible with almost no need of additional resources.

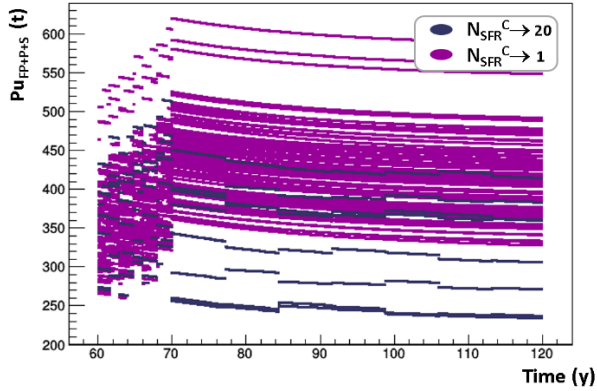


Fig 21. Plutonium evolution in fabrication plants, pools and stocks with 20 SFRs in dark blue or 1 SFR in purple

VI. CONCLUSION

This paper presents the analysis of ASTRID-like SFR integration into a PWR fleet impact on in-cycle plutonium management through scenario studies.

First, new dedicated multi-zone physic models have been developed in the CLASS code to dynamically simulate the fuel fabrication and irradiation, while taking into account the core heterogeneity and fuel interaction. The new multi-zone fuel loading model presented here is based on two criteria at BOC: a targeted power distribution and a targeted multiplication factor.

Then, impacts of different SFR parameters and cycle parameters such as SFR spent fuel reprocessing management have been studied to investigate it. Finally, observations based on this previous part of the analysis have been used for a preliminary understanding of steady-state possibilities involving ASTRID-like SFRs.

From our calculations, some strong conclusions can be drawn for mix fuel cycle involving PWR and ASTRID-like reactors.

First of all, ASTRID-like behaviors depend on the cycle strategy. Regarding the plutonium origin, these reactors may be operated as plutonium breeder, break-even or plutonium burner with the same reactor design. On one hand, the cycle seems to have an impact on the reactor physic. On the other hand, ASTRID-like SFRs strongly impact the cycle.

Recycling plutonium from PWR-UOX spent fuel for SFR fresh fuel fabrication may decrease the plutonium quality for PWR-MOX fuel fabrication. Consequently it increases the plutonium content in PWR-MOX fuel, leading to an increase of plutonium incineration into PWR-MOX.

Recycling plutonium from PWR-MOX spent fuel into ASTRID-like SFR fresh fuel leads to an improvement of plutonium quality which remains lower than PWR-UOX spent fuel plutonium quality. The

plutonium multi-recycling into SFR fresh fuel has then no effect on the rest of the cycle.

Finally, the plutonium quantity remains in any case function of the PWR-UOX burnup and the PWR-MOX fraction as in a classical PWR fleet. The number of ASTRID-like reactors into the fleet has also a significant impact as they replace PWRs, mainly plutonium breeder.

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