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Symbiotic equilibrium between Sodium Fast Reactors and Pressurized Water Reactors supplied with MOX fuel



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ABSTRACT

The symbiotic equilibrium between 1.51 GWe breeder SFR (Sodium Fast Reactors) and 1.6 GWe EPRTM (European Pressurized water Reactors) is studied. EPRTM are only supplied with MOX (Mixed OXide) fuel to avoid the use of natural uranium. The equilibrium is studied by considering the flows of plutonium. Its isotopic composition is here described by a single real number referred to as the Pu grade. Plutonium flows through both reactor types are characterized by using linear functions of the Pu grade in new fuels. These functions have been determined by fitting data from a former scenario study carried out with the COSI6 simulation software.

Two different reprocessing strategies are considered. With joint reprocessing of all spent fuels, total and fissile plutonium flows balance for a unique fraction x of EPRTM in the fleet, equal to 0.2547. This x value is consistent with the results reported in the former scenario study mentioned above. When EPRTM spent fuels are used in priority to supply SFR (distinct reprocessing), x reaches 0.2582 at most. COSI6 simulations have been performed to further assess these results. The EPRTM fraction in the fleet at symbiotic equilibrium barely depends on the applied reprocessing strategy, so that the more flexible joint reprocessing constitutes the reference option in that case.

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1. Introduction

Closing the fuel cycle is a major challenge to improve the sustainability of civil nuclear power, and complex systems have been studied in this respect (see e.g. Gao and Ko, 2014; Lindley et al., 2014). In this context, a symbiotic nuclear system denotes a fleet composed of various reactor types: reactors which produce fissile elements compensate for their consumption (Chersola et al., 2015). Here, the main fissile element is plutonium, produced in breeder SFR (Sodium Fast Reactors) and consumed in EPRTM (European Pressurized water Reactors) only supplied with MOX (Mixed OXide (U,Pu)O₂) fuel. Indeed, a fleet composed of SFR and EPRTM can dispense with natural resources as long as some depleted or reprocessed uranium is available to supplement Pu in new fuels.

A recent article (Martin et al., 2016) reported scenarios of the French fleet evolving towards a nuclear system including both these reactor types exclusively. The mixed fleet at the end of the scenarios was composed of *circa* a quarter of EPRTM, so that the total plutonium inventory was nearly steady, which indicates a fleet composition close to a symbiotic equilibrium when all irradiated fuels are reprocessed. Joint reprocessing of all spent fuels was

applied to improve the fuel management flexibility. Another viable strategy would have consisted in recycling the Pu from SFR spent fuels in EPRTM in priority (distinct reprocessing). These two reprocessing strategies are presented in Fig. 1.

The aim of the present study is to assess the conditions under which a symbiotic equilibrium exists for each reprocessing strategy. The basic equations which drive the symbiotic equilibrium for a joint reprocessing of spent fuels are set up. They are solved by considering only the flows of plutonium, whose isotopic composition is described by a single number referring to its grade. The way plutonium evolves under irradiation has been deduced from data collected from the previous scenario study mentioned above (Martin et al., 2016). The joint reprocessing strategy leads to a unique fleet composition at symbiotic equilibrium.

The symbiotic equilibrium between EPRTM and SFR applying distinct reprocessing of spent fuels is then described. Several symbiotic equilibria are found. The fraction of EPRTM in the fleet is maximal when all the plutonium introduced in EPRTM MOX fuels comes from SFR spent fuels. Nevertheless the gain with respect to joint reprocessing appears marginal, which means that fissile plutonium savings associated to this complex reprocessing strategy remain quite low. In this context, joint reprocessing no doubt constitutes the reference option for such a symbiotic nuclear system.

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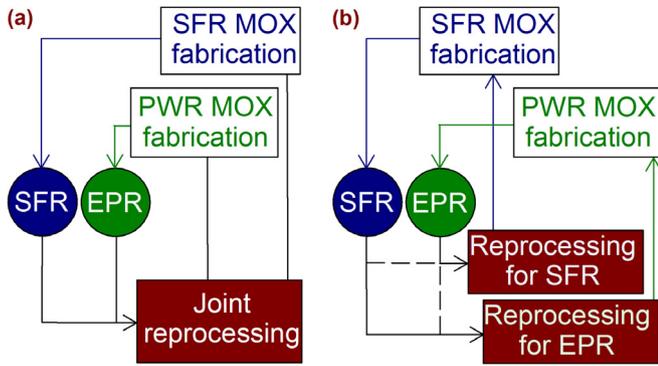


Fig. 1. Joint reprocessing (a) and distinct reprocessing (b) of EPR™ and SFR spent fuels.

2. Previous work

Mixed nuclear fleets composed of EPR™ and SFR were previously simulated (Martin et al., 2016) using the COSI6 scenario software (Coquelet-Pascal et al., 2015), developed by CEA. COSI6 can simulate in detail the time evolution of a nuclear reactor fleet with its associated fuel cycle facilities. New fuel compositions can be estimated by applying equivalence models. COSI6 was here coupled with the CESAR5.3 code (Vidal et al., 2012) to calculate the composition evolution of matters in pile or in storage conditions. CESAR5.3 solves the Bateman equation for 109 heavy nuclides and more than 200 fission products using JEFF3.1.1 nuclear data and one-group cross-section libraries for reactor modeling.

Two simulations of the French fleet evolving step by step (Chabert et al., 2015) towards a symbiotic nuclear system were run (Martin et al., 2016). They were built within the limits of conservative criteria defined in concert with French industrialists (AREVA and EDF), so that they are realistic as regards our current knowledge and feedback (Martin et al., 2016). Electricity production curves of both scenarios are shown in Fig. 2.

In these scenarios, EPR™ and SFR operate in diverse conditions over several decades. In this respect all fuel batches passing through breeder SFR (1076 batches) and EPR™ only fueled with MOX (321 batches) during the progressive scenario (see Fig. 2.a) provide a consistent reference dataset for describing the fuel evolution in pile (see Section 3.2). The cores of these reactors are

respectively managed by thirds and fifths. Main characteristics of simulated EPR™ and SFR are reported in Table 1.

At the end of the simulations, mixed nuclear fleets were composed of 10 EPR™ with 28 or 30 SFR. If the real number x stands for the fraction of EPR™ in the fleet, simulations were carried out at $x = 0.2632$ and $x = 0.25$. These fleet compositions led to rather stable plutonium inventories, but even so not strictly constant as shown in Fig. 3. A slight increase of the plutonium stock counts for too much breeder SFR in the fleet ($x = 0.25$), whereas a decrease counts for the opposite ($x = 0.2632$). Therefore one may expect that the EPR™ fraction in the fleet which perfectly satisfies the symbiotic equilibrium is comprised between these two values.

Table 1

Description of 1.51 GWe breeder SFR and of EPR™ fueled with MOX only.

	Reactors	
	EPR™ 100% MOX	Breeder SFR CFV V1
Power (GWe)	1.60	1.51
Net yield (%)	35.6	40.3
Core mass (tHM)	125	129
Core composition	MOX only	40% fissile 60% fertile
Fuel need (tHM/yr)	MOX: 25.4	fissile: 8.1 fertile: 8.7
Fissile fuel BU	53.5 Gwd/t	116.3 Gwd/t

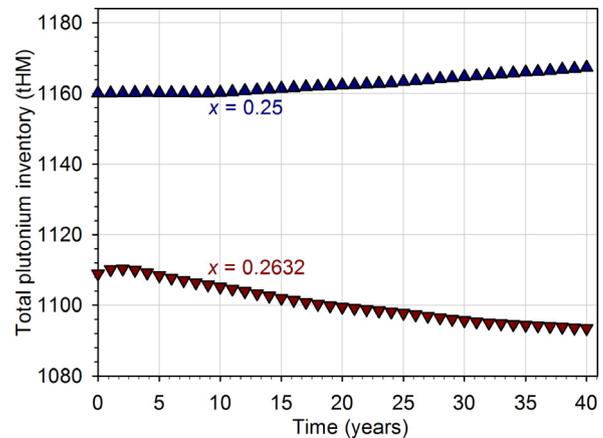


Fig. 3. Evolution over 40 years of the total plutonium inventory associated to two mixed EPR™ – SFR fleets (Martin et al., 2016), x being the EPR™ fraction.

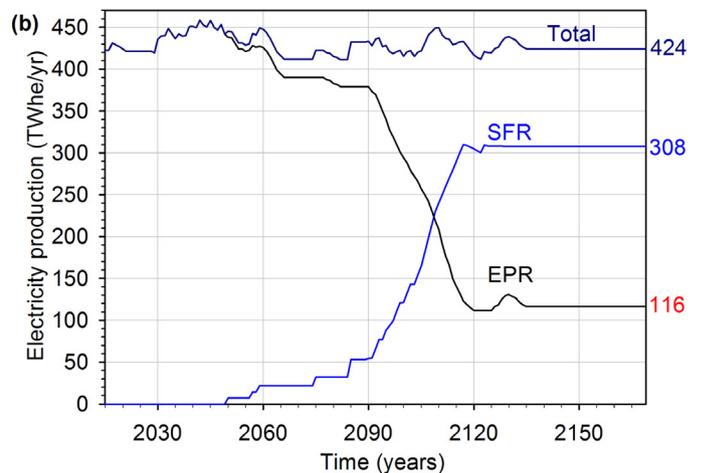
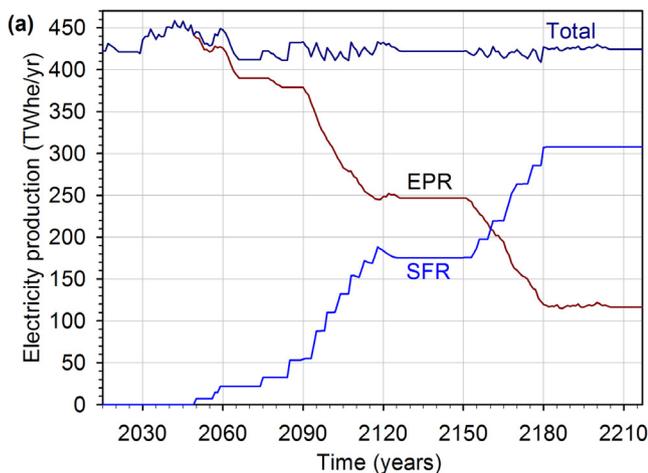


Fig. 2. Electricity production of EPR™ and SFR during the progressive (a) and fast (b) transition scenarios to a symbiotic nuclear fleet (Martin et al., 2016).

3. Joint reprocessing

3.1. Description

Joint reprocessing of all spent fuels has first been considered. As in similar scenario studies (Martin and Girieud, 2016), a minimal cooling time of 5 years occurs between spent fuel unloading and reprocessing operations. Reprocessing essentially consists in extracting from spent fuels the plutonium which enters into MOX fuel fabrication (for EPR™ and SFR). Then, at least two additional years elapse before a new MOX fuel can be loaded in reactor. The minimal time during which the plutonium decays before its recycling in pile is therefore of 7 years. The fuel cycle with joint reprocessing is illustrated in Fig. 4.

In Fig. 4 are reported the parameters which describe the plutonium flows in the closed fuel cycle. N_E and N_S represent the Pu consumptions of EPR™ and SFR respectively, whereas P_E and P_S stand for Pu productions. Joint reprocessing results in the same plutonium isotopic vector in all new fuels: G denotes its grade at symbiotic equilibrium. In a general case, one can note that Pu grades should be defined as isotopic vectors whose size is the number of Pu isotopes present in irradiated fuels. Here however, the Pu grade has been reduced to a single real number according to the weight ratio (2) (see Section 3.2). This way to proceed is further discussed in Section 5. Table 2 reports all parameters used along this article, some of them referring to the distinct fuel reprocessing strategy described in Section 4.

All the isotopes present in the fuels in pile contribute to neutron capture and/or thermalization processes, and participate in the core neutron behavior. Here however, only plutonium isotopes are assumed in first order to impact the fuel flows drawn in Fig. 4. It is then possible to write the conditions of the symbiotic

equilibrium with joint reprocessing as a system of two equations (see system (1)).

$$\begin{cases} xN_E(G) + (1-x)N_S(G) = xP_E(G) + (1-x)P_S(G) \\ G = \frac{(1-x)P_S(G)\Gamma_S(G) + xP_E(G)\Gamma_E(G)}{(1-x)P_S(G) + xP_E(G)} \end{cases} \quad (1)$$

The first equation is here a balance between plutonium production and consumption. Pu need and production functions depend here upon the plutonium grade G . Only two Pu isotopes contribute significantly to fissions inside the reactor core, namely ^{239}Pu and ^{241}Pu . The second equation in system (1) provides that, with joint reprocessing, the plutonium grade G in new fuels is a weighted average of plutonium grades in irradiated fuels unloaded from both reactor types (Γ_E and Γ_S for EPR™ and SFR respectively). The balance of fissile Pu isotopes can be deduced by multiplying both equations in system (2).

3.2. Assumptions

The plutonium grade is here described by a single real number. The Pu grade does not include ^{241}Am (Martin et al., 2016) which derives from ^{241}Pu and acts as a neutron absorber. This element is usually accounted for since its concentration increases as Pu ages. However, in the steady-state fleet, the time interval between spent fuel unloading and the reloading in pile of the Pu that it contains should ideally not vary: the fastest possible recycling (7 years) applies since it constitutes the best option in terms of plutonium management. Steady Pu aging explains why the Pu grade can be defined without ^{241}Am , according to relation (2).

$$g = \frac{^{239}\text{Pu} + ^{241}\text{Pu}}{\sum_{M=236}^{M=244} M\text{Pu}} \quad (2)$$

Plutonium need, production and output grade functions here characterize each reactor present in the mixed fleet: EPR™ and SFR. These three functions for both reactor types depend on the plutonium grade in new fuels. They are presented in Fig. 5 (6 graphs). Fuel batches from the progressive transition scenario previously simulated (Martin et al., 2016) (see Section 2) have been used to calculate them: these data appear as dots in Fig. 5.

All the reactor functions have here been defined as linear functions of the plutonium grade in new fuels (see Fig. 5). This has been partly inferred from the equivalence model for SFR (Baker and Ross, 1963) which linearly depends on each Pu isotope concentration, although this particular aspect of the simulations may be improved (Krivtchik, 2014). For the period between spent fuel unloading and the reloading of the Pu that it contains, only the decay of fissile ^{241}Pu , of half-life of 14.4 years, should significantly impact the symbiotic equilibrium. A 7-year decay of ^{241}Pu has therefore been applied to fuel batches which were just irradiated to account for intermediate cooling, reprocessing and fuel fabrication steps: this decay is accounted for in Fig. 5.b, c, e and f. Pu losses during spent fuel reprocessing are neglected.

The fuels after irradiation in SFR show a large variety of plutonium contents and grades. Whereas high-grade Pu has been kept for EPR™ MOX fuel fabrication since its Pu content should not exceed a limit for safety reasons (Martin et al., 2016), the SFR CFV core has a particularly large fuel acceptance (Buiron and Dujcikova, 2015). Spent fuels containing low-grade plutonium, namely enriched reprocessed uranium, PWR MOX and mostly aged fuels, therefore supplied SFR as far as possible (Martin et al., 2016). As a consequence of this, plutonium isotopic composition in new SFR fuels varied strongly, which explains the dispersion of the corresponding outcomes (Fig. 5.e and f). In particular, fuel batches with plutonium of similar grade g but different aging led to markedly different results.

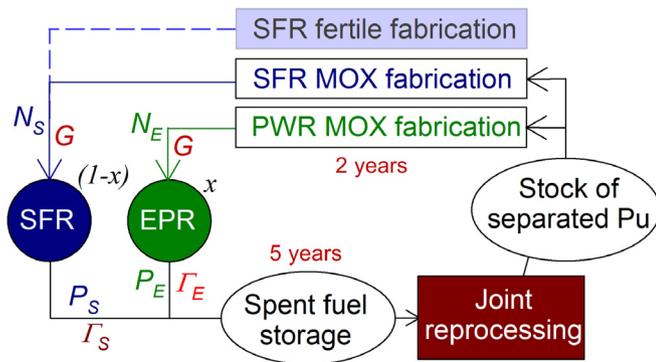


Fig. 4. Fuel cycle of a mixed EPR™ – SFR fleet with joint reprocessing of spent fuels.

Table 2
Symbol table.

Parameters	Unit	Description
x	$\in [0, 1]$	EPR™ fraction in the fleet
N_E	tHM/yr	Pu consumption in an EPR™ reactor
N_S	tHM/yr	Pu consumption in a SFR reactor
P_E	tHM/yr	Pu output from an EPR™ reactor
P_S	tHM/yr	Pu output from a SFR reactor
Γ_E	$\in [0, 1]$	Pu grade in EPR™ spent fuel
Γ_S	$\in [0, 1]$	Pu grade in SFR spent fuel
g	$\in [0, 1]$	Plutonium grade in new fuel
G, G_E^*, G_S^*	$\in [0, 1]$	Equilibrium Pu grades
ϵ_E	$\in [0, 1]$	EPR™ Pu fraction recycled into EPR™
ϵ_S	$\in [0, 1]$	SFR Pu fraction recycled into SFR

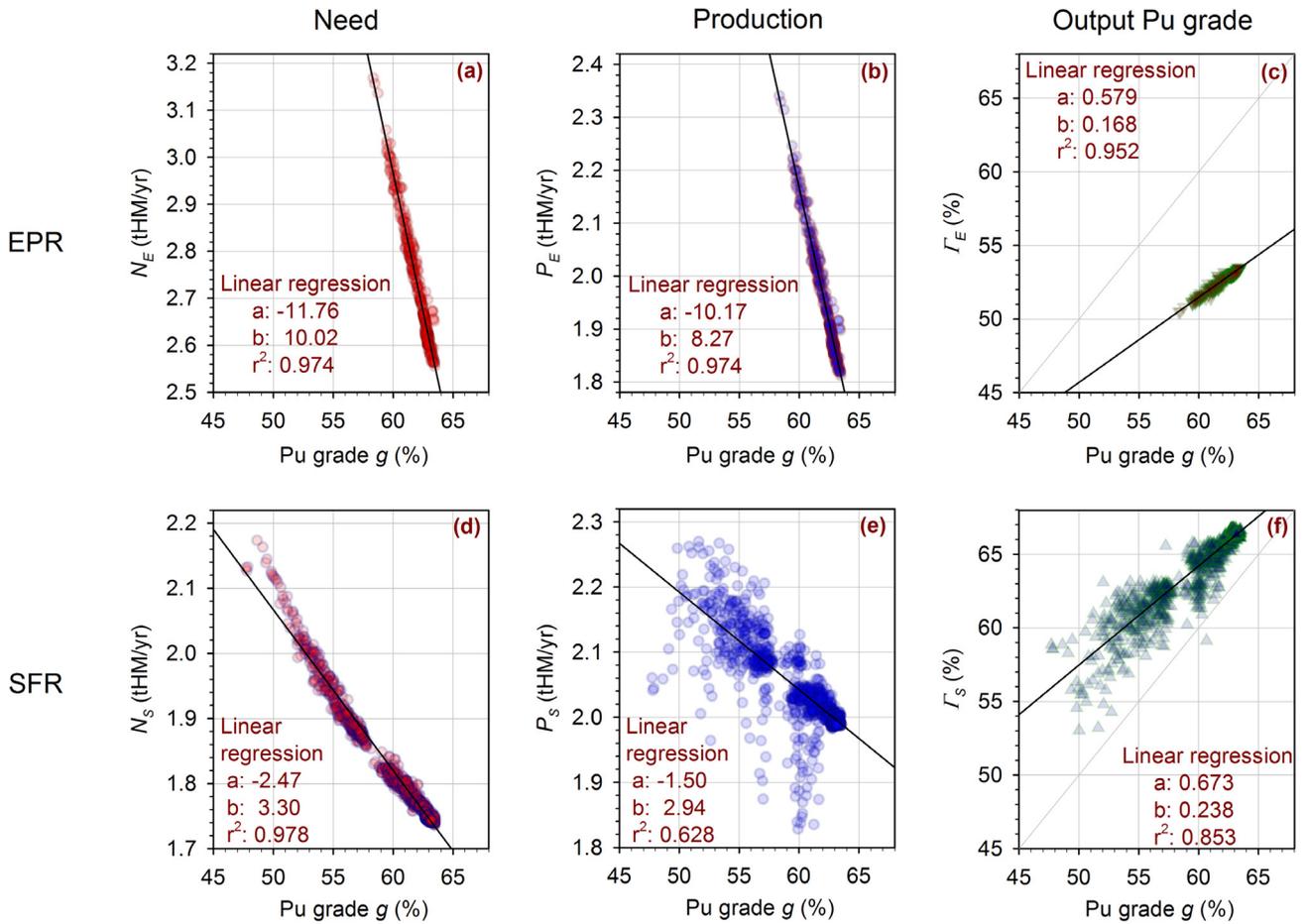


Fig. 5. Linear fits of the data relative to plutonium consumption, production and grade evolution (Martin et al., 2016) for both reactor types.

3.3. Solution

The system of Eqs. (1) is solved in this section. The 2 unknowns are the fleet composition (EPR™ fraction x) and the Pu grade in fresh MOX fuels G at symbiotic equilibrium. The first equation in this system stands for the balance between total plutonium production and consumption. It leads to a collection of fleet composi-

tions (x values) as a function of the plutonium grade G at equilibrium, as shown in Fig. 6.

The second equation in system (1) can also be reduced to a relation between x and G . The system is therefore solved by intersecting two functions $x(G)$, inferred from both equations in system (1) (see Fig. 7). The mixed nuclear system of EPR™ and SFR with joint reprocessing is symbiotic for a unique fleet composition, corre-

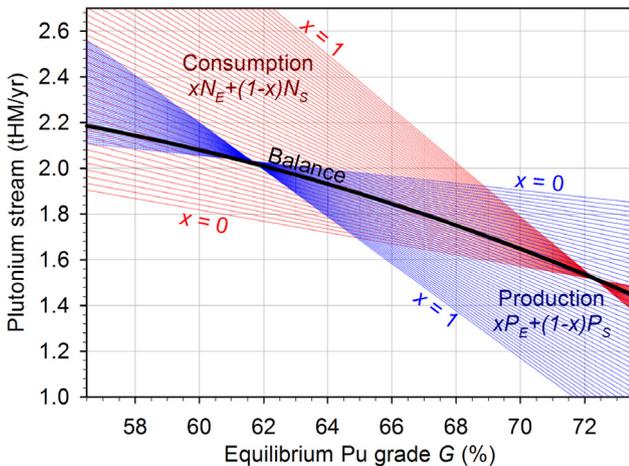


Fig. 6. Balance between Pu production (blue lines) and consumption (red lines) applying joint reprocessing of spent fuels. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

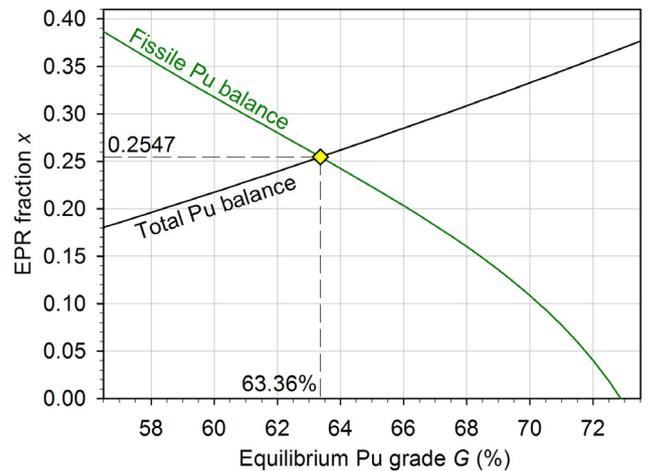


Fig. 7. Symbiotic equilibrium with joint reprocessing.

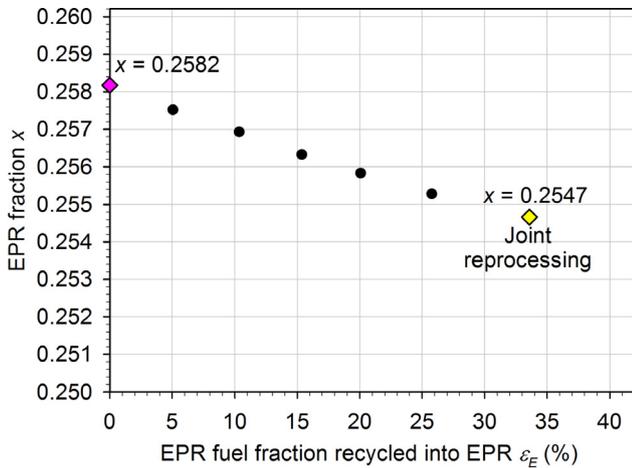


Fig. 10. Symbiotic equilibrium as a function of the spent fuel fraction ϵ_E self-recycled into EPRTM.

Table 3

Solutions corresponding to the highest x value with distinct reprocessing and to joint reprocessing of spent fuels.

Variable	Main results	
	Distinct reprocessing	Joint reprocessing
x	0.2582	0.2547
G_E^+	65.84%	$G = 63.36\%$
G_S^+	62.43%	
ϵ_E	0	0.336
ϵ_S	0.605	$(1 - \epsilon_E) = 0.664$

The slight increase of x when distinct reprocessing applies cannot be attributed to a higher fissile Pu production in SFR as expected initially. Indeed, the mean plutonium grade in SFR new fuels G_S^+ is 62.43%, implying lower total and fissile Pu productions with regard to joint reprocessing ($G = 63.36\%$) according to Fig. 8. The production of fissile Pu isotopes in SFR would only be improved for Pu grades lower than 60%, which would require more EPRTM in the fleet.

To explain this x difference, one has to consider the fissile Pu consumption in EPRTM. The net consumption of fissile plutonium isotopes in an EPRTM can be estimated by $gN_E(g) - P_E(g)\Gamma_E(g)$. It decreases from 0.654 tHM/yr to 0.637 tHM/yr when G_E^+ rises from 63.36% (joint reprocessing) to 65.84% (distinct reprocessing). This effect is nonetheless an extrapolation since 65.84% lies outside the range of values covered by the EPRTM dataset (see dots in Fig. 5.a, b and c). This is why the solutions presented in Table 3 have further been assessed through additional COSI6 simulations.

5. COSI6 simulation

The symbiotic equilibria reported in Table 3 have been simulated using COSI6 (Coquelet-Pascal et al., 2015). In addition, mixed fleets of same composition as those previously studied (see Section 2) have been simulated. Reprocessing has been modeled as in the most recent scenarios built in collaboration with the French industry (Chabert et al., 2015; Tiphine et al., 2015; Martin et al., 2016). Besides, since it appeared impossible to model in practice precise reactor fractions using whole numbers of reactors, power plants have been modeled as parts of a single reactor unit. This amounts to considering, for instance, that the fuel stream through x EPRTM equal x times that of a reactor of 1.6 GWe. Ten reactors have been operated in total ($10 \times x$ EPRTM and

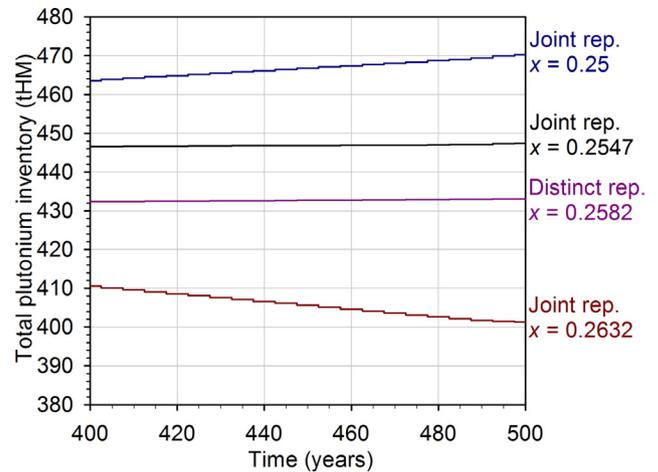


Fig. 11. Evolution for 100 years of plutonium inventories during COSI6 simulation of mixed EPRTM – SFR fleets (10 reactors).

$10 \times (1 - x)$ SFR). All the fractional reactors start within a same 5-year period. A Pu stock of around 500 tHM initially supplies MOX fuel fabrication plants when no spent fuel is still available. Poor and reprocessed uranium stocks are also withdrawn to make fertile and fissile fuels respectively. The simulations cover 500 years to ensure that a steady-state is reached. The total Pu inventories over the last 100 years of simulation are reported in Fig. 11.

A fairly stable plutonium inventory is obtained from the x values representative of joint reprocessing (0.2547) and distinct reprocessing of spent fuels (0.2582). However one can observe that the plutonium stock grows slowly. The low deviation from symbiotic equilibrium can be attributed to the slight difference between the applied linear regressions and the highest values of plutonium production (see Fig. 5). Indeed, the highest values of plutonium production mostly correspond to a minimum aging of plutonium close to 7 years, used to equate the symbiotic equilibrium with plutonium isotopic vectors collapsed into single scalar vectors (see Section 3.2). Nevertheless, linear regressions are not far from the highest values of Pu production and output grade data, especially for plutonium grades greater than 60% in SFR (see Fig. 5.e and f). This explains why the deviation from a perfect Pu balance remains marginal.

These COSI6 simulations eventually assess the results obtained relatively to symbiotic equilibria and further support that there is no significant difference in equilibrium fleet compositions for both reprocessing strategies. Therefore the more flexible joint reprocessing certainly constitutes a preferable option for the studied symbiotic nuclear system, composed of EPRTM and SFR.

6. Conclusion

The symbiotic equilibrium of a mixed fleet of 1.6 GWe EPRTM and 1.51 GWe breeder SFR is studied. EPRTM are fueled with MOX only: a symbiotic equilibrium indeed consists in a balance between the consumption and the production of fissile elements without any supply of natural resources when all irradiated fuels are reprocessed. The problem is tackled considering few simplifying assumptions:

- Only plutonium is assumed to impact the symbiotic equilibrium.
- A single real number, referred to as the Pu grade (see Eq. (2)), is supposed to account for the plutonium isotopic composition.

- At least 7 years elapse between a spent fuel unloading operation and the in pile reintroduction of the Pu that it contains. A 7-year decay of ^{241}Pu is applied as regards this minimal Pu aging, which optimizes plutonium management at equilibrium.
- The plutonium need, production and grade evolution which characterize both irradiation sequences in EPRTM and SFR are reduced to linear functions upon the Pu grade in new fuels. These functions have been determined from the results of a previous scenario study (Martin et al., 2016) carried out with COSI6 (Coquelet-Pascal et al., 2015).

Two different reprocessing strategies are considered. With joint reprocessing of all spent fuels, only a single EPRTM fraction $x = 0.2547$ in the fleet can balance total and fissile plutonium flows (symbiotic equilibrium). As expected from a former study (Martin et al., 2016), this x value lies well between 0.25 and 0.2632. When the plutonium from EPRTM spent fuels supplies SFR in priority (distinct reprocessing), x may slightly increase up to 0.2582. This increase is mainly due to a lower net plutonium consumption in EPRTM as the Pu grade in new fuels gets better. SFR breeding performance does not improve in that case.

Additional COSI6 simulations have been carried out to further assess the symbiotic equilibriums which have been found. One can therefore conclude that the EPRTM fractions in the fleet barely stand apart at symbiotic equilibrium whatever the reprocessing strategy, since they should correspond to the same fleet composition in practice (applying whole numbers of reactors). In this respect the more flexible joint reprocessing of spent fuels no doubt constitutes the reference option for the studied nuclear system.

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