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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 EPR™ (European Pressurized water Reactors) is studied. EPR™ 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 EPR™ in the fleet, equal to 0.2547. This x value is consistent with the results reported in the former scenario study mentioned above. When EPR™ 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 EPR™ 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.

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 EPR™ (European Pressurized water Reactors) only supplied with MOX (Mixed OXide $(U,Pu)O_2$) fuel. Indeed, a fleet composed of SFR and EPR™ 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 EPR™, 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 EPR™ 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 EPR™ and SFR applying distinct reprocessing of spent fuels is then described. Several symbiotic equilibriums are found. The fraction of EPR™ in the fleet is maximal when all the plutonium introduced in EPR™ 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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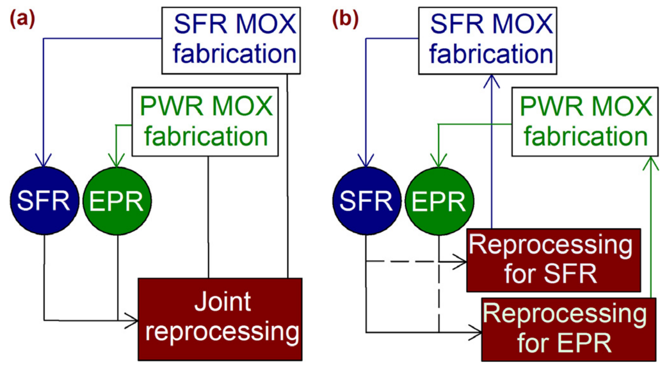

Fig. 1. Joint reprocessing (a) and distinct reprocessing (b) of EPR™ and SFR spent fuels.

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

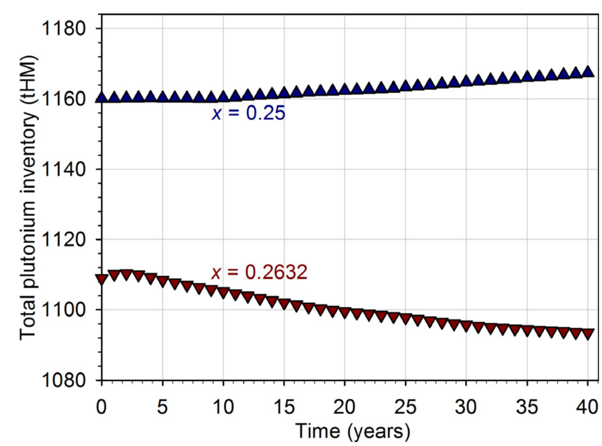

Fig. 3. Evolution over 40 years of the total plutonium inventory associated to two mixed EPR™ – SFR fleets (Martin et al., 2016), x being the EPR™ fraction.

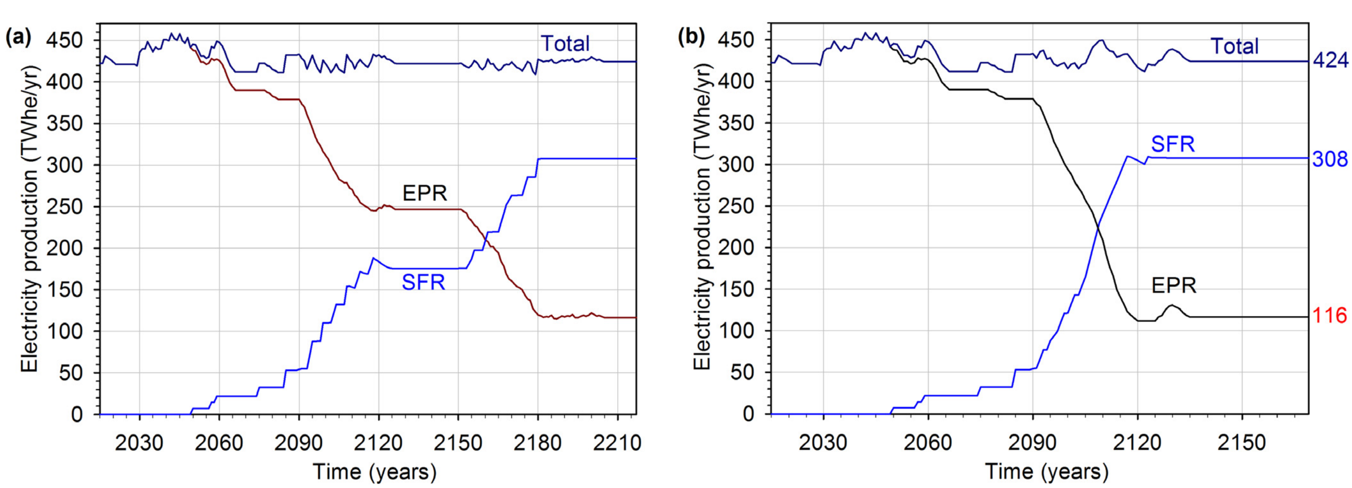

Fig. 2. Electricity production of EPR™ and SFR during the progressive (a) and fast (b) transition scenarios to a symbiotic nuclear fleet (Martin et al., 2016).