Study of a mixed fleet of breeder sfr and epr supplied with leu and mox fuels to balance the plutonium inventory

G. Martin

STUDY OF A MIXED FLEET OF BREEDER SFR AND EPR SUPPLIED WITH LEU AND MOX FUELS TO BALANCE THE PLUTONIUM INVENTORY

Guillaume MARTIN

CEA - DEN/DER, bât. 230, 13108 Saint-Paul-Lez-Durance Cedex, France
Phone: 33 (0)4 4225 2731, fax: 33 (0)4 4225 4849, e-mail: guillaume.martin@cea.fr

Scenarios of the evolution of the French nuclear fleet are developed by CEA, EDF, ORANO and FRAMATOME, following conservative assumptions in terms of technology, safety, regulation and costs. In the next decades, the SFR demonstrator ASTRID paves the way to the deployment of a few fast reactors used to consume PWR MOX spent fuel in priority. In the 2090 to 2120 period, the number of SFR goes on growing. The fleet eventually comes to a mix of breeder SFR and EPR (European Pressurized water Reactor) supplied with LEU and MOX fuels. Such a fleet composition enables the stabilization of spent fuel and plutonium inventories. Previously, a steady-state regime was reached in the next century, thanks to a fleet composed of ~40% SFR.

A new methodology has been applied. This methodology was recently developed to put into equations the equilibrium conditions of nuclear power systems composed of various reactor types. Fleets with the less SFR are now favored, since SFR are reputed to be more expensive than thermal reactors. Results show that the fraction of SFR in the fleet can be reduced of around 10% in comparison to the fleet previously deployed. However, the fleet composition which minimizes the SFR fraction at equilibrium leads to plutonium contents in EPR MOX fuels near the safety limit which is currently accounted for.

I. INTRODUCTION

Scenarios of the evolution of the French nuclear fleet are simulated with the aim of improving spent fuel recycling, natural resource savings and wastes reduction. These scenarios are developed by CEA, EDF, ORANO and FRAMATOME following conservative assumptions in terms of technology, safety, regulation and costs. In particular, a progressive deployment of SFR leads to possible strategies to close the fuel cycle by the end of the next century (ref. 1). In the next decades, the SFR demonstrator ASTRID paves the way to the deployment of a few fast reactors used to consume PWR MOX spent fuel in priority. In the 2090 to 2120 period, the number of SFR goes on growing. The fleet eventually comes to a mix of breeder SFR and EPR (European Pressurized water Reactor) supplied with LEU and MOX fuels. Such a fleet composition enables the stabilization of spent fuel and plutonium inventories. Previously (ref. 1), a steady state regime was reached by the middle of the next century, thanks to a fleet composed of ~40% SFR.

For a further understanding of this kind of nuclear systems, a new methodology has been applied (ref. 2). This methodology was recently developed to put into equations the equilibrium conditions of nuclear power systems composed of various reactor types. It relies on quantities and grades of plutonium batches that balance through the U/Pu cycle, accounting for the Pu241 decay between a spent fuel unloading operation and its recycling into a new fuel. In-pile irradiation in each reactor type is simulated by 3 functions: plutonium consumption, production, and evolution of its grade.

Fleets with the less SFR are now favored, since SFR are reputed to be more expensive than thermal reactors (ref. 3). Moreover, fast reactor technology still needs development at industrial scale. This study has therefore been performed to determine whether a mixed fleet may be deployed with a reduced fraction of SFR at equilibrium.

II. SFR - EPR nuclear system

A mixed SFR - EPR symbiotic nuclear system is here designed to balance plutonium production in LEU EPR and breeder SFR with plutonium consumption in MOX EPR. Fig. 1 schematizes such a system. It reports the various variables associated to it. In-core and blanket fuels from SFR are reprocessed together.

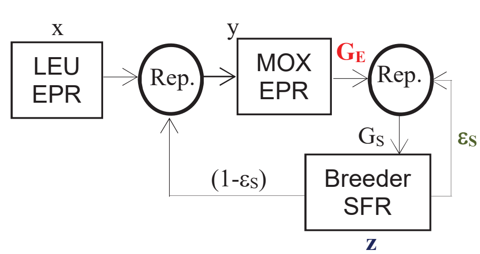

Fig. 1. Scheme of the SFR - EPR symbiotic system.

The fleet in a steady state regime illustrated in fig. 1 is put into equations and solved by applying the methodology described in ref. 2. This methodology has already been successful in describing 100% MOX EPR and breeder SFR symbiotic fleets that close the fuel cycle. Here, LEU in EPR precludes a total independence from uranium ore, but the goal is rather to reduce as far as possible the fraction of SFR it contains.

Table I describes the variables to describe the symbiotic fleet. In a steady state regime, plutonium inventory levels off, as do plutonium fissile grades in MOX EPR and SFR new fuels, respectively noted G_E and G_S.

Table I. Symbol table. Variables are bolded.

Parameter	Unit	Description
x	€[0,1]	LEU fuel fraction in the fleet
y	€[0,1]	EPR MOX fraction in the fleet
z	€[0,1]	SFR fuel fraction in the fleet
N_E	tHM/yr	Pu quantity in new EPR MOX
N_S	tHM/yr	Pu quantity in SFR fuel
P_L	tHM/yr	Pu quantity in spent EPR LEU
P_E	tHM/yr	Pu quantity in spent EPR MOX
P_S	tHM/yr	Pu quantity in spent SFR fuel
Γ_L	€[0,1]	Pu grade in spent EPR LEU
Γ_E	€[0,1]	Pu grade in spent EPR MOX
Γ_S	€[0,1]	Pu grade in spent SFR fuel
g	€[0,1]	Pu fissile grade in new fuel
$\mathbf{G_E, G_S}$	€[0,1]	Equilibrium Pu grades
$\boldsymbol{\varepsilon_S}$	€[0,1]	Self-recycled SFR fuel fraction

Total and fissile plutonium balances can then be written according to system (1), assuming that reactor functions for plutonium quantities and grades at reactor unloading account for Pu241 decay between spent fuel unloading and recycled fuel loading operations, as in ref. 2. Constant cooling and aging times for plutonium recycling make it possible to consider the Am241 stream as an implicit variable. A total and fissile plutonium equilibrium is considered downstream of each reprocessing plant, which explains that there are 4 balance equations in this case.

$$\left|\begin{array}{l} x + y + z = 1 \\ x.P_L + z.(1-\varepsilon_S).P_S(G_S) = y.N_E(G_E) \\ x.P_L.\Gamma_L + z.(1-\varepsilon_S).P_S(G_S).\Gamma_S(G_S) = y.N_E(G_E).\Gamma_E(G_E) \\ y.P_E(G_E) + z.\varepsilon_S.P_S(G_S) = z.N_S(G_S) \\ y.P_E(G_E).\Gamma_E(G_E) + z.\varepsilon_S.P_S(G_S)\ ).\Gamma_S(G_S) = z.N_S(G_S).\Gamma_S(G_S) \end{array}\right. \qquad (1)$$

Table II gathers the main characteristics of EPR and SFR reactors in a nominal regime of operation. EPR and SFR reactors here deliver about the same electrical power. The breeder SFR core is a CFV heterogeneous concept with fertile fuels only made of depleted uranium. These fuels are axially disposed in the core to reach a low void coefficient with respect to safety issues (ref. 5). Fertile blankets are placed at the core periphery in order to reach a conversion ratio around 1.2 (ref. 2). Plutonium content is limited in new MOX fuels for safety reasons. The current limit is fixed to 12% applying conservative margins (Ref. 1).

Tab. II. Description of EPR and breeder SFR.

	LEU EPR	100% MOX EPR	Breeder SFR CFV V1
Power (GWe)	1.529	1.600	1.510
Net yield (%)	35.6	35.6	40.3
Core mass	129 t_{HM}	125 t_{HM}	129 t_{HM}
Core Composition	LEU only	MOX only	40% fissile 60% fertile
Fuel needs (t_{HM}/yr)	LEU: 25.1	MOX: 25.4	Fissile: 8.1 Fertile: 8.7
Fissile fuel BU	51.8 GWd/t	53.5 GWd/t	116.3 GWd/t

III SYMBIOTIC EQUILIBRIUM

System (1) contains 5 equations, whereas 6 variables impact the mixed fleet at equilibrium (in bold in table I). This should result in the existence of several solutions. However, fixing the value of one of these variables makes it possible to find a unique solution to system (1).

In this framework, the value of the SFR fuel fraction that is self-recycled into SFR, ε_S, is first setup between 0 and 1. The nonlinear system (1) is then solved numerically, by minimizing the sum of the squared differences between the left and right members of the 5 equations that compose it, by means of a generalized gradient algorithm. The system converges very quickly to a single solution, whatever the starting solution is. The sum of the squared differences remains below 10^{-9}.

Reactor functions N_E, P_E, Γ_E, N_S, P_S and Γ_S are linear regressions that were previously determined and applied to another type of symbiotic fleet (ref. 2). Fig. 2 presents these functions. It was shown in ref. 2 that results are accurate despite the relatively low correlation coefficient of some linear regressions. Raw data to which regressions apply come from the previous scenario study mentioned above (ref. 1). Plutonium fissile grade g is here expressed as a weight ratio according to relation (2), which does not account for Am241: it refers to the Pu fissile content in total Pu.

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

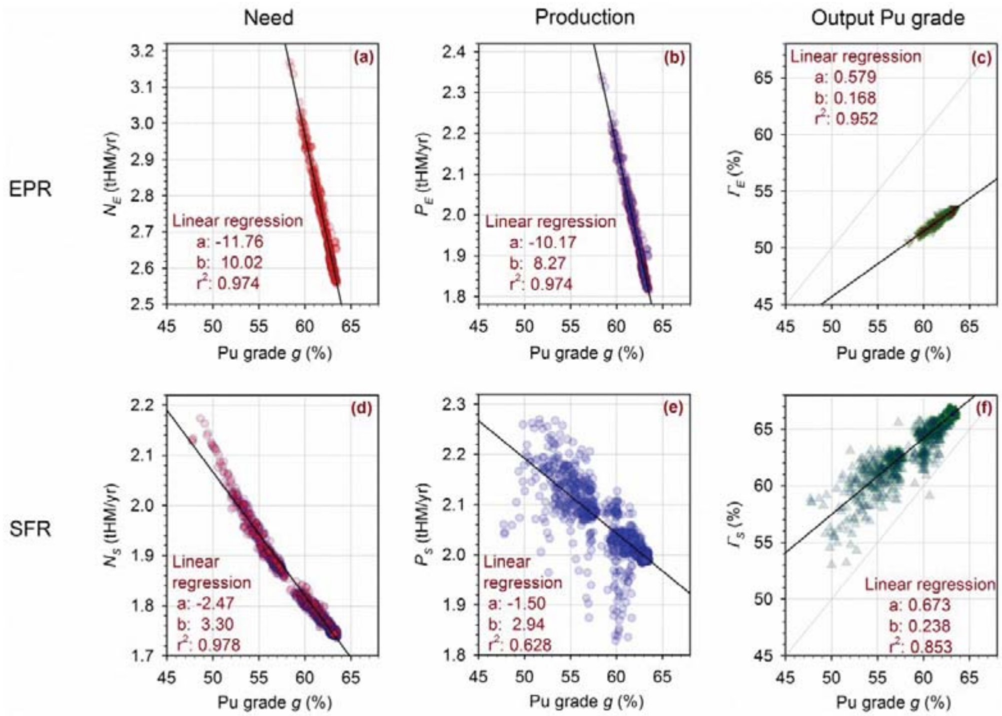

Fig. 2. Reactor functions for MOX EPR and breeder SFR. Reprinted from Ref. 2 with permission from Elsevier.

Plutonium total and fissile gross production functions for MOX EPR and SFR (P_E, Γ_E, P_S and Γ_S) all account for a cooling period of spent fuels of 5 years, followed by 2 years dedicated to the fabrication of new fuels after reprocessing. In the same way, LEU SF plutonium composition is fully determined once the recycling time is defined for this fuel. Recycling time refers to the time that elapses between SF unloading and new fuel loading operations.From ref. 1, the recycling time for LEU SF in the transition scenario of the French fleet is typically 27 years: 25 years of cooling before reprocessing, and 2 years for new fuel fabrication. The equilibrium fleet composition for the studied system has therefore first been determined for this recycling time of 27 years, considering various ε_S values. Fig. 3 reports the results in terms of SFR fraction in the mixed fleet and of plutonium content in new EPR MOX fuels.

IV. DISCUSSION

Fig. 3 reveals that SFR fraction in the fleet as plutonium content in new MOX EPR fuels are both correlated to ε_S. Indeed, SFR in breeder mode are known to improve plutonium fissile grade, so that more SFR fuel is self-recycled, more Pu grade in new fuels improves, but more SFR are required to consume this additional Pu. Since acceptable solutions should minimize the fraction of relatively expensive SFR, but should stand within the domain where the Pu content in new MOX fuel remains below 12% for safety reasons, fig. 3 shows that there exists a best compromise for the composition of the mixed fleet.

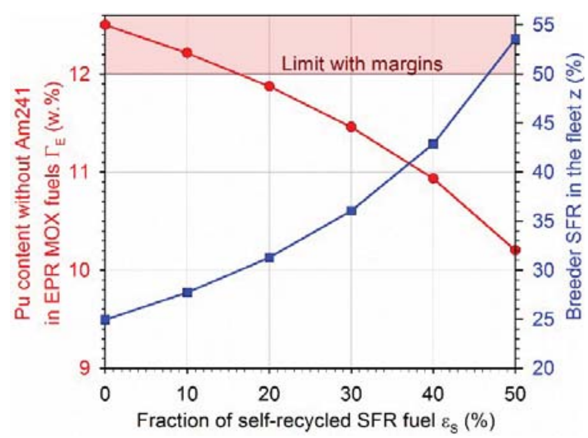

Fig. 3. Symbiotic fleet composition assuming a LEU SF recycling period of 27 years.

Indeed, for ε_S near 20%, plutonium content in new MOX fuel lies just below 12%, while the fraction of SFR in the fleet falls down near 30%. This is about 10% (absolute value) less than the SFR fraction in the mixed fleet that has been deployed in the previous scenario (ref. 1). In ref. 1, when the fleet operates between 2130 and 2150, plutonium content in new MOX fuels decreases below 11%. The previous mixed fleet actually corresponds to a solution near ε_S = 40%, with a SFR fraction above 40%. Indeed, this previous scenario study did not target the reduction of the SFR fraction in the fleet.

Results reported in fig. 3 are however relative to a 27-year recycling period of LEU SF. This period applied in the previous progressive transition scenario in ref. 1. The mixed fleet that stabilized the plutonium inventory was deployed by the middle of the next century. The reprocessing in use, based on a FIFO management of SF, stabilized the mean SF cooling time at reprocessing.

However, a new progressive transition scenario is now being built to reduce as far as possible the SFR fraction in the fleet. For this new transition scenario applied to the French fleet, a different reprocessing strategy than before may be used for a further reduction of the SFR fraction z. This might be the case if the equilibrium fleet composition varies strongly with the grade of the plutonium from LEU SF, which falls as time elapses due to Pu241 decay notably. Fig. 4 reports the evolution of the Pu grade of LEU SF with time.

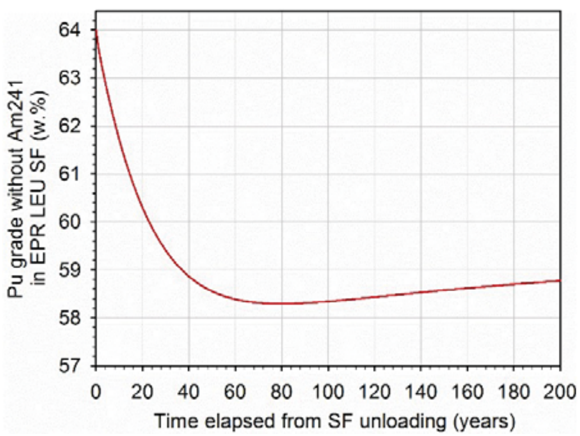

Fig. 4. Pu fissile grade in LEU SF as time elapses.

Plutonium contained into LEU SF degrades due to Pu241 decay (half-life 14.4 years) during first decades of cooling. After 80 years however, there is almost no Pu241 left, whereas Pu238 decays with a period of 87.8 years. The quantity of plutonium inside LEU SF goes on decreasing, but its grade improves. Thus, plutonium grade is minimum after 80 years.

In these conditions, relevant Pu grades for LEU SF can be described as mixtures of 80-year cooled plutonium (cold) with fast-recycled plutonium of high grade (hot). Considering that minimum cooling and fabrication times are respectively of 5 and 2 years in our scenario studies, hot plutonium cools down for 7 years only. Its Pu grade is of 62.3% whereas cold plutonium degrades to 58.3% after 80 years of cooling and 2 years of aging. In this respect, a 27-year recycling time of LEU SF corresponds to a mix containing 70% of cold Pu in weight ratio.

Thus, system of equations (1) has been solved for several mixtures of hot and cold plutonium from LEU SF. Fig. 5 reports the equilibrium fleets found for several values of ε_S. When more plutonium from hot LEU SF is put in the mix, for a given Pu content in MOX fuels Γ_E near the 12% limit, the fraction of SFR falls, as the fraction of self-recycled SFR fuel ε_S. Fig. 5 shows that there should be around 2.5% SFR less in the fleet when hot LEU SF are reprocessed only (LIFO).

Assuming a constant electricity production, the French fleet should be composed of near 40 1.5 GWe reactors. In this context, reprocessing hot LEU SF only (LIFO) may save about one SFR in a steady state regime. LIFO management would however induce a rapid aging of the remaining SF.

Moreover, construction costs can be significantly reduced by building 2 same reactors in a single site (ref. 1). Saving less than 2 reactors may eventually be expensive in these conditions, if numbers of EPR and SFR become odd. Finally, the reduction of the SFR fraction with alternative reprocessing strategies appear relatively low. This is why the reprocessing strategy should remain unchanged in the new scenario under construction. This new transition to a symbiotic fleet of LEU EPR, MOX EPR and SFR should nonetheless reduce the SFR fraction in the fleet of around 10% at equilibrium. Fleet should finally contain 12 SFR instead of 16 (ref. 1). COSI6 (ref. 6) is being used to simulate the new scenario, that will be described in a future paper.

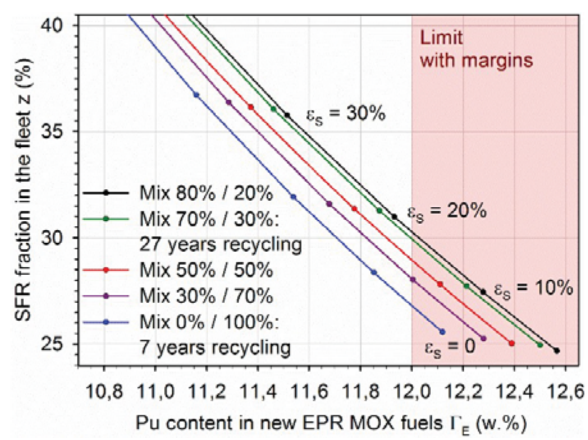

Fig. 5. Symbiotic fleet composition with various mixtures of Pu extracted from cold and hot LEU SF respectively.

V. CONCLUSION

In the framework of scenarios simulating the evolution of the French fleet, reactor composition may eventually come to a mix of breeder SFR and EPR supplied with LEU and MOX fuels. Such a fleet composition enables the stabilization of spent fuel and plutonium inventories. Previously, a steady state regime was reached by the middle of the next century thanks to a fleet composed of ~40% SFR.

For a further understanding of this kind of nuclear system, a new methodology has been applied. This methodology was recently developed to put into equations the equilibrium conditions of advanced nuclear power systems. It relies on quantities and grades of plutonium batches that balance through the U/Pu cycle, accounting for the Pu241 decay between a spent fuel unloading operation and its recycling into a new fuel. In-pile irradiation in each reactor type is simulated by 3 functions: plutonium consumption, production, and evolution of its grade.

Fleets with the less SFR are now favored, since SFR are reputed to be more expensive than thermal reactors. Results show that the fraction of SFR in the fleet should be reduced of around 10% in comparison to the fleet previously deployed. However, the solution that minimizes the SFR fraction in the fleet at equilibrium leads to plutonium contents in EPR MOX fuels near the safety limit that is currently accounted for.

A new scenario of progressive SFR deployment in France will be published soon based on this theoretical study. The fleet near 40 reactors should finally contain 12 SFR at equilibrium, instead of 16 previously.

NOMENCLATURE

ASTRID French SFR demonstrator.
COSI6 CEA scenario software.
EPR European Pressurized Water Reactor.
FIFO First In First Out SF management.
LEU Low Enriched Uranium.
LIFO Last In First Out SF management.
MOX Mixed (U,Pu) Oxide.
PWR Pressurized Water Reactor.
SF Spent Fuel.
SFR Sodium Fast Reactor.

ACKNOWLEDGEMENTS

The authors are grateful to ORANO, FRAMATOME and EDF for their support to this work through the ACF research program.

REFERENCES

1. G. MARTIN et al., “French transition scenarios toward a symbiotic nuclear fleet”, Proc. of ICAPP, San Francisco, USA (2016)
2. G. MARTIN et al., “Symbiotic equilibrium between sodium fast reactors and pressurized water reactors supplied with MOX fuel”, Annals of nuclear energy 103 (2017) 356-362
3. C. CHABERT et al., “Feasibility of future prospects and transition scenarios for the French fuel cycle”, Proc. of GLOBAL, Seoul, Korea (2017)
4. G. MARTIN et al., “French transition scenarios toward Sodium Fast Reactors in this century”, Proc. of GLOBAL, Seoul, Korea (2017)
5. L. BUIRON, L. DUJCIKOVA, “Low void effect (CFV) core concept flexibility: from self-breeder to burner core”, Proceedings of the ICAPP 2015 Conference, Paper 15091 (2015)
6. C. COQUELET-PASCAL et al., “Cosi6: a tool for nuclear transition scenarios studies and application to SFR deployment scenarios with minor actinides transmutation”, Nuclear Technology 192 (2015) 91-110