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In France, the COSI6 software can simulate prospective scenarios of nuclear energy evolution. Nuclear scenarios focused these last years on the development of SFR technology. However, SFR are more expensive to build than thermal reactors. In case SFR would not become economically competitive in the next decades, MOX spent fuels would pile-up in the backend of the fuel cycle, unless alternative solutions of plutonium management in PWR were found. In this study, advanced EPR (European Pressurized water Reactor) fuel designs are applied to enable plutonium multi-recycling and stabilization of all spent fuel: CORAIL refers to fuel assemblies containing LEU and MOX rods, and MIX (also called MOXEUS) to assemblies where fuel rods are composed of plutonium mixed with enriched uranium.

Scenarios results reveal that introducing MIX and CORAIL in EPR by the middle of the century can lead to a fast stabilization of spent fuel and plutonium inventories. With respect to open cycle, more minor actinides (MA) accumulate (about +70%), but the production of transuranic elements (Pu + MA) remains almost 3 times less. Furthermore, all high-level wastes are now packaged for long-term storage.

Besides, spent fuels still contain significant quantities of fissile uranium. In MIX scenarios however, this uranium may be enriched and easily recycled into dedicated EPR for efficient natural uranium savings. In this case, the resource balance is significantly better than in open cycle (-30%). Multi-recycling in PWR appears therefore to be a viable temporary solution, allowing for spent fuels and wastes management until we expect the running out of natural uranium.

I. INTRODUCTION

Scenario studies are used in France to explore possible prospective developments of nuclear energy. Within this framework, scenarios are built within the limits of conservative criteria defined and validated with the French industry: EDF, ORANO and FRAMATOME. These criteria make the scenario realistic as regards to our current knowledge of safety, regulation, technology and costs. The COSI6 software developed by CEA (Ref. 1), which relies on the CESAR5.3 irradiation and evolution simulation code, is used to simulate these scenarios and to evaluate them with respect to uranium and plutonium management, fuel reprocessing and wastes production notably.

Nuclear scenarios focused these last years on the development of SFR technology. In the next decades, a progressive deployment of SFR of increasing power may occur in France to recycle the plutonium from the spent PWR MOX fuels (Ref. 2). Indeed, Pu in LEU spent fuel is currently recycled into MOX fuel assemblies, but the low-grade plutonium that MOX spent fuels contain cannot be recycled into new MOX fuel. Pu content in new PWR fuel is limited for safety reasons (Ref. 3), whereas successive recycling steps make Pu content increasing as its fissile grade falls down. Thereafter, in the next century, SFR technology might be applied to stabilize the Pu inventory, and ultimately to close the fuel cycle (Ref. 4).

However, SFR are expected to be more expensive than thermal reactors (Ref. 5). In case SFR would not become economically competitive in the next decades, MOX spent fuels would pile-up in the backend of the fuel cycle, although at a much slower pace than LEU would without MOX, unless alternative solutions of plutonium management in PWR were found. In this study, the use of advanced EPR (European Pressurized water Reactor) fuel designs is presented to enable plutonium multi-recycling and stabilization of all spent fuel. Two PWR assembly designs are studied in this paper. CORAIL refers to fuel assemblies containing LEU and MOX rods, and MIX to an assembly where fuel rods are composed of plutonium oxide mixed with enriched uranium oxide (Ref. 6).

II. SIMULATION

II.A. CORAIL and MIX EPR concepts

Plutonium multi-recycling in PWR requires maintaining the Pu content in new fuels below a safety limit, currently defined to 12% (Ref. 3) by applying conservative margins. In this context, natural uranium resources, whose availability justifies postponing SFR development, may be used to compensate for the degradation of the fissile quality of the plutonium. A supply in enriched uranium may therefore help keeping the plutonium content inside new PWR fuels below the safety limit.

In this context, loading standard EPR cores with innovative fuel assemblies is an attractive option, since EPR should replace current French PWR in the next decades. This may constitute a flexible and quick response to the current accumulation of plutonium and PWR MOX spent fuels. However, EPR are Gen 3+ PWR with a conventional core design, which means a rather low conversion rate in a thermal neutron spectrum. In those conditions, plutonium multi-recycling in EPR would be acceptable as long as a U235 input could compensate for its net consumption in fissile isotopes. In this study, 2 concepts were retained for their industrial maturity in terms of reactor and cycle technologies:

- CORAIL: Each fuel assembly consists in 17×17 fuel rods containing a mixture of LEU and MOX rods. MOX fuel is classically made of plutonium completed by depleted uranium. The numbers of LEU and MOX rods in each assembly are 181 and 84 respectively, with MOX rods placed far from guide tubes to avoid undesirable power peaks: CORAIL consists therefore in MOX ringed assemblies, as shown in Fig. 1. Each LEU rod is enriched to a high value, 5% in U235, in order to reduce the Pu content as far as possible despite its degradation.
- MIX (also called MOXEUS): each fuel assembly is composed of fuel rods with a fixed Pu content. Plutonium is completed with uranium enriched to a content in U235 suited to compensate for the low Pu grade. Here, Pu contents are as follows: 8%, 9.54%, or 12%.

For CORAIL and MIX concepts, neutron transport calculations at the scale of the EPR core did not reveal any positive void coefficient. Since the proximity of LEU assemblies with such assemblies should lead to power peak issues, starting cores of EPR are here made of CORAIL or MIX fuel assemblies only. For the time being, no reloading pattern has been defined for the first cycles of operation, so that only fresh fuel is considered to be loaded. This assumption is challenging in terms of plutonium availability since fresh fuel contains more Pu than required to guarantee the core reactivity. In nominal operation, all EPR deliver 1.53 GWe, with fuel batches irradiated to 51.8 GWd/t after 3 cycles of 517 EFPD. Core mass is 129 tHM and a load factor of 83% is considered, accounting for power ramps.

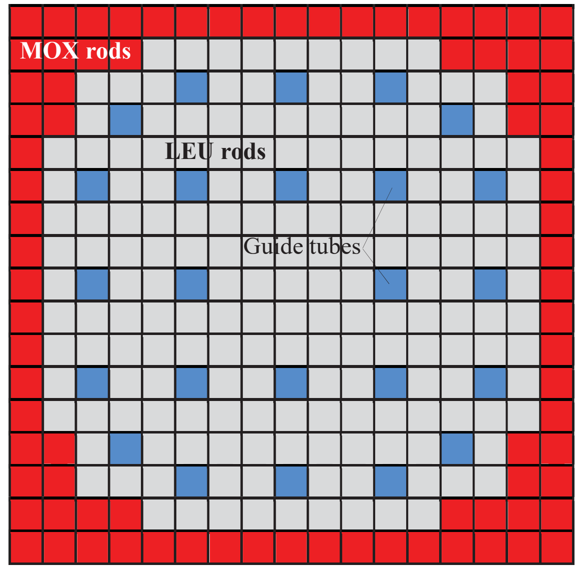


Fig. 1. CORAIL 17×17 heterogeneous assembly in EPR.

II.B. Scenarios

In total, 5 CORAIL and MIX scenarios were simulated. Table 1 below summarizes the main characteristics of the fleets in equilibrium deployed during these scenarios before the end of this century. The main objectives of these scenarios are: fast recycling of all used MOX fuels, then the stabilization of the plutonium inventory as well as of all spent fuel stocks. In equilibrium fleets, Pu production in LEU compensates for Pu consumption in CORAIL or MIX fuels. The CORAIL EPR concept presented here is near the break-even point in terms of Pu balance, explaining why only a few LEU EPR are deployed in a steady-state regime in that case.

Tab. I. CORAIL and MIX scenarios: fleet composition in a steady-state regime (Pu and SF stabilized).

Scenario name	(U,Pu) fuel	EPR fleet composition		
		CORAIL or MIX	LEU	ERU
CORAIL	MOX, with a variable [Pu]	36	2	0
MIX 8%	MIX, with [Pu] = 8%	14	24	
MIX 9,54%	MIX, with [Pu] = 9.54%	13	25	0
MIX 12%	MIX, with [Pu] = 12%	11	27	
9.54% MIX with ERU	MIX, with [Pu] = 9.54%	13	18	7

First, a transition scenario was simulated toward an EPR fleet essentially supplied with CORAIL fuels. A transition to a fleet of EPR supplied with LEU and MIX fuels was built for each of the 3 Pu contents considered for the MIX fuel: 8%, 9.54% and 12%. Finally, the 9.54% MIX scenario led to a last MIX scenario by substituting some LEU fuel batches by ERU fuel batches, in order to stabilize the stock of reprocessed uranium (RepU).

Electric power production is here assumed to remain constant, so a reactor shutdown has to occur to start a new unit. The replacement period of the current French fleet to the new EPR fleet occurs typically between 2030 and 2060. The lifetime of EPR is assumed 60 years. Fuel fabrication lasts 2 years and a 5-year cooling period is at least required before spent fuel reprocessing.

Until 2045, the scenarios are almost identical to the baseline scenario described in Ref. 2. The deployment of the first EPR (excluding Flamanville 3) begins in 2029, with the introduction of the first MOX refills around 2036 in these new reactors. Before 2045, a notable difference with the scenario from Ref. 2 remains the absence of the ASTRID SFR demonstrator from the late 2030's.

II.C. Timeframe of reactor deployment

In Fig. 2, the scenario CORAIL leads to a massive and fast deployment of CORAIL fuel batches from 2045. It is therefore necessary to supply with CORAIL all the EPR started between 2029 and 2045: they are shut down in 2045 and then restarted with CORAIL assemblies only. From the early 2060's, the fleet is predominantly composed of CORAIL EPR (95%) in a steady-state regime. The equilibrium fleet composition is adjusted in order to control the accumulation of plutonium in the cycle. Under these conditions, the MOX ratio remains high, the flow of MOX fuels accounting for nearly 30% of the total fuel flow. This is about 3 times greater than the MOX flow in the current French fleet.

The number of MIX EPR in the equilibrium fleet depends on the plutonium content in MIX fuels, as shown in Fig. 3. The higher it is, the more the plutonium consumption in each MIX reactor, and the fewer MIX reactors are needed to compensate for the plutonium production in the complementary LEU batches. Thus, while 14 8% MIX EPR are required to stabilize the plutonium inventory in the presence of 24 LEU EPR, only 11 EPR are required for LEU when the MIX plutonium content equals 12%. The MIX ratio of the fleet varies between 29% and 37% depending on the plutonium content inside MIX fuels. In the case of MIX scenarios, it should be easier to limit plutoniferous fuels in only a small part of reactors and facilities. This is in favor of the MIX concept, since Pu has appeared relatively hard to manage in the front-end of the fuel cycle.

6 PWR of 1300 MWe are loaded with ERU fuels between 2025 and 2029 to stop the growth of the reprocessed uranium (RepU) stock. Under these circumstances, the last batch of ERU fuel is loaded into these PWR in 2047. However, ERU management can resume in EPR to go on limiting the growth of the RepU

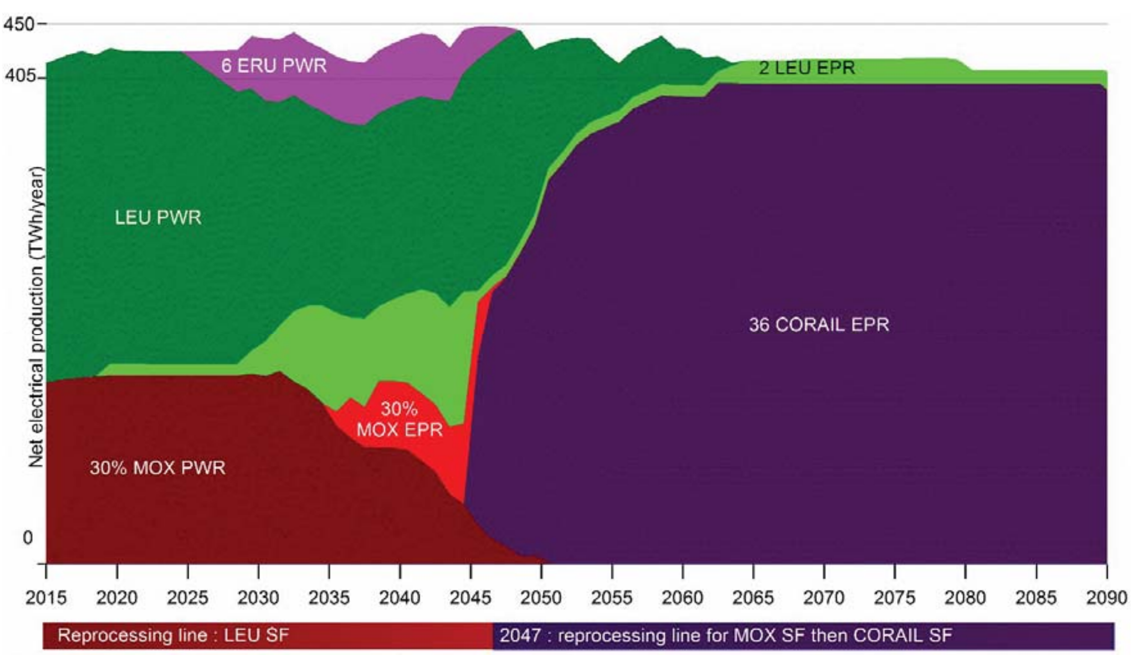


Fig. 2. Scenario CORAIL.

stock. This is what is done during the MIX 9.54% scenario with ERU, shown in Fig. 4. To stabilize the RepU stock, it is necessary to supply 7 EPR with URE.

Where 4 ERU EPR were sufficient to stabilize the RepU stock in Ref. 2, it now takes 7 in the 9.54% MIX scenario. This difference is mainly because there is still a lot of U235 in reprocessed uranium from spent MIX fuel. This increase in fissile uranium therefore supplies more reactors at equilibrium. ERU is easy to load in EPR which would have been supplied with LEU fuel instead. With only 2 EPR supplied with LEU in the CORAIL equilibrium fleet, RepU recycling into ERU fuel appears therefore harder to apply.

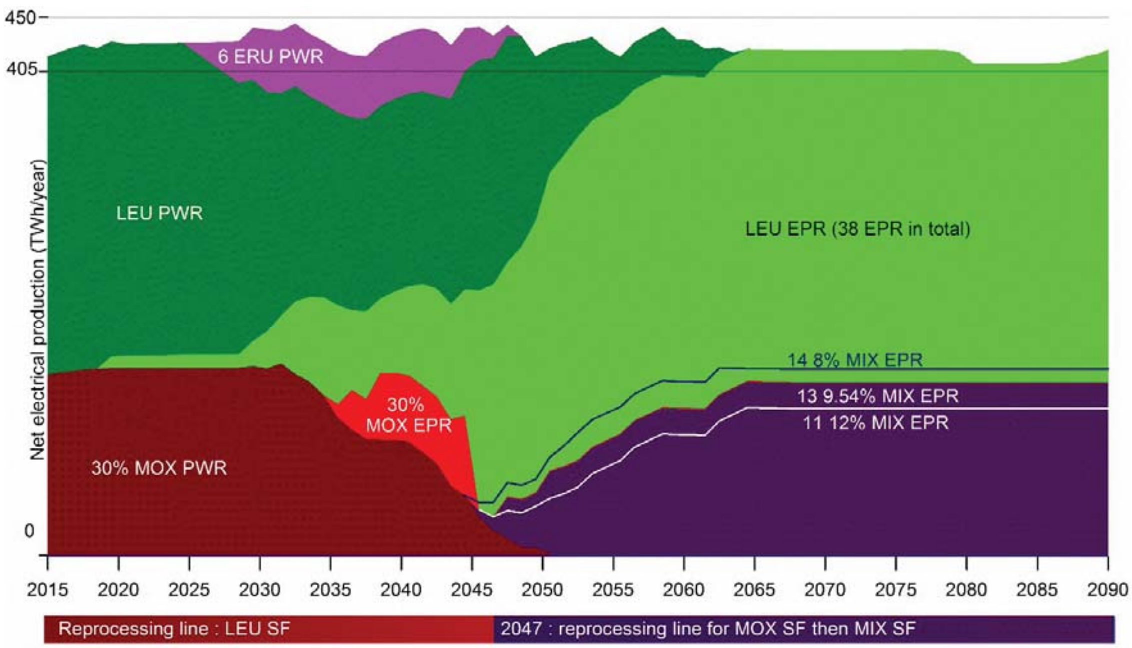


Fig. 3. Scenarios MIX without uranium recycling into ERU fuel.

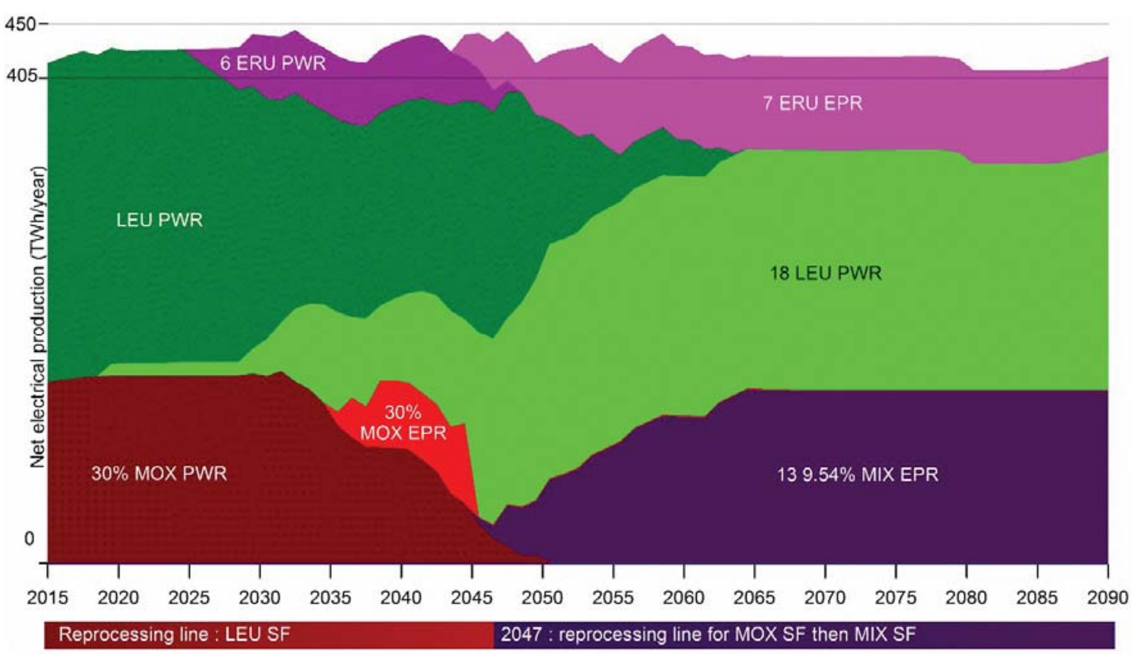


Fig. 4. Scenario 9.54% MIX with ERU.

III. CYCLE FRONT-END

III.A. Uranium

There are basically 2 ways to reduce natural uranium consumption in the U / Pu cycle. The first goes through a better consumption of the fissile part of the resource: U235. When spent LEU fuel is unloaded from a reactor, it still contains fissile U235 atoms. Under certain conditions, the increase in the LEU fuel burnup can contribute to reducing this residual. In addition, making ERU fuel through reprocessed uranium enrichment amounts to recycling part of it.

The second way to reduce natural uranium consumption is to better utilize the fertile part of the resource (U238 essentially). This part converts into fissile plutonium under neutron flux. In plutonium multi-recycling conditions, reactor with conversion ratio close to unity makes it possible to close the fuel cycle. Finally, the natural uranium consumption in a fleet reflects its efficiency in consuming the heavy nuclei contained in natural resources, whether they are fissile or fertile.

Natural uranium consumption in CORAIL and MIX fleets is compared to the one for "step A" (Ref. 5). "Step A" refers to a realistic situation in France, where plutonium and U235 are respectively mono-recycled into MOX and ERU fuels, for resource savings around 20% with respect to open cycle. Fig. 5 reveals that without ERU, CORAIL and MIX scenarios lead to natural uranium consumption slightly higher than for "step A".

Indeed, plutonium multi-recycling, which comes to a better consumption of the fertile part of uranium, leads to a lesser consumption of its fissile part: U235 introduced in CORAIL and MIX assemblies is poorly used, so that it can still weight almost 2% of MIX spent fuel. In comparison, standard LEU spent fuel contains less than 0.8% of U235.

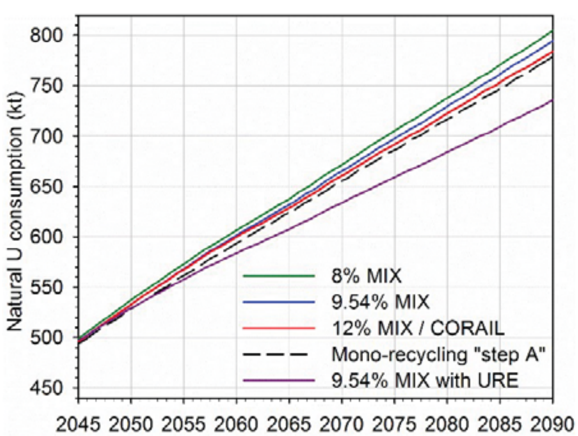


Fig. 5. Natural uranium consumption.

The MIX 9.54% scenario with URE applies U235 recycling. Compared to "step A", this scenario therefore leads to a reduction in resource consumption near 10%, for a cumulative consumption around 740 kt by 2090. Since ERU is harder to introduce in the CORAIL equilibrium fleet, associated resource savings appear more hypothetical with CORAIL.

III.B. Fresh CORAIL and MIX fuels

The plutonium grade falls down when plutonium is multi-recycled in standard PWR: this is illustrated in Fig. 6, which reports the isotopic composition of the plutonium in new MIX fuels during the 9.54% MIX scenario. Until 2049, the high fissile grade of the plutonium inside first MIX refills comes from the fact that they are made of Pu from LEU SF. After that, plutonium even isotopes tend to accumulate in new MIX and CORAIL fuels, in particular Pu242. Plutonium isotopic vector seems however to tend to an asymptote near 2090. Actually, simulations of equilibrium fleets over 3 centuries have shown that the fissile grade of the plutonium levels off around 45% (including Am241), for a Pu242 content over 20%. This has demonstrated that plutonium multi-recycling in PWR may physically work.

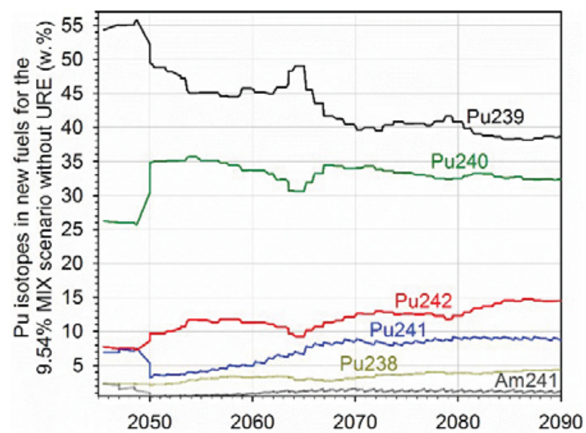


Fig. 6. Plutonium isotopic composition of MIX new fuels for the 9.54% MIX scenario.

Fig. 7.a indicates that the Pu content inside MOX rods of CORAIL assemblies remains below 8%. Fig. 7.b reports the enrichment of the uranium in MIX fuels. From 2050, since the Pu of MOX SF is relatively degraded, its introduction rapidly rises the enrichment of uranium in MIX fuels. Cyclic variation of the enrichment stems here from reprocessing of SF always in chronological order of their arrival in the stock (FIFO): relevant mixing of Pu from the various SF would no doubt smooth its evolution.

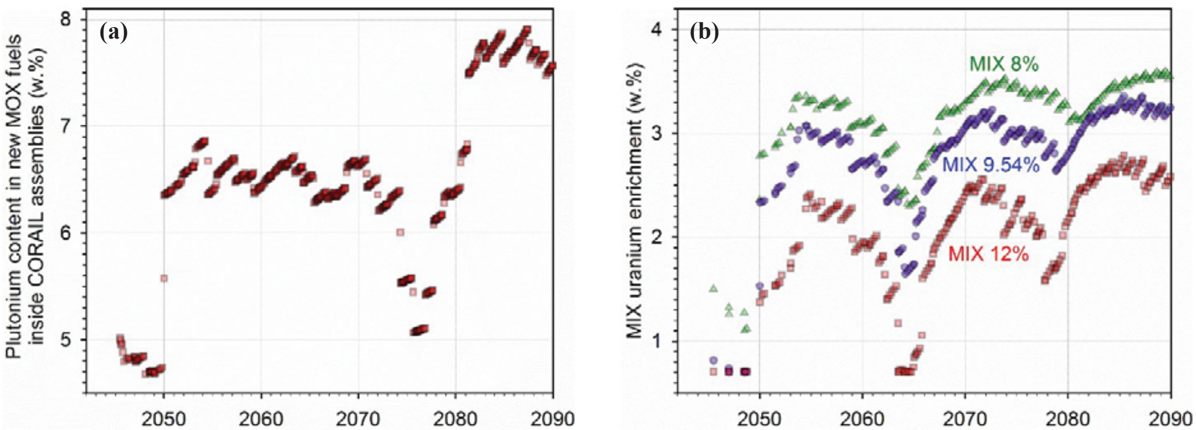


Fig. 7. Pu content in MOX rods of fresh CORAIL assemblies (a) and uranium enrichment in new MIX fuels (b).

III.C. Fuel fabrication

Fig. 8 reports the fuel fabrication for the CORAIL scenario (Fig. 8.a) and for the 9.54% MIX with ERU scenario (Fig. 8.b), this last being representative of the other MIX scenarios. In Fig. 8.a, since most EPR aim at being supplied with CORAIL assemblies once the equilibrium fleet is deployed, fuel fabrication is rapidly dedicated mostly to CORAIL assemblies after 2045. This constitutes an industrial penalty for the CORAIL concept presented here, even if CORAIL fabrication is already accessible in France since LEU and MOX fuel rods are today commonly used. Anyway, a new fabrication plant would be required to make enough CORAIL assemblies for the fleet in a steady-state regime. Moreover, in current conservative assumptions relative to core management (see section II.A), the massive introduction of CORAIL fuel leads around 2045 to stopping and restarting most of EPR cores, which induces a strong fabrication overcapacity for several years (Fig. 8.a).

In the current French MOX fuel fabrication plant, the criticality management of uranium is scaled to depleted uranium or natural uranium, not to enriched uranium. A new plant would be also required to make MIX fuel in this case. Besides, in a steady-state regime, far less MIX fuel is needed in comparison to CORAIL, although MIX fabrication capacity would have to rise of a factor around 3 above the current one dedicated to MOX fuels in France. Indeed, LEU remains the main fuel in the equilibrium MIX fleets, even when a fraction of LEU is replaced by ERU to improve U235 valorization (Fig. 8.b).

IV. CYCLE BACK-END

IV.A. Reprocessing

As currently done in France, spent fuel reprocessing extracts plutonium and uranium for further recycling in one hand, and minor actinides and fission products for wastes storage in the other hand. Plutonium and uranium are managed separately. Minor actinides and fission products are embedded into glass packages.

Fig. 9 reports SF reprocessing during the CORAIL and 9.54% MIX scenarios. In Fig. 9.a, the reprocessing capacity applied to each kind of fuel is same as the fabrication capacity when the CORAIL fleet has reached a steady-state regime (Fig. 8.a). This makes the quantity of each SF stabilized.

Fuel flows at fabrication and reprocessing steps are equalized in the equilibrium MIX fleets that exclude ERU use likewise. Fig. 9.b is typical of the reprocessing for MIX scenarios. When ERU fuel is operated, it is not reprocessed since current assumptions do not consider ERU reprocessing for this century. Total SF quantity is nevertheless stabilized, but ERU spent fuel accumulates while LEU spent fuel is consumed at the same rate in this period.

Fig. 9.b also reveals a high reprocessing capacity dedicated to MOX fuels between 2047 and 2060, until the MOX SF stock dries out. It is of 418 tHM/yr. This proactive recycling is consistent with the main objective of these scenarios: recycling all used MOX fuels as quickly as possible. However, if priority would no longer be given to the recycling of MOX SF, the capacity for this fuel reprocessing may be substantially reduced.

Fig. 9.a shows a lower MOX reprocessing capacity during the CORAIL scenario, as MOX SF take more time to recycle in this case (see section IV.B). As compared to the current situation in France where only LEU fuels are recycled, new facilities should be built for rich-Pu SF reprocessing at industrial scale from 2047.

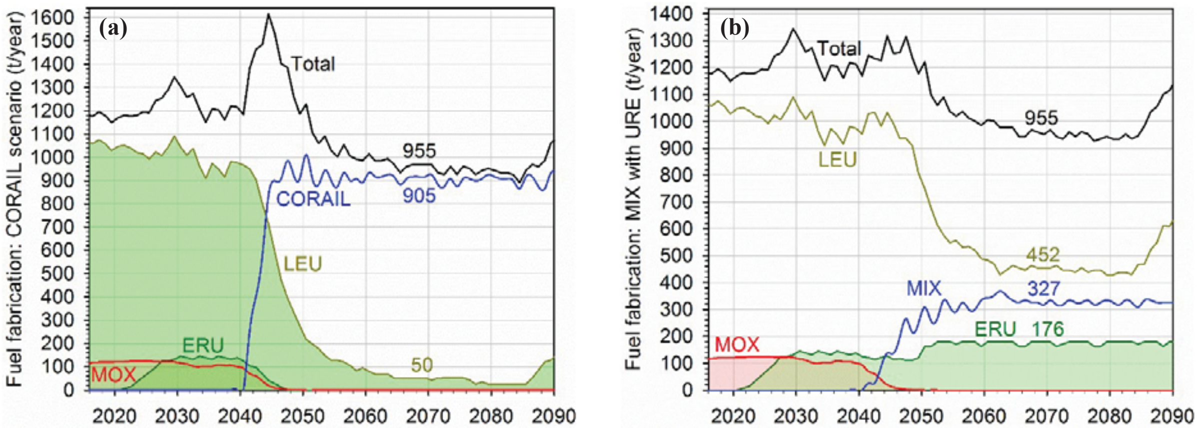


Fig. 8. Fuel fabrication during the CORAIL scenario (a) and during the 9.54% MIX with ERU scenario (b).

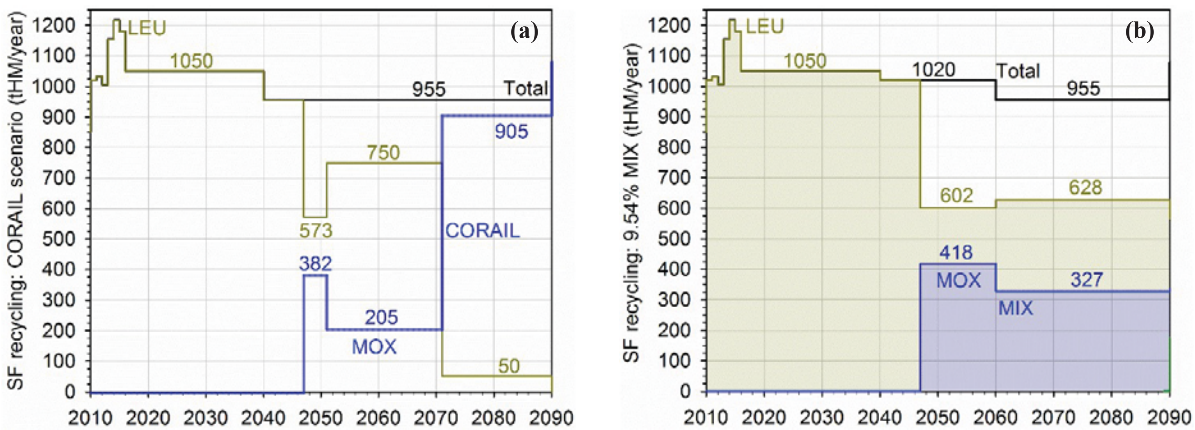


Fig. 9. Fuel reprocessing during the CORAIL scenario (a) and during the 9.54% MIX scenarios (b).

IV.B. Spent fuel

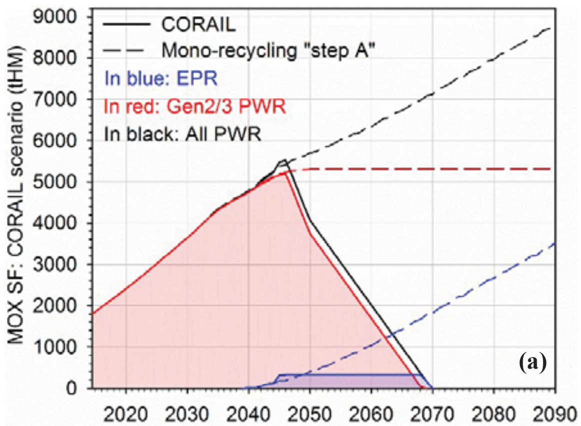
Fig. 10 reports the evolution of the quantity of MOX spent fuels for multi-recycling scenarios. MOX SF reprocessing starts in 2047. In the case of the CORAIL scenario, there is no longer MOX SF from 2070 (Fig. 10.a). MOX SF run out 10 years sooner during MIX scenarios, with a complete recycling of all MOX fuels only 15 years after the first introduction of innovative fuel batches in EPR, in 2060 (Fig. 10.b). MOX recycling takes 10 years more for CORAIL, because less plutonium is introduced in CORAIL fuels compared to MIX fuels, so that the recycling of the Pu in MOX SF lasts longer. It is worth noting that the quantity of MOX SF would be increasing if the “step A” mono-recycling option remained applied, as shown in dot curves in Fig. 10.

Fast recycling of MOX SF is the first goal of these multi-recycling scenarios, and results show that this objective is reached applying ambitious reprocessing (see section IV.A). Capacity associated to MOX SF reprocessing would nevertheless be reduced if more time was left for their recycling.

Fig. 11 draws the total quantity of spent fuels along the various scenarios. MIX scenarios stabilize the stock to 21 ktHM, while for CORAIL spent fuels represent about 24 ktHM when the steady-state is reached. This 3 ktHM difference stems essentially from the fact that MOX SF have to be reprocessed more slowly during the CORAIL scenario.

IV.C. Plutonium

The total plutonium inventories in the different scenarios are shown in Fig. 12: they are relatively stable from 2060, especially during fleet equilibrium periods. This stabilization, which is the second main objective of the multi-recycling scenarios after the recycling of all MOX SF at the earliest, is therefore reached only about 15 years after the introduction in EPR of the first MIX or CORAIL batch (2045). With inventories around 650 tons at the end of the scenarios, the levelling-off of the inventory appears clearly in Fig. 12.



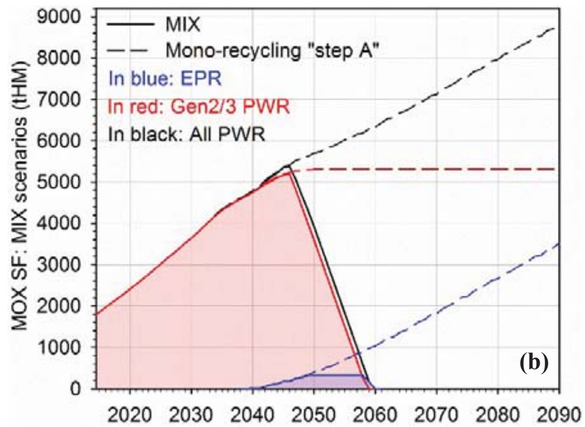


Fig. 10. MOX spent fuels for the CORAIL (a) and MIX (b) scenarios.

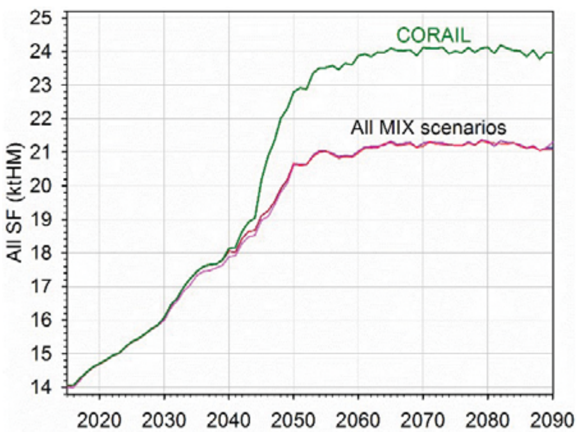


Fig. 11. Spent fuels: total quantity.

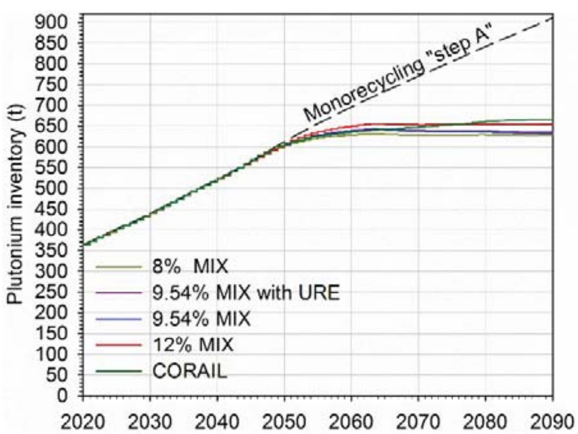


Fig. 12. Plutonium inventory.

Fast plutonium stabilization contrasts well with the plutonium production that continues when applying “step A” mono-recycling, reported in dots in Fig. 12. In this latter case, plutonium inventory reaches 900 tons in 2090. Compared to 650 tons, this is far more favorable to an ambitious deployment of fast reactors, if natural resources were to become scarce.

In this context, one should keep in mind that these multi-recycling scenarios maximize the use of innovative EPR fuels, with the aim of stabilizing the plutonium inventory at the earliest, and therefore at the lowest. This objective is contradictory with a massive deployment of fast reactors, which requires having accumulated a lot of plutonium. In the end, a choice must be done: either we want to reduce the amount of plutonium, or we want to accumulate enough Pu to close the cycle, but we cannot fully commit into both ways. An introduction of new EPR fuels at a more moderate pace would no doubt make it possible to stabilize the plutonium at a higher level, considered satisfactory with respect to the risk on the scarcity of resources.

IV.D. Minor actinides

Minor actinides (MA) refer here to americium, neptunium and curium (without protactinium). Fig. 13 presents MA production for CORAIL and MIX scenarios. It is compared to MA production during the “step A” mono-recycling option that could already apply in France. In multi-recycling fleets at equilibrium, MA production is 30% to 35% higher than in mono-recycling, at 4.2 to 4.5 t/yr instead of 3.3 t/yr. for “step A”. It is particularly high when ERU fuel is used (9.54% MIX with ERU scenario), since ERU fuels contain U236 that leads to an additional neptunium production through successive neutron captures.

Large amounts of Pu even isotopes (reputed non-fissile) are introduced in new fuels in equilibrium fleets, which explains why MA production is enhanced. However, whereas plutonium fissile grade tends to 45%, one can estimate that about 55% of plutonium atoms lead to a power generating fission. Indeed, some Pu even isotopes convert into fissile Pu odd isotopes, and some minor actinides such as Am242 or Cm245 are very fissile.

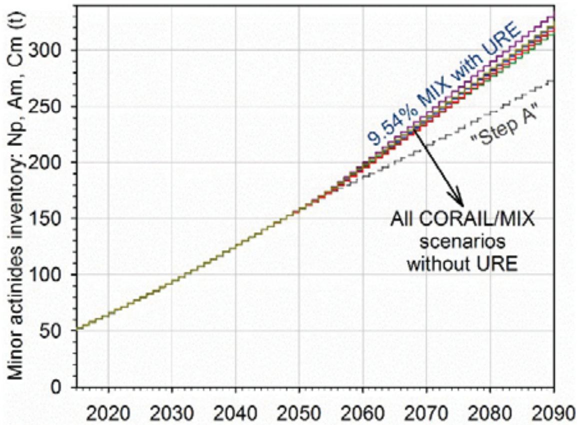


Fig. 13. Minor actinides.

As MA constitutes the first contribution to the high-level wastes once the plutonium has been extracted from spent fuels, enhanced MA formation should increase glass packages production as compared to the mono-recycling situation. However, multi-recycling implies that all the wastes produced by the fleet are managed in a steady-state regime, whereas for "step A", a part of high-level wastes accumulate into increasing stocks of spent fuels (*i.e.* MOX and ERU fuels). Multi-recycling constitutes therefore a step toward sustainability, although the associated fuel cycle remains partly open as regards uranium resource consumption.

V. CONCLUSIONS

Closing the fuel cycle thanks to SFR is a top-ranking strategy for the long-term development of nuclear power in France. But SFR may not become economically competitive in the next decades if uranium resources remain available, and MOX spent fuels might pile-up in the backend of the fuel cycle, unless alternative solutions of plutonium management in PWR were found. In this study, advanced fuel batches, called CORAIL and MIX, are applied to enable multi-recycling in standard PWR. In the context of this study, CEA, ORANO, FRAMATOME and EDF have decided to propose alternative scenarios that aim fast MOX recycling and swift stabilization of all spent fuel and plutonium inventories in the cycle back-end.

Scenarios results reveal that introducing MIX and CORAIL in EPR by the middle of the century can lead to a fast stabilization of spent fuel and plutonium inventories, after all MOX SF have been recycled. Also, total plutonium inventory is fast stabilized at a low level. Low Pu level may hinder a massive deployment of fast reactors, which might be required to close the fuel cycle in case of resource rarefaction. An introduction of new EPR fuels at a more moderate pace should nevertheless make it possible to stabilize the Pu at a higher level.

Plutonium multi-recycling enhances minor actinides production. The production of transuranic elements (Pu + MA) remains however almost 3 times less than in open cycle, which is significant considering that plutonium would remain the main contributor to wastes radiotoxicity if it were not be recycled. In addition, with respect to open cycle and the "step A" mono-recycling strategy with standard MOX and ERU fuels, there are no more wastes accumulation in spent fuel assemblies: all the minor actinides and fission products are confined into glass waste packages at the same pace they are produced. Finally, little savings on resource consumption may be reached, but only by recycling U235-rich RepU into ERU fuels, which favors the MIX concept, while ERU might be hard to operate in a fleet mainly supplied with CORAIL assemblies. Studies on alternative CORAIL assembly designs are however being performed now.

Table II proposes a comparison of studied multi-recycling options with respect to open cycle and "step A" mono-recycling options. Multi-recycling in PWR may constitute a promising intermediate strategy if the fuel cycle is not being closed in the next decades. In this context, these preliminary results pave the way to further studies on multi-recycling in PWR. Indeed, this option remains industrially challenging, since the plutonium flow through the cycle would be significantly higher than in the current French fleet. Multi-recycling in PWR should require building new fabrication and reprocessing facilities, with specific radiation protection and criticality issues notably.

NOMENCLATURE

ASTRID French SFR demonstrator.
CORAIL assemblies with LEU and MOX rods.
COSI6 CEA scenario software.
EFPD Equivalent Full Power Day.
EPR European Pressurized Water Reactor.
ERU Enriched Reprocessed Uranium.
FIFO First In First Out fuel batch management.
LEU Low Enriched Uranium.
MA Minor Actinides (Am, Np and Cm).
MIX Fuel containing plutonium and enriched uranium.
MOX Mixed (U,Pu) Oxide.
PWR Pressurized Water Reactor.
RepU Reprocessed uranium.
SF Spent Fuel.
SFR Sodium Fast Reactor.
TRU Transuranics (Pu + MA).

Tab. II. Description of various PWR fleets in a steady-state regime.

Scenario	« Step A » mono-recycling	CORAIL	MIX	Open cycle
Fraction of EPR MOX/CORAIL/MIX assemblies near 2090	29%	**95%**	8% MIX: 37% 9.54% MIX: 34% 12% MIX: 29%	**0%**
Natural U consumption	6.0 kt/y	6.3 kt/y	8% MIX: 6.6 kt/y 9.54% MIX: 6.5 kt/y With ERU: **5.2 kt/y** 12% MIX: 6.3 kt/y	**7.5 kt/y**
Fabrication	955 t/y (for an EPR fleet scaled to ~ 420 TWh/y)			
Reprocessing	770 tHM/y	955 tHM/y		**0 tHM/y**
Spent Fuels	+ 185 tHM/y	**~ 0 tHM/y**		**+ 955 tHM/y**
Pu production	6.7 t/y	**~ 0 t/y**		**9.9 t/y**
MA production	3.3 t/y	**4.2 t/y - 4.5 t/y**		**2.7 t/y**
TRU production	10 t/y	**≤ 4.5 t/y**		**12.6 t/y**

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REFERENCES

1. C. Coquelet-Pascal, M. Tiphine, G. Krivtchik, D. Freynet, C. Cany, R. Eschbach, C. Chabert, “Cosi6: a tool for nuclear transition scenarios studies and application to SFR deployment scenarios with minor actinides transmutation”, Nuclear Technology, Vol 192, 91-110 (2015).
2. G. Martin, G. Krivtchik, M. Tiphine, R. Eschbach, “French transition scenarios toward Sodium Fast Reactors in this century”, Proceedings of the Global 2017 Conference, Paper 098 (2017).
3. G. Martin, M. Tiphine, C. Coquelet-Pascal, “French transition scenarios toward a symbiotic nuclear fleet”, Proceedings of the ICAPP 2016 Conference, Paper 15732 (2016).
4. M. Tiphine, C. Coquelet-Pascal, G. Krivtchik, R. Eschbach, C. Chabert, B. Carlier, M. Caron-Charles, G. Senentz, L. Van Den Durpel, C. Garzenne, F. Laugier, “Simulations of progressive potential scenarios of Pu multirecycling in SFR and associated phase-out in the French nuclear power fleet”, Proceedings of the Global 2015 Conference, Paper 5326 (2015).
5. C. Chabert, A. Saturnin, G. Krivtchik, G. Martin, M. Tiphine, G. Mathonnière, S. Gabriel, A. Allou, E. Fillastre, FX. Giffard, P. Sarrat, JL. Girotto, H. Hancok, B. Carlier, G. Senentz, F. Laugier, “Feasibility of future prospects and transition scenarios for the French fuel cycle”, Proceedings of the Global 2017 Conference, Paper 087 (2017).
6. J.P. Grouiller, J.Y. Doriath, A. Vasile, A. Zaetta, J.L. Guillet, D. Greneche, Different possible scenarios for plutonium recycling in PWRs, Proceedings of the Global 2001 Conference, Paper 124 (2001).