PROSPECTIVE INVENTORY OF RADIOACTIVE MATERIALS AND WASTE PRODUCED BY THE FRENCH NUCLEAR FLEET ACCORDING TO DIFFERENT PLUTONIUM MULTIPLE RECYCLING OPTIONS IN THE FRAME OF THE FRENCH LAW FOR WASTE MANAGEMENT

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Abstract

In accordance with the French Act of 28 June 2006 on the sustainable management of radioactive materials and waste, the CEA in partnership with EDF, Orano and Framatome, has studied prospective scenarios using different fuel cycle options: open cycle,mono-recycling of plutonium and uranium in PWRs (current option for the French nuclear power fleet), multiple recycling of reusable materials in SFRs and multiple recycling of plutonium in PWRs.

This information has been submitted by the CEA to the Ministry of Energy within the scope of Article 51 of the Ministerial Order dated 23 February on the French National Radioactive Materials and Waste Management Plan (PNGMDR).

Rather than suddenly switching over to the large-scale deployment of sodium fast reactors (SFRs) as assumed in past scenarios, it is now deemed preferable to ensure the progressive implementation of this technology through successive phases: each phase involves an increase of fast reactors within installed nuclear capacity achieving specific objectives.

Phase A corresponds to the current state of the French nuclear reactor fleet wherein plutonium and uranium are recycled in mixed-oxide (MOX) and enriched reprocessed uranium (ERU) fuels in pressurised water reactors (PWR).

Phase B consists in recycling spent MOX fuel from PWRs in a limited number of SFRs. The objective of this phase is to stabilise the quantities of spent MOX fuels from light water reactors.

Phase C is designed to be able to stabilise the plutonium inventory by deploying a symbiotic fleet comprising UOX-PWRs, MOX-PWRs and SFRs.

The objective of phase D is to deploy a fleet of reactors that no longer burns natural uranium. There are two possible options for a nuclear fleet that can generally be considered as self-sufficient, i.e. D1, a homogeneous fleet with 100% SFRs, and D2, a mixed fleet comprising breeder SFRs producing plutonium and PWRs fuelled with 100% MOX to burn this plutonium.

A phase 0 was also defined. This phase corresponds to a hypothetical French fleet having operated in an open-cycle configuration only.

However, SFRs may not become economically competitive in the next few decades as uranium resources would remain readily available. Therefore, MOX spent fuels may start to pile up at the back-end of the fuel cycle unless alternative plutonium management solutions in PWRs are developed. In this study, advanced fuel technologies, called CORAIL and MIX, are applied to enable multiple recycling of plutonium in standard PWRs. The main objectives of these scenarios consist in stabilizing the plutonium inventory as well as all spent fuel stockpiles.

For this initial study, we consider CORAIL assemblies composed of 181 UOX rods and 84 MOX rods (a mixture of plutonium and depleted uranium). This configuration was studied in the early 2000s. As the U-235 enrichment of UOX rods is maximised at 5%, the plutonium content is adapted to make up for its loss of fissile quality with each recycling phase.

MIX assemblies consist of identical rods containing a mix of plutonium and enriched uranium to a content in U-235 suited to compensate for the isotopic degradation of plutonium. Three plutonium contents have been considered in our study : 8%, 9.54% and 12%.

The initial conditions of the scenarios corresponds to the current French fleet with its 58 PWR units generating around 420 TWh(e) per year. This annual electricity production was taken as being constant over time. Future reactor lifespans (PWRs and FRs) of 60 years are considered. A lifespan of 50 years was assumed for the fuel cycle plants (reprocessing and fuel manufacturing).

For scenarios involving the progressive deployment of SFRs, the start-up of commercial SFRs was considered to occur 25 years after the industrial commissioning of the Astrid-600 MW reactor (assumed in this study to be in 2039), i.e. in the mid-2060s. This timescale takes into account the need for sufficient feedback from the operation of Astrid and for realistic lead times for technical and regulatory actions.

For scenarios involving the multiple recycling of Pu in PWRs, it has been considered that the industrial deployment of CORAIL and MIX concepts would be theoretically possible in 2045, a timescale that seems at this stage in the studies to be reasonable, allowing qualification of these new fuel products.

1. MAIN CHARACTERISTICS OF EACH FUEL CYCLE OPTIONS

Tables 1 and 2 summarize the characteristics of the different phases under investigation in relation to the fleet composition, flows and characteristics inventories.

The transition from phase A through to phase D improves – at each phase – the characteristics of the sustainable management of materials, particularly regarding the consumption of natural uranium or interim storage of materials (e.g. plutonium in spent fuels) or the waste produced. Each phase allows to improve the industrial maturity of the fast reactors whose integration into phase B remains very minor (4.5% of the fleet).

Implementing about 31% of FRs into the fleet (in phase C) enables to stabilize the total plutonium inventory.

By integrating about 30% of MIX PWRs or 87% CORAIL-2000 PWRs into the fleet, it is theoretically possible to start up MIX or CORAIL fleets to achieve a balance in the material flows within a period of about forty years and to 'absorb' the spent MOX and ERU inventories. The results of these scenarios studies show a stabilisation of spent fuel and plutonium inventories, the latter at a level between 600 and 700 tonnes.

These concepts can lead to additional savings in uranium resources up to about 10% compared with the current once-through recycling (for a total exceeding 25% compared with an open fuel cycle) in a configuration where reprocessed uranium is recycled.

The MIX/ CORAIL concepts or the phase C with MOX and FRs enable to recycle all spent fuel and stabilize plutonium inventory but lead to an increased production of minor actinides (by about 30% in the scenario investigated compared with once-through recycling, or by about a factor 2 compared with a 100% SFR fleet).

The CORAIL concept considered here is close to isogeneration of plutonium and will be less efficient than the MIX concept to reduce the spent MOX fuels inventory. Stabilizing the plutonium inventory will necessitate to deploy almost all the reactors with CORAIL-2000 fuels.

TABLE 1. PROGRESSIVE DEPLOYMENT OF SFRS – SCENARIOS RESULTS – MAIN CHARACTERISTICS FOR EACH PHASE

	A	B	C	D2	D1	Open Cycle (0)
Fraction of SFRs in the fleet	0%	4.5%	31%	73%	100%	0
Unat consumption (t/year)	6000	5700	3400	0	0	7500
Pu inventory (t/year)	↗ 7.2	↗ 6.8	Stabilised	Stabilised	Stabilised	↗ 9.9
Minor actinide inventory (t/year)	↗ 3.3	↗ 3.1	↗ 4.4	↗ 3.4	↗ 2.3	↗ 2.7
Increase in the spent fuel inventory (t/y)	180	130	0	0	0	950

TABLE 2. MULTIPLE RECYCLING OF PU IN PWRS – SCENARIOS RESULTS – MAIN CHARACTERISTICS FOR EACH PHASE

	A	CORAIL	MIX 9.54% with ERU management	MIX 9.54% without ERU management	D1	Open Cycle (0)
Fraction of MIX/CORAIL or SFRs in the fleet	0%	87%	35%	35%	100%	0
U_{nat} consumption (t/year)	6000	6300	5500	6900	0	7500
Pu inventory (t/year)	↗ 7.2	↗ 6.8	Stabilised	Stabilised	Stabilised	↗ 9.9
Minor actinide inventory (t/year)	↗ 3.3	↗ 4.2	↗ 4.5	↗ 4.2	↗ 2.3	↗ 2.7
Increase in the spent fuel inventory (t/y)	180	130	0	0	0	950

2. FUEL CYCLE TRANSITION SCENARIOS

In those studies, two types of transitional scenarios have been chosen and compared. In all cases, the initial conditions applied are those that currently exist in France, i.e. once-through recycling of Pu in PWRs (phase A).

Scenarios involving the progressive deployment of SFRs:

— Scenario ABCD1 involves the successive deployment of all phases, starting with phase A (once-through recycling of Pu in PWRs), then phase B (stabilisation of spent PWR MOX by recycling in a few SFRs), followed by phase C (stabilisation of the Pu inventory using a symbiotic PWR-SFR fleet), and finally phase D1 (100% SFR fleet);
— Scenario ABCD2 ends with a hybrid fleet comprising SFRs and 100% MOX PWRs;
— Scenario ABD2 is an alternative to scenario ABCD2 where deployment of D2 is accelerated (this scenario could apply in the case where the price of natural uranium rises rapidly or there is a shortage of natural uranium).

Scenarios involving the multiple recycling of Pu in PWRs

— Scenarios implementing the MIX concept for the multiple recycling of Pu until its total inventory has stabilised. Three alternatives have been studied with Pu concentration in the fuel: 8%, 9.54% and 12%. We also investigated a MIX scenario based on the recycling of reprocessed uranium through the management of ERU PWRs;
— The scenario implementing the CORAIL concept for the multiple recycling of Pu until its total inventory has stabilised.

Examples of the changing composition of the fleet over time are given in Figs 1, 2 and 3 for transitional scenarios ABCD1, MIX and CORAIL.

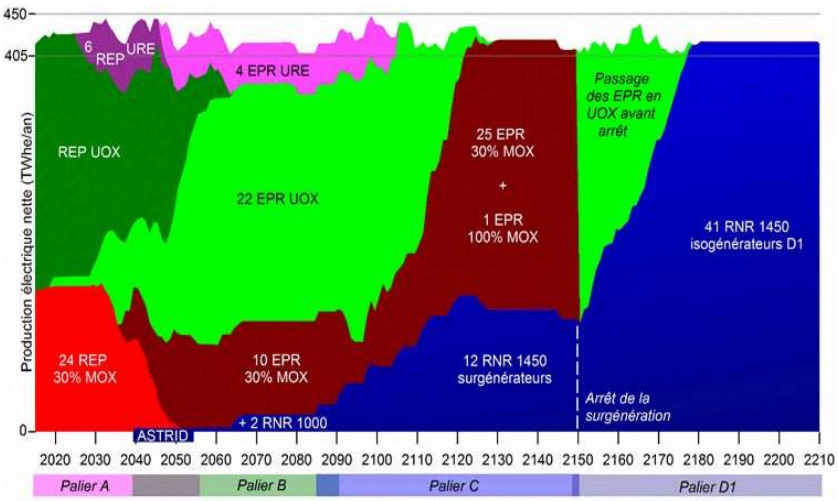

FIG. 1. Changing composition of the fleet for transitional scenario ABCD1.

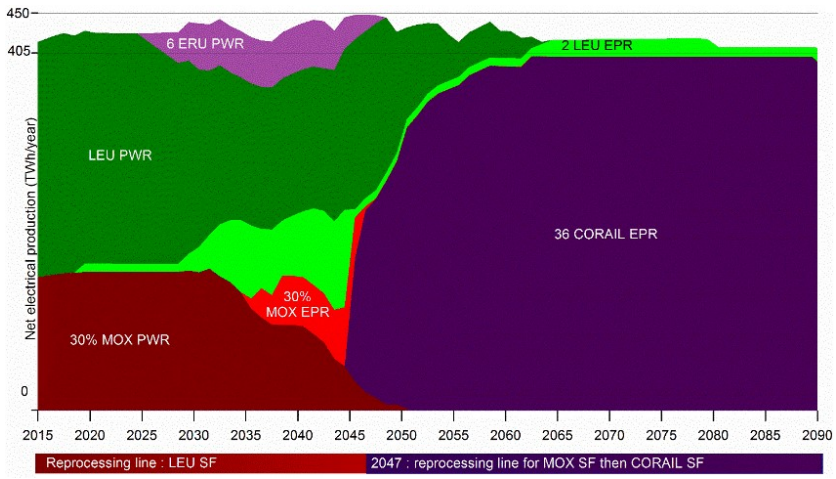

FIG. 2. Changing composition of the fleet for transitional scenario with the CORAIL-2000 concept.

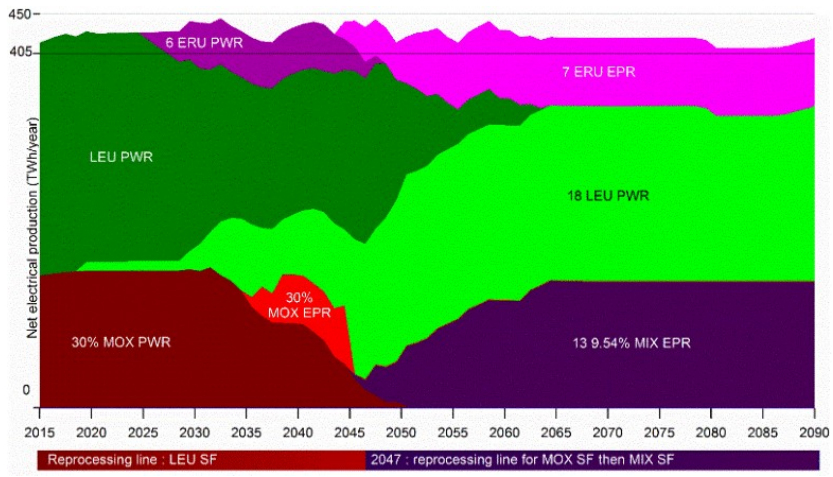

FIG. 3. Changing composition of the fleet for transitional scenario with the MIX 9.54% concept and with ERU.

These scenarios achieve the objective of stabilising the plutonium inventory at a value close to 1200 tonnes in the case of the progressive deployment of SFRs. For CORAIL and MIX scenarios, the Pu inventory can be stabilised with inventories ranging between 640 and 680 tons in 2100, in contrast with the regular increase in the

Pu inventory for scenario A (continuation of the current situation) which generates about 1000 tons at the same period in time (Fig. 4).

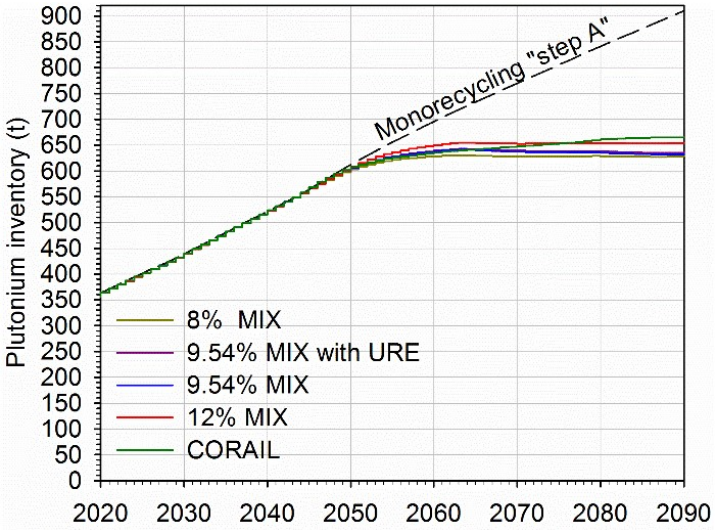

FIG. 4. Plutonium inventory for the CORAIL and MIX scenarios compared to scenario A.

Figure 5 shows the cumulative consumption of natural uranium for the different scenarios; self-sufficiency with respect to natural uranium can only be achieved by opting for the closed fuel cycle, i.e. deployment of SFRs.

The multiple recycling of Pu in PWRs can lead to additional savings in uranium resources up to about 10% compared with the current once-through recycling (for a total exceeding 25% compared with an open fuel cycle) in a configuration where reprocessed uranium is recycled (9.54% MIX with ERU).

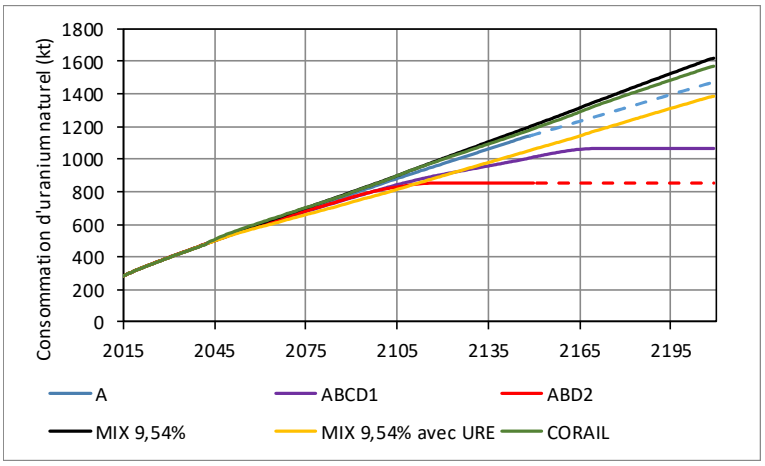

FIG. 5. Consumption of natural uranium (kt) in the MIX and CORAIL scenarios compared with scenarios A, ABD2 and ABCD1.

3. WASTE AND GEOLOGICAL DISPOSAL

The waste disposal surface area required for the different options has been assessed in terms of the thermo-hydro mechanical (THM) and thermal design criteria (90°C on waste package surfaces) relying on data provided by Andra, corresponding to current hypothesis of CIGEO project. This study does not pre-empt the location of the disposal site for the waste considered, nor any evolution or optimisations of the disposal design. However, for this study, we assumed that the deep geological repository was located in clayey rock similar to the layer of argillaceous rock studied in the Meuse/ Haute-Marne region for the Cigéo project. This assumption allowed us to base our concepts on the current knowledge collected from the project.

The theoretical surface areas required for the disposal of HLW (vitrified packages) conditioned at the spent fuel reprocessing operation associated with phases A, B, C, D1, D2, MIX and CORAIL-2000 lasting for a period of 60 years have been estimated considering an interim storage period of 80 years prior to disposal (see Fig. 6).

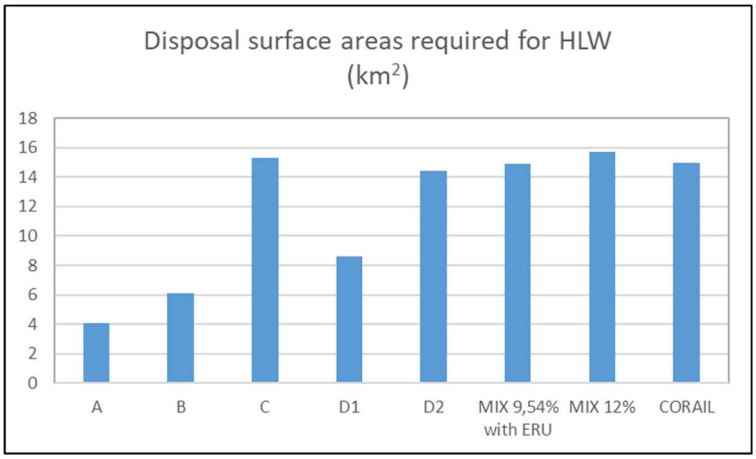

FIG. 6. Disposal surface areas required for HLW (km²).

Non reprocessed spent fuel emitting high thermal releases in phases 0, A and B would require adequate areas to be disposed of. At this stage of the study, the required area for has not been determined. We have only calculated the annual thermal power following 80 years of interim storage by the quantity of spent fuel produced in one year. It will be important to estimate the required disposal surface areas in subsequent studies carried out in collaboration with Andra (Fig. 7).

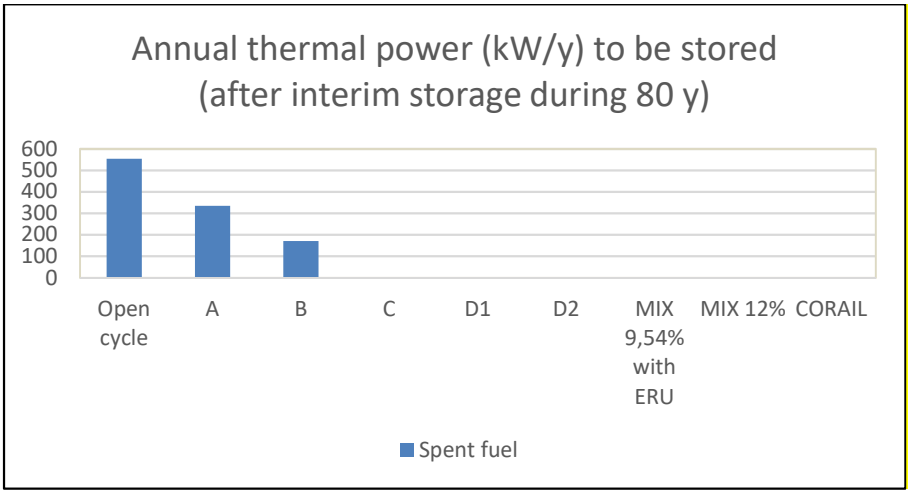

FIG. 7. Annual thermal power to be stored (kW/year)).

4. CONCLUSION

These scenarios studies considered several multiple recycling options for plutonium using sodium fast reactors and/or PWRs.

The results provided herein confirm that transitioning from once-through recycling (current solution in France) to a closed fuel cycle improves the key parameters of a sustainable fuel cycle. However reaching such a phase, i.e ; investing in an SFR fleet will depend on the natural uranium market prices.

The preliminary studies performed with MIX and CORAIL concepts show they are capable of recycling spent MOX and ERU fuel and of stabilising the spent fuel and plutonium inventories. Compared with the once-through recycling of uranium and plutonium, these concepts reduce the need for natural uranium when reprocessed uranium is recycled, which in turn generates a saving over 25% in natural resources compared with an open fuel cycle. Although all spent fuel are reprocessed, the production of

minor actinides is increased by about 30% compared with once-through recycling. Concerning the impact of options on the waste disposal footprint, at this stage of the study, only the disposal surface area required for vitrified waste packages has been estimated, considering current hypothesis of the French disposal project. These studies are still ongoing in collaboration with Andra to estimate the surface area required to dispose of the non-recycled spent fuels (Phases 0, A and B).

In the case of a transitional scenario between the current once-through recycling solution and the full deployment of SFRs, the option of being able to implement multiple recycling in PWRs would enable to improve the processes and industrial maturity of the fuel cycle plants infrastructures required to implement a closed cycle with SFRs.

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