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Feasibility of future prospects and transition scenarios for the French fuel cycle

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Abstract – This paper presents the industrial feasibility analysis of scenarios involving the progressive deployment of multiple recycling of plutonium in French sodium fast reactors (SFR), in line with the French Act dated 28 June 2006 on the sustainable management of radioactive materials and waste. Four successive phases have been defined with different degrees of SFR deployment in order to understand how best to accomplish this fuel cycle transition.

- Phase A corresponds to the current state of the French nuclear reactor fleet; 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 PWRs. It also provides an outlet for plutonium produced by the current PWR fleet. This phase does not, however, provide an outlet for plutonium contained in spent SFR fuels.
- The plutonium inventory is stabilised during phase C through the deployment of a symbiotic fleet comprising UOX-PWRs, MOX-PWRs and SFRs. This phase is characterised by the industrial reprocessing of spent SFR fuels and the recycling of Pu in SFRs and MOX-PWRs. SFRs provide an outlet for Pu extracted from spent MOX fuel while enabling isotopic correction so the Pu can be recycled in MOX-PWRs.
- The objective of phase D is to deploy a fleet of reactors that no longer burn natural uranium. This may involve the full deployment of SFRs (D1) or their partial deployment in a symbiotic fleet comprising breeder SFRs and MOX-PWRs (D2).

The areas of research recommended under this programme for the 2016-2018 period are also discussed in this paper.

I. MAIN CHARACTERISTICS OF THE PHASES

Table I summarises the characteristics of the different phases studied in relation to the fleet composition, fuel flows and characteristic spent fuel inventories. All the cases studied in this paper are based on the assumption of a nuclear reactor fleet generating about 430 TWh/y.

The quantities of materials associated with sustainable management tend to improve with each phase transition (A through to D). This is particularly true for the consumption of natural uranium, the interim storage of materials (e.g. plutonium in spent fuels), and the final quantity of waste produced.

Each phase makes it possible to improve the industrial maturity of the fast reactors, which only represent 5% of the fleet in phase B.

Design issues and the complex operating configuration remain to be resolved for phase C. It may be decided to

move directly from phase B to phase D if the conditions at the time allow it.

The idea behind phase C is to halt the constant increase in the Pu inventory so as to avoid stockpiling quantities of plutonium that exceed those estimated for the scenarios. This phase therefore considers the treatment of all types of spent fuel, particularly fast reactor fuels and the multiple recycling of plutonium that has been recovered. The notion of stabilising the Pu inventory implies the deployment of a significant fraction of reactors capable of burning Pu, i.e. MOX-PWRs. This strategy requires the multiple recycling of plutonium in these reactors. To do this, the isotopic composition of the plutonium must be compatible with the recycling configuration.

As the plutonium contained in spent fuel from fast reactors has a too low energetic value to be recycled directly in MOX-PWRs, its isotopic composition must first be improved by putting it through an SFR one or two more times. In phase C, SFRs not only provide an outlet

for plutonium from spent MOX fuels, but are also used to correct the isotopic composition of Pu so it can be re-used in PWRs.

Being able to restore the isotopic quality of Pu so it can be recycled in MOX-PWRs is the most complex issue of phase C, which explains why many variations were considered. Two key parameters were used to define phase C:

- The breeding gain of fast reactors: as the plutonium produced in the fertile areas of fast reactor cores has excellent isotopic characteristics ($^{239}\text{Pu}/\text{Pu}_{\text{tot}} > 90\%$), we can expect breeder fast reactors to improve the quality of Pu much better than self-sufficient fast reactors since they offer a higher fertile surface area.
- The management method for plutonium resulting from the treatment of fast reactor fuels: a Pu improvement process involving a series of separate stages is more effective than a system that mixes plutonium with differing isotopic qualities, though it does entail a more complex management configuration on an industrial level.

The final reference phase C is based on the deployment of breeder reactors to accelerate the correction of Pu, and the mixture of different Pu qualities to simplify fuel cycle operations.

TABLE I

Main characteristics of each phase.

	A	B	C	D1	D2	0
Fraction of SFRs in the fleet	0%	5%	40%	100%	75%	0
U_{nat} consumption (t/year)	6300	5800	2700	0	0	7600
UOX (+ERU) manufacturing (t/year)	800 (+75)	730 (+75)	335			960
MOX manufacturing (t/year)	83	75	220		255	
FR (core) manufacturing (t/year)		26	215	480	375	
UOX (+ERU) reprocessing (t/year)	820	750	570 (+20)			
MOX reprocessing (t/year)		65	170		255	
FR (core + radial blankets) reprocessing (t/year)			275	480	470	
Pu inventory (t/year)	↗ 7.4	↗ 7.1	Stabilised	Stabilised	Stabilised	↗ 10.5
Minor actinide inventory (t/year)	↗ 3.2	↗ 3.1	↗ 3.6	↗ 2.2	↗ 3.3	↗ 2.5

II. FUEL CYCLE TRANSITION SCENARIOS

After having characterised each phase, the transition between these phases was analysed according to various assumptions (especially time). It was possible to assess the technical, economic and industrial feasibility and realism of the different options leading to the global scenarios comprising each phase.

As a result of this process, four global scenarios were defined: 1) scenario ABCD1; 2) scenario ABD1, which is an alternative to ABCD1 where the deployment of a 100% SFR fleet is accelerated (due to the increasingly higher cost or shortage of natural uranium); 3) scenario ABCD2 where the final fleet is symbiotic and composed of SFRs and 100% MOX EPRs; 4) scenario ABD2, which is an alternative to ABCD2 where the deployment of a symbiotic fleet is accelerated.

The year 2050 was chosen as the commissioning date for the first SFR in phase B. Phase C starts with the implementation of spent SFR fuel treatment and the deployment of additional SFRs. According to our assessment, there appears to be no pressing incentive to launch phase C any earlier, which led us to choose a B-to-C transition from 2090 corresponding to the renewal of the fuel cycle plants. Nevertheless, the deployment of three additional SFRs before 2090 is considered during this transition since it does not seem to be industrially realistic to build a new series of SFRs from 2090 at a sustained pace following a 30-year period without any construction.

The transition between C and D is estimated to take about 30 years for D1 and 50 years for D2. Equilibrium is then reached around 2190-2210 depending on the option chosen for phase D. The early transition from B to D makes it possible to reach this equilibrium much faster and to overcome our dependency on natural uranium resources sooner. In this case, our independence with respect to natural uranium is gained about 60 years earlier. This early transition from phase B to D requires an increase in the treatment capacities of plants so as to recover the plutonium contained in the spent fuels, which is needed for the accelerated deployment of a 100% SFR fleet while maintaining its total power generation at a constant level.

II.A. Total plutonium inventory

The variation in the overall plutonium inventory is shown in Figure 1. Contrary to scenario A, the transition scenarios make it possible to reach the objective of stabilising the plutonium inventory. The accelerated transition scenarios (ABD1 and ABD2) stabilise the Pu inventory at a lower level due to the fact that the spent fuel stocks are used to optimise the transition, with the

additional possibility of being able to increase the fuel treatment capacity during the 2090-2120 period.

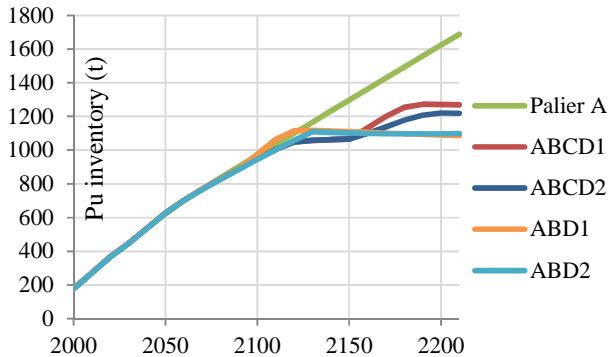


Fig. 1. Variation in the total Pu inventory for the transition scenarios.

II.B. Storage of spent fuels

The accelerated transitions make it possible to significantly reduce the storage of spent fuels since it is necessary to recover as much plutonium as possible from these stockpiles. Figure 2 shows the variation in these stockpiles for the different scenarios.

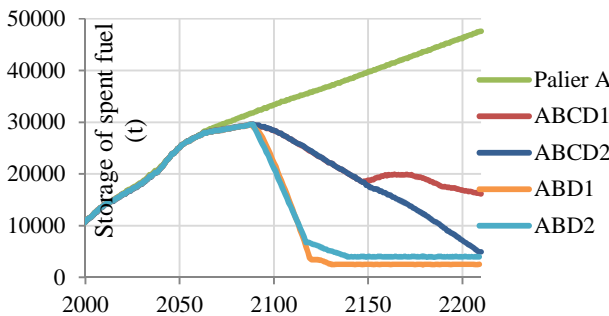


Fig. 2. Variation on the storage of spent fuels for the transition scenarios

II.C. Natural uranium requirements

The consumption of natural uranium obviously stabilises faster in the scenarios with an accelerated transition. Scenario ABD1 makes uranium savings of about 18% compared with scenario ABCD1, while scenario ABD2 makes savings of about 16% compared with scenario ABCD2. Regardless of the transition scenario, the natural uranium requirements are significantly reduced compared with a French fleet that continues to operate with the once-through recycling of Pu in EPRs (scenario A).

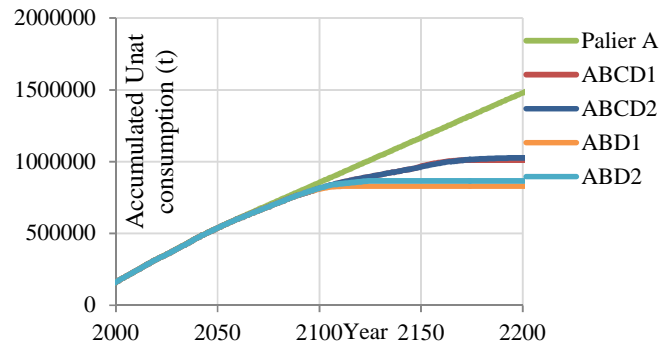


Fig. 3. Accumulated consumption of natural uranium for the transition scenarios.

II.D. Transport of SFR fuel sub-assemblies

The feasibility of transporting SFR fuel sub-assemblies does not appear to be called into question by our preliminary studies. Based on current regulations and transport cask designs similar to those used today, however, the number of SFR sub-assemblies will have to be reduced per transport cask. This will result in an increased number of transport operations. According to our studies, the criticality risk limits the number of SFR fuel sub-assemblies that can be transported in a cask. In terms of heat releases, SFR fuel sub-assemblies in transport casks must be kept in a helium atmosphere to promote thermal conductivity and heat removal. It will also be necessary to improve the resins used in these transport casks with respect to their heat removal performance. This issue requires further research within the scope of optimising transport casks for SFR fuels.

The table below lists the number of transport operations for three transition scenarios with respect to scenario A, i.e. continuing the current strategy of once-through recycling of Pu in PWRs. The total has been calculated for the 2050-2210 period.

As expected, it can be seen that the differences with respect to scenario A increase with the proportion of SFRs integrated into the fleet. The faster deployment of SFRs (scenario ABD1) also logically results in a higher total number of transport operations, excepting from UOX fuels and new radial blankets.

TABLE II

Total number of transport operations between 2050-2210 compared to an extended scenario A

Proportion of SFRs	75%	100% from 2181	100% from 2122
Scenario	ABCD2	ABCD1	ABD1
UOX + ERU + new radial blankets	0.6	0.5	0.4
New MOX	8.1	8.9	12.0
Spent sub-assemblies	2.8	3.0	3.9
New and spent sub-assemblies	1.9	2.0	2.5

II.E. Waste and geological disposal

The total disposal surface area required for the three transition scenarios has also been calculated on the basis of the 2005 Andra disposal concept. These results do not currently take into account the latest concept changes recently recommended by Andra which incorporate thermo-hydro-mechanical criteria. The disposal surface areas have thus been calculated on the basis of thermal criteria, which consider a limit temperature of 90°C on the walls of the hottest waste package in the disposal facility. Scenario ABD1 requires the smallest surface area but it must be stressed that the differences in surface areas are of the same order of magnitude as the uncertainties on the study assumptions. This information will be specified in greater detail in future studies, taking into account the latest results from Andra.

TABLE III

Estimate of HLW and LL-ILW over the 2050-2210 period

	Scenario ABCD1	Scenario ABCD2	Scenario ABD1
LL-ILW	1.1	1.1	1.3
HLW	15.9	17.4	13.8
Total	17.0	18.5	15.1

As a comparison, scenario A requires an overall surface area of about 6.5 km² (assumption: 722 CSD-V waste packages per year for 160 years). It is important to point out that, in this case, the disposal requirements for spent fuel will continue to rise to reach more than 47,000 tons in 2210. The deep geological disposal of these spent fuels is expected to represent an additional surface area of about 21.5 km².

II.F. Economic competitiveness

The economic analyses all indicate that the economic competitiveness of SFRs is highly dependent on the additional investment cost of the reactor compared to PWR and on the price variations of natural uranium. The competitiveness of SFRs may be reached sometime between 2080 and 2110 if an additional investment cost of 30% is made in comparison with PWRs. If this extra investment cost was increased to 50%, the date of competitiveness of SFRs would be shifted by fifteen years or so. This explains why we chose an ABD-type scenario over an ABCD scenario. Once the ABCD scenario has reached equilibrium (around 2150), the ABCD1 scenario appears to be more expensive than ABCD2 owing to the greater number of SFRs in the fleet; the contribution of the reactor cost to the fleet cost is greater than the fuel cycle cost.

III. FUTURE PROSPECTS

On the basis of these promising results, these studies will continue to explore certain avenues of research and new options. Among the needs that have been identified, the following areas are being investigated:

1. Robustness of the conclusions reached in 2015 with respect to the assumptions applied

2. Industrial overview of the transition from phase A to B, particularly with respect to the industrial fuel cycle facilities and integration of the Astrid technology demonstrator into this transition.

This transition is currently being assessed on the basis of the possible commissioning of the Astrid reactor in the late 2030s. The first-in-series of the 1000 MWe SFRs will start up 25 years later. The main objective of phase B for the first SFR units will be to manage the increase in spent MOX fuel quantities from PWRs. In the meantime, Astrid must be able to demonstrate that it is possible to recycle Pu from MOX fuels in a SFR on the scale of a full reactor core. Two options for the AB scenario have been developed: either this Pu will be burned by three 1000 MWe SFRs (option 1), or Astrid will be made to contribute, which means only two 1000 MWe SFRs will be built (option 2). At the end of phase B, option 2 saves building a third 1000 MWe SFR, which represents a high investment cost considering that this reactor will not benefit from a standardised "series" effect. However, this option means that the fleet objectives are partially conditioned by this demonstrator whose fuel load plan is already rather restricted. More specifically, option 2 requires a more complex reprocessing system at the end of phase B; from 2070, Astrid must be able to demonstrate its

capacity to recycle plutonium multiple times, while helping to produce Pu from MOX fuels in support of the two 1000 MWe SFRs. Option 2 is currently the reference solution in our studies.

3. The results of the disposal surface area required, which are being updated to take into account the latest developments recommended by Andra, e.g. incorporation of thermo-hydro-mechanical criteria.

Andra has been asked to reassess the estimations of the disposal surface areas and excavated volumes required for each of the different phases. The results are expected in October 2017.

4. Tech watch of other reactor concepts capable of recycling plutonium from spent UOX and MOX fuels and of new MOX products, including their integration into the above scenarios.

For this reason, an analysis is currently underway on the basis of past studies and within the scope of the 1991 Act on the management of radioactive waste. The different concepts have been compared against the current reference fuel cycle with the once-through recycling of Pu in PWRs and with a closed fuel cycle for sustainable SFRs. These concepts include: i) recycling MOX in PWRs two or three times by dilution or isotopic zoning, ii) multiple recycling of Pu in PWRs using a uranium-enriched "MIX concept", iii) mixture of MOX and UOX fuel rods in PWR fuel assemblies (CORAIL concept), iv) plutonium on inert structures (APA concept), and v) reactors with high conversion factors.

With respect to closed fuel cycle issues (recovering materials and optimising waste management), qualitative comparisons are currently focusing on spent fuel inventories, raw material (natural uranium) savings, waste production, and costs. Two fuel concepts have been highlighted by this analysis: MIX and CORAIL concepts. Without challenging the sustainability of fast reactors and their related fuel cycle, these two concepts appear to be relatively effective and capable of reaching the Pu multiple recycling objectives. Scenarios taking into account these two concepts are currently being studied.

5. The transport capacities not only for spent and new SFR and PWR fuels, but also for PWR fuels recycling Pu. These capacities are currently being analysed and refined.

6. The costs of fuel cycle facilities and reactors, and new methodologies for improved economic assessments.

7. The environmental impact of the different options and the life cycle analysis (LCA).

These new results will allow us to meet the different requirements governing radioactive material and waste

management issued by the French government (PNGMDR plan) under the 2006 Act on radioactive waste management.

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NOMENCLATURE

EPR European Pressurized Water Reactor (*EPR is a registered trademark of the AREVA NP group in the USA or other countries*).

ERU Enriched Reprocessed Uranium.

MOX Mixed (U,Pu) Oxide.

PWR Pressurized Water Reactor.

SFR Sodium Fast Reactor.

FR Fast Reactor.

UOX Low enriched uranium oxide.

HLW High Level Waste

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