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ARTICLE

Simulation of the Performances of a Pressurized Water Reactors Multi-Recycling Nuclear System for Material Valorization

Aimeric EUSTACHE [1*], Guillaume MARTIN [1], Christine CHABERT [1], François SUDREAU [2], Cécile EVANS [3], Frédéric LAUGIER [4], Guillaume VAAST [4], Bertrand CARLIER [5] and Olivier TOUGAIT [6]

[1] *CEA, Energy Division/IRESNE/DER,-CEA Cadarache, 13115 Saint Paul-lez-Durance, France*
[2] *CEA, Energy Division/Programs Division for Energy , CEA Saclay,91191 Gif-sur-Yvette Cedex, France*
[3] *Orano, Marketing and New Nuclear, 125 avenue de Paris, 93200 Saint-Denis, France*
[4] *EDF, Nuclear Fuel Division, 1 Place Pleyel, 93200 Saint-Denis, France*
[5] *Framatome, Engineering and Design Authority, 1 place Jean Millier, 92400 Courbevoie, France*
[6] *Framatome, Fuel Business Unit, 2 rue du Pr.J.Bernard; 69007 Lyon, France*

Multi-recycling PWRs' valuable materials such as uranium and plutonium would not only bring benefits in terms of reduction of natural uranium consumption but could also allow the overall stabilization or reduction of spent nuclear fuel and plutonium inventories. These aspects are considered of fundamental importance by the French government to achieve the target of a future sustainable nuclear system (reactors and fuel cycle facilities). Using COSI6, the simulation tool for scenarios analyses developed by CEA, different nuclear power capacity trajectories were studied. The feasibility and performance in terms of materials and waste management of PWR multi-recycling system up to the end of the 21st century were assessed. All types of spent nuclear fuel, Enriched Natural Uranium (ENU), Enriched Reprocessed Uranium (ERU) and Mixed OXide (MOX) are reprocessed. The plutonium is recycled through the use of an innovative nuclear ceramic called MOX Multi-Recycling (MOX-MR). Additional savings of about 20 % to 25 % of natural uranium consumption were observed compared to a mono-recycling strategy (recycling of ENU spent nuclear fuel), thus enabling a step toward a closed nuclear fuel cycle.

KEYWORDS: fuel cycle, plutonium and uranium PWR multi-recycling, scenario, MOX-MR, COSI

I. Introduction

By 2050, the French electricity mix is expected to include a significant nuclear fleet to meet the high forecasted demand for decarbonized electricity required for the energy transition.[1)2)] France has historically reprocessed and recycled its Enriched Natural Uranium (ENU) Spent Nuclear Fuel (SNF) to save natural resources and reduce the environmental impact of high-level waste. However, fuel assemblies containing recycled fissile materials such as, Mixed OXides (MOX) and Enriched Reprocessed Uranium (ERU), are currently not reprocessed at industrial scale, due to technological and facility limits. MOX and ERU SNF, containing valuable fissile materials (^{235}U, ^{239}Pu and ^{241}Pu in thermal neutron spectrum), are safely stored pending future use. Since 2019, the French government has adapted its mid-term energy management policy.[3)] One of the milestones introduced is to demonstrate the industrial feasibility of the plutonium multi-recycling in PWRs with an objective of industrial commissioning deemed feasible in the 2040s, while preserving the capability to introduce a Fast neutron Reactor (FR) fleet at a later stage in the 21st century. The aim of this strategy is to use the significant energy still available in the MOX and ERU SNF by extracting fissile materials one more time to produce new fresh fuel assemblies in order to stabilize the SNF inventory as well as the overall plutonium inventory in the fuel cycle. In 2019, the R&D program Multi-Recycling REP (MRREP, meaning Multi-Recycling in PWRs in French) was established, to explore the possibility of multi-recycling in PWRs and in particular the use of lower fissile quality plutonium coming from MOX SNF. This program involves Orano, EDF, Framatome and CEA. Nuclear industrial scenario studies are conducted to evaluate fuel cycle performances based on various nuclear fuel and installation strategies, constraints and hypotheses. This paper describes the results of latest scenarios performed to assess multi-recycling fuel management in future PWRs considering MOX-MR Fuel Assembly (FA) design[4)] in new nuclear fleets with installed capacities of 40 GWe and 50 GWe, in comparison to a prolongation of the currently implemented mono-recycling strategy.

II. Tools and Hypotheses

1. Scenario Simulation

This paper evaluates the performances of fuel cycle options for several new French nuclear installed power trajectories through industrial nuclear system scenarios using the COSI6 software,[5)] developed by CEA. COSI6 is capable of simulating the mass fluxes of radioactive materials within a fleet of nuclear reactors and their associated fuel cycle facilities over a timescale ranging from several decades to several centuries. In order to replicate reactors physics and

*Corresponding author, E-mail: aimeric.eustache@cea.fr

fuel cycle physics, COSI6 is embedded with three distinct physics models:

- Equivalence model: The objective of the equivalence model is to assess the initial composition of a fuel at the reactor entry, taking into account the parameters of irradiation, such as the fissile quality of the fuel or the targeted burn-up.
- Depletion model: The depletion model aims to compute the irradiated composition of the spent nuclear fuel at the unloading of the reactor core in accordance with the fresh fuel composition and the irradiation parameters.
- Decay model: The decay model is used to calculate the evolution of the radioactive materials outside the neutron flux of reactors' core.

The depletion and the decay models are based on the CEA evolution code CESAR 5.3[6] while the equivalence models uses various calculation methods such as: polynomial regression, Baker-Ross formula or neuronal network depending on the FA.[7] CESAR5.3 is used as the reference code to compute the composition of spent nuclear fuel at the reprocessing plant La Hague. It solves the Bateman equation using the JEFF3.1.1 database and one group cross section libraries.

Nuclear system scenarios are therefore studies that allow the analysis of fuel cycle options through the calculation of mass fluxes of specific isotopes. These scenarios can be classified according to whether they are bound by a wide range of constraints. On the one hand, academic scenarios follow a small number of constraints and make simplifications to show simple trajectories in order to explore many parameters.[8] Industrial scenarios, on the other hand, are used to represent an industrial fuel cycle and, in order to represent its complexity, a number of constraints and hypotheses need to be defined.[9,10] For example, unlike most academic scenarios, an industrial scenario explicitly models all reactor fuel batch histories. Consequently, the number of industrial scenarios that can be simulated is limited.

Typical results of these simulations can be the consumption of resources in order to supply nuclear materials to the fleet, the needed capacity of the plants over time or the tracking of the isotopic contents of radioactive materials in the fuel cycle.

In this paper, the scenarios considered are limited to the French nuclear power sector, no exchange with foreign countries are considered. Moreover, the renewal of nuclear capacities is only based on PWRs and no FR are deployed. The historical fleet evolution is also simulated as the scenario starts in 1975, and only PWRs reactors are taken into account.

2. Nuclear Power Trajectories

The French multiannual energy plan of 2016 (PPE1)[11] has initially limited nuclear power generation to a maximum of 50% of electricity production share by 2025 and then by 2035 in PPE2 of 2019.[3] However, this target was cancelled by the French government in 2023[12] and today the nuclear power generates 65% of French electricity.[13] In addition, RTE, the French electricity transmission system operator, has published scenario studies on France's possible future energy mix in 2050, showing that overall energy consumption is expected to fall while electrification increases demand for decarbonized electricity.[2] As a 100% renewable electricity grid poses many risky challenges, they confirmed the interest in a mix based on the extension of the existing reactor fleet, the construction of new nuclear power plants and the massive deployment of renewables. Accordingly, the French government launched concertation in order to build new power plants of third-generation, known as EPR2.[1] Three sites have already been identified: Penly, Gravelines and Bugey.[13] In a future in which the place of nuclear is confirmed as an asset for decarbonizing the electricity mix and high electricity demand is forecast, nuclear power sector will therefore continue to play an important role.

To perform nuclear system scenario, a nuclear deployment and decommissioning history is necessary. The deployment chronicles of EPR2 in the scenarios presented in this paper are based on RTE forecast until the mid 21st century as shown in **Fig. 1**. In this paper, two power trajectories are studied, one with 24 EPR2s, ie. 40 GWe capacity, and one with 30 EPR2s, ie. 50 GWe capacity. The latest scenarios have increased the power production of the future fleet comparing to 2022 industrial scenarios,[9] where only 20 GWe or 30 GWe of EPR2 were installed. Furthermore, the current installed fleet is set to have an operating lifetime of around 60 years in the 2024 scenarios, in line with the current reference by French industry and government of extending operation life of reactors, as long as the nuclear safety requirements are met.[13] There are some discrepancies in the shutdown date depending on the scenario. The last reactor of the current fleet is supposed to shut down by 2060 horizon (EPR Flamanville 3 excepted). The **Fig. *2*** illustrates the overall predicted installed capacities of the future reactor fleet until the end of this century.

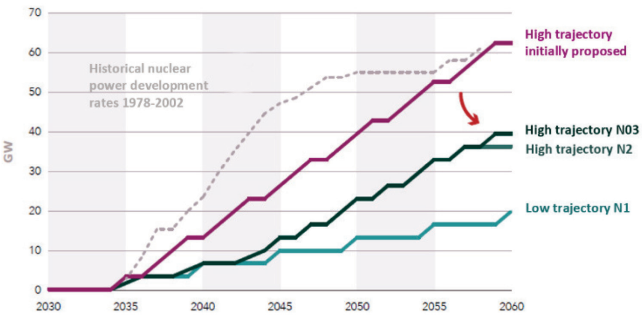

Fig. 1 EPR2 construction forecast for the 2050 horizon[2]

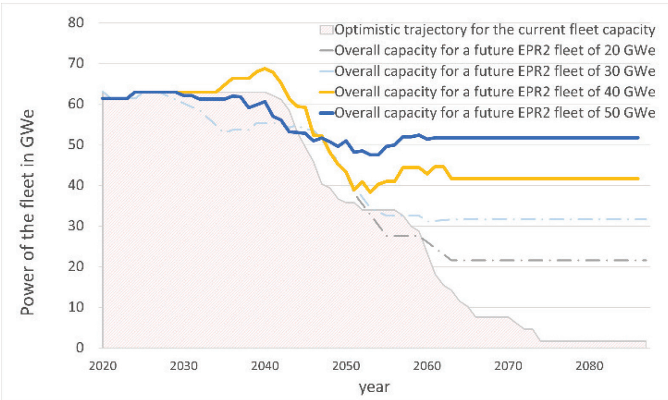

Fig. 2 Selected future nuclear capacities for the scenarios

3. Multi-Recycling System

Since 1987, with the installation of the first MOX FA in the Saint Laurent reactor[14], France has adopted a fuel cycle strategy consisting of a single time recycling of valuable matters inside ENU SNF, called mono-recycling. A schematic description is given in **Fig. 3**. The valorized materials extracted in the reprocessing process are the plutonium and the Reprocessed Uranium (RepU). The plutonium is used to manufacture a new plutonium-based fuel with Depleted Uranium (DU) called MOX and the RepU is re-enriched to produce a new enriched uranium fuel called ERU. Spent fuels from recycling are stored after irradiation for future use. The main objective of the mono-recycling strategy is to stabilize the ENU SNF stockpile by deploying MOX FA while controlling the RepU level in the fuel cycle by introducing ERU FA. However, this strategy is not able to limit the accumulation of the total SNF inventory. Hence, research and development were pursued in order to deploy Fast Reactors (FR) after the water reactor fleet to stabilize the SNF inventory and eventually close the fuel cycle.

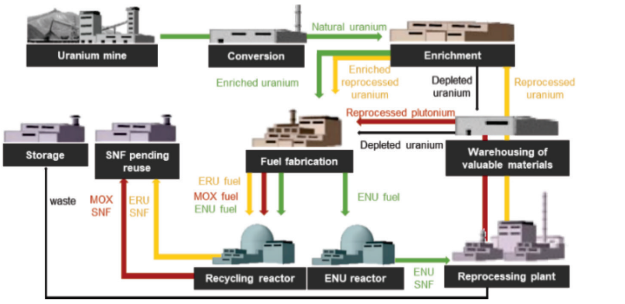

Fig. 3 Schematic representation of a mono-recycling strategy

Due to the current price of Natural Uranium (NU) and the projected costs of construction of fast reactors, the deployment of FR was postponed to the end of the century, as decided in the PPE2.[3] Multi-recycling in PWRs (MRREP) then appeared as an interim solution to stabilize all the SNF and the plutonium inventories until the deployment of a fleet of FRs. The MRREP project was then launched by a consortium including CEA, EDF, Framatome and led by Orano.[15]

The multi-recycling of FA consists of extracting valorized materials from all types of SNF, by reprocessing MOX, ERU and producing new recycled fuels as described in **Fig. 4**. As the fissile quality of plutonium decreases when irradiated in PWR spectrum, it is necessary to either increase the fissile content or correct the fissile quality of the plutonium extracted from MOX spent fuel. Two new options have been studied:

- The MIX FA: The plutonium content is kept constant and the diminishing fissile quality is compensated by increasing the ^{235}U enrichment in the $(U,Pu)O_2$ matrix.[16] The fissile quality is between 49.5% and 53%.
- The MOX-MR FA: Similar to the MOX fuel, the MOX-MR FA uses a DU matrix and compensate its lower FA fissile quality vector by increasing the reload size with additional FA and maintaining a minimum share of plutonium coming from enriched uranium SNF.[4,15] The fissile quality is between 52.5% and 55 %.

The MOX-MR has been selected as the reference fuel in the MRREP project, and the MIX fuel has been retained as a potential long-term solution as it requires more efforts for the development and qualification of several new processes.[15] Other FA concepts have been studied in the past for multi-recycling plutonium in PWRs.[17] In this paper, scenarios based on the reference solution, MOX-MR are detailed. It is considered that MOX-MR should be introduced only in the future fleet of EPR2 and will compose 50 % of the core. A 50 % loaded EPR2 with MOX fuel is a net plutonium consumer.[4,17] The RepU extracted from plutonium-based SNF is not valorized in the scenarios but could be used to manufacture fuels for FR. The RepU coming from ENU and ERU fuel are mixed together and enriched to create new ERU fuels. A limited amount of maximum 20% of ERU SNF in the mix is used in the mix in order to limit the high amount of even isotopes such as ^{232}U, ^{234}U and ^{236}U.

The multi-recycling strategy objectives, i.e. stabilization of both the SNF stockpile and the overall amount of plutonium in the fuel cycle are reached by deploying 50% MOX-MR loading size. Similarly to the mono-recycling strategy, ERU FA are loaded in order to manage the RepU stockpile.

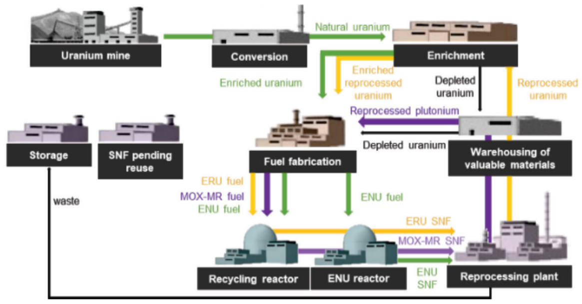

Fig. 4 Schematic representation of a multi-recycling strategy

In order to manufacture, transport, store and recycle future FA, back end assets are needed to maintain and renew industrial capacity.[15,18-20] In this paper, we take into account hypotheses and constraints of the current and the future installations of the fuel cycle:

- Constraint on the fuel fabrication: isotopic constraints on the ^{241}Am, ^{240}Pu and ^{238}Pu are considered, but none on the plant fabrication capacity. A fabrication time of two years is considered.
- Constraint on transportation: A five years minimum time of cooling before reprocessing for all SNF is applied.
- Constraint on SNF treatment: historical reprocessing capacities of the La Hague are used until 2022[14] and reprocessing capacity are not limited after 2022.
- Transfer coefficients to waste are employed to determine the mass flux fraction by element going to waste or being extracted.

III. Scenarios Results

1. Electricity Generation

The total electricity production of the nuclear fleet by fuel types for the four scenarios is detailed in **Fig. 5** and shows an overall production of 302 TWhe/y and 375 TWhe/y for the 40 GWe scenario and the 50 GWe scenario respectively after 2065. The transition from the current fleet to the future reactor fleet will result in a decline of nuclear electricity production by the years 2050's. To stabilize the plutonium inventory in the multi-recycling scenarios, it is necessary to increase the proportion of MOX type fuel in the fleet up to 30% of all the fuel batches, i.e. 60% of all the reactors will load 50% of MOX-MR FA.

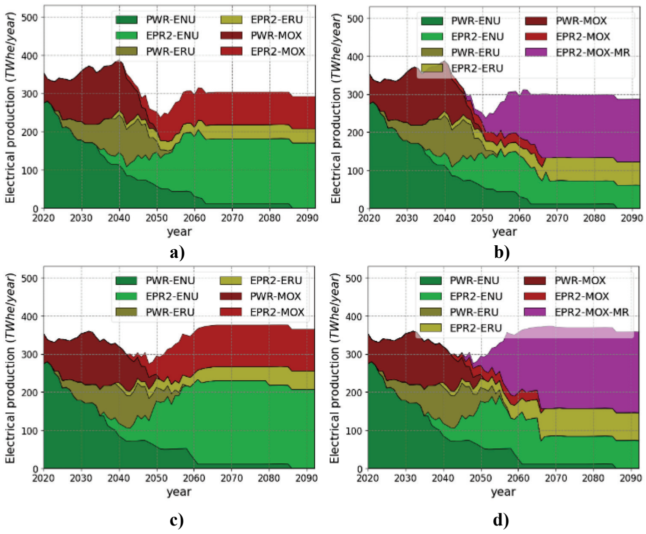

Fig. 5 Evolution of electricity production by fuel management for the scenarios a) 40 GWe mono-recycling, b) 40 GWe multi-recycling, c) 50 GWe mono-recycling, d) 50 GWe mutli-recycling.

2. Front end Results

(1) Fuel Fabrication Capacities of Recycled Fuel

The multi-recycling scenarios show a threefold increase of plutonium-based FA production, as shown in **Fig. 6**, from 65 tHM/y (tHM: tons of Heavy Metal or tiHM: initial tHM) and 85 tHM/y in mono-recycling to 210 tHM/y and 270 tHM/y in multi-recycling for the 40 GWe and the 50 GWe trajectory scenarios respectively.

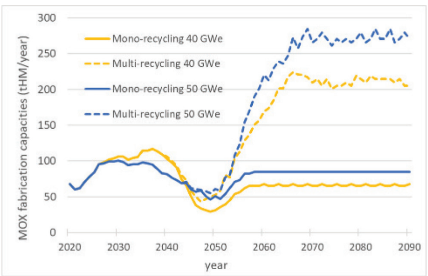

Fig. 6 Evolution of fabrication capacities for all the scenarios

The time evolution of fissile quality of MOX-MR fuel is illustrated for the 50 GWe scenario in the **Fig. 7**. By 2060, the fissile quality of MOX-MR FA needed to be decreased in order to save ENU SNF to maintain MOX-MR loading up to the end of the century. Indeed, a high fissile quality demands a high amount of ENU or ERU SNF to be reprocessed.

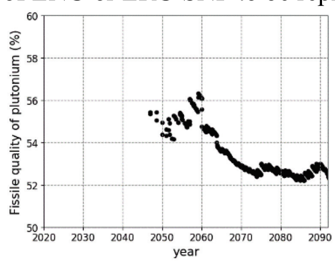

Fig. 7 Evolution of the fissile quality (with ^{241}Am taken into account) of MOX-MR FA for the 50 GWe multi-recycling scenario

(2) Natural Uranium Consumption and Enrichment Work

The MOX-MR FA, using Depleted Uranium (DU), does not need any natural uranium, nor ERU fuel whereas ENU fuel does. Multi-recycling enables a saving of 20 % to 25 % of natural uranium compare to mono-recycling, representing in order of magnitude a total savings of approximately 40 % compared to an open fuel cycle. The cumulative natural uranium consumption is illustrated in **Fig. 8**. An average annual of 10.2 tHM/(y.TWhe) of natural uranium is consumed at the end of the multi-recycling scenario compared to approximately 18.9 tHM/(y.TWhe) for an equivalent open cycle. The enrichment work needed to feed the fabrication of ENU and ERU FA follows the same trend as the natural uranium consumption as seen in **Fig. 9**.

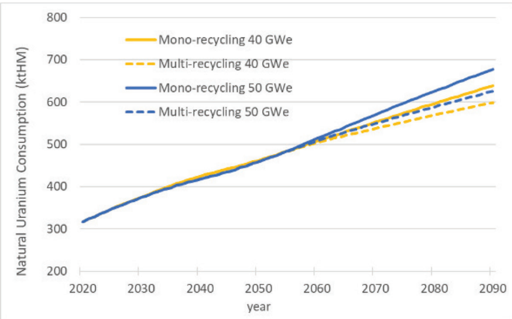

Fig. 8 Evolution of NU consumption for all the scenarios

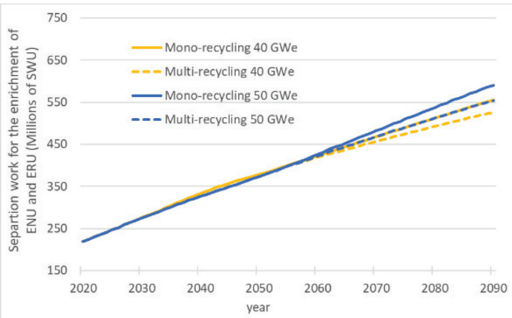

Fig. 9 Evolution of enrichment work for all the scenarios

3. Back End Results

(1) Reprocessing Capacities

At equilibrium, the SNF reprocessing capacities are set to grow by at least 60% (620 tiHM/y to 1000 tiHM/y in the 40 GWe trajectory) in the multi-recycling scenarios compared to mono-recycling as more plutonium is recycled (**Fig. 10**). Reprocessing quantities in these scenarios are finely tuned to the annual requirements for plutonium at fabrication. Therefore, the diminishing ability to MOX during the transition from PWR to EPR2 (**Fig. 6**) is also seen in the reprocessing factories. Multi-recycling scenarios lead to a large amount of MOX SNF to be reprocessed with cumulative quantity of respectively more than 8 ktiHM to 11 ktiHM in the 40 GWe and the 50 GWe simulated scenarios.

Furthermore, the **Fig. 11** shows that in the multi-recycling scenarios, the plutonium used in the fabrication in the MOX-MR FA is approximately at 60% coming from MOX or MOX-MR SNF. As the MOX SNF stockpile is being resorbed, an increased amount of MOX-MR is being reprocessed.

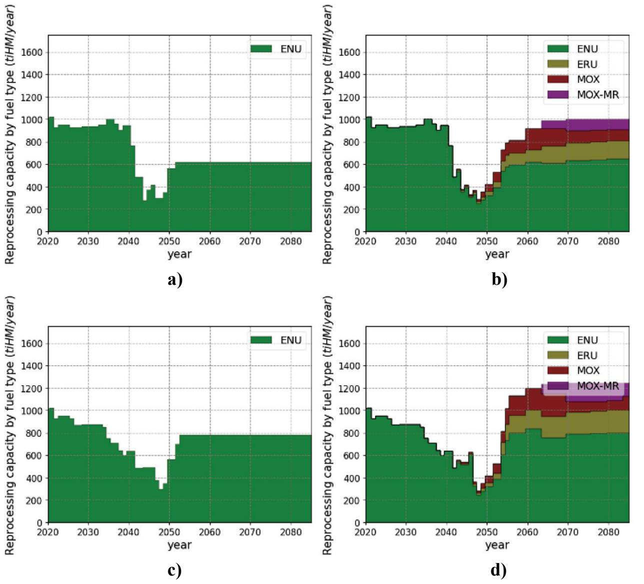

Fig. 10 Evolution of reprocessing capacities by SNF for the scenarios a) 40 GWe mono-recycling, b) 40 GWe multi-recycling, c) 50 GWe mono-recycling, d) 50 GWe mutli-recycling.

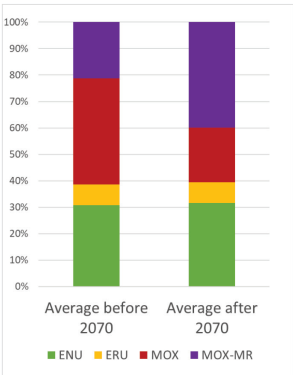

Fig. 11 Normalized plutonium origin distribution at the reprocessing plant used for the fabrication of MOX-MR FA

(2) Inventory of Spent Nuclear Fuel

The **Fig. 12** and **Fig. 13** illustrate that the total SNF and plutonium-based SNF inventories increase with a mono-recycling fuel strategy to more than 25000 tiHM and 7500 tiHM in 2090 in 40 GWe and in 50 GWe trajectories. In the multi-recycling scenario, the plutonium-based SNF inventory is stabilized between 4000 tiHM and 5000 tiHM at the same date and the total SNF inventory is reduced to 13000 tiHM in 50 GWe trajectory. The fissile quality of plutonium required for the MOX-MR (high compared to other multi-recycled FA[16,17]) leads to a reduction of the SNF inventory which may pose a challenge in the long term, as a shortage of ENU SNF could be foreseen when pursuing the multi-recycling scenario beyond the 21st century. Nevertheless, for the simulated 40 GWe and 50 GWe trajectories, the amount of SNF available for reprocessing allows the use of MOX-MR fuel until the end of the century. These scenarios are therefore compatible with the possible deployment of FR at the end of the century, after multi-recycling in PWRs, as called for in the draft PPE.[3)]

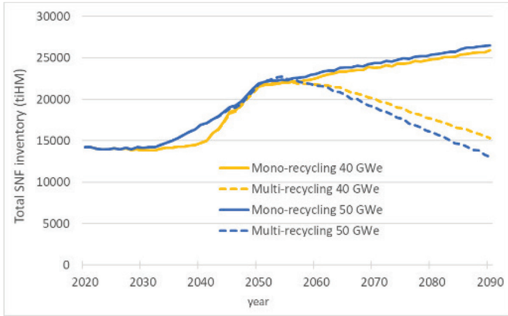

Fig. 12 Evolution of the total SNF inventory for all the scenarios

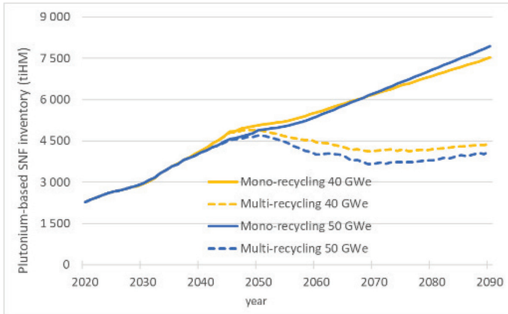

Fig. 13 Evolution of the plutonium-based SNF inventory for all the scenarios

(3) Inventory of Actinides of Interest

The **Fig. 14** shows that the plutonium inventory increases for both trajectories in the case of mono-recycling, exceeding 780 t by 2090 in 50 GWe trajectory whereas it is stabilized, as requested by PPE2,[3)] in the multi-recycling scenarios between 600 t and 650 t. On the other hand, **Fig. 15** highlights that the Minor Actinides (MA: Np, Am, Cm) inventories rise by approximatively 11% although the total transuranic inventory also decreases by an average of 11% in both power trajectory multi-recycling scenarios.

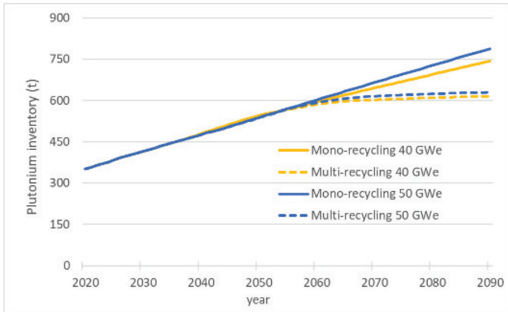

Fig. 14 Evolution of plutonium inventory for all the scenarios

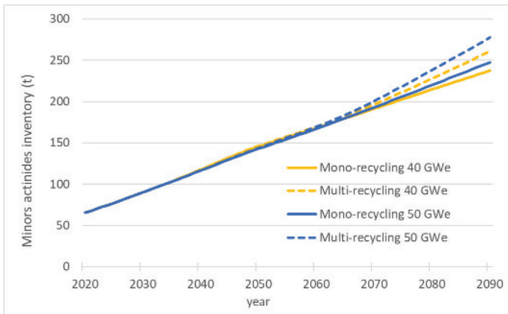

Fig. 15 Evolution of the MA inventory for all the scenarios

Furthermore, in both strategies, the plutonium is mainly found in the plutonium-based SNF as seen in **Fig. 16**.

However, the plutonium inventory in the multi-recycling scenarios increased in the fuel cycle facilities, in particular in fuel fabrication installation, and in the reactors. The total minor actinides are mostly encapsulated in the waste in the multi-recycling scenario due to the increase in reprocessing capacity.

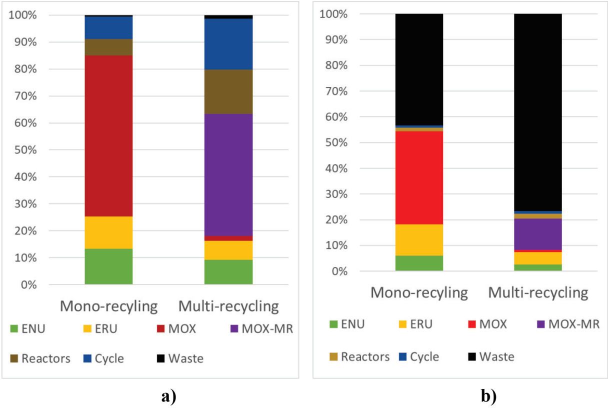

Fig. 16 Averaged normalized plutonium a) and MA b) repartition in the fuel cycle in the mono-recycling and the multi-recycling scenarios after 2090

IV. Conclusion

Multi-recycling strategies, in which plutonium and reprocessed uranium from all spent fuel types are recycled in PWRs, are evaluated in the frame of the MRREP project, a R&D collaboration between Orano, EDF, Framatome and CEA. This strategy would offer the possibility to optimize the SNF stockpiles and the plutonium inventories, which is considered as a key element of a future sustainable nuclear system by the French government. This paper details recent nuclear system scenarios based on two power trajectories using COSI6, the simulation tool developed by CEA for scenarios analyses, based on a series of industrial hypotheses. The results show the feasibility to implement a multi-recycling strategy in PWRs until the end of 21st century with the MOX-MR fuel assembly design. It would lead to a stabilization of plutonium inventory at around 600 tons for both 40 GWe and 50 GWe fleets, to a decrease of SNF inventory and to the reduction of natural uranium consumption by ≈ 20 % compared to a mono-recycling case, and ≈ 40% compared to an open cycle.

V. Acknowledgements

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FRANCE 2030

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