



DE LA RECHERCHE À L'INDUSTRIE

Pu multi-recycling scenarios towards a PWR fleet for a stabilization of spent fuels inventories in France

June 28th 2021

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Commissariat à l'énergie atomique et aux énergies alternatives - www.cea.fr

CONTEXT & TOOLS

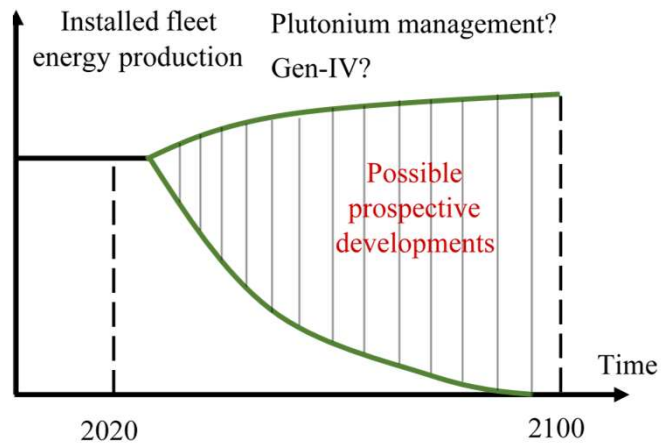
▶ INDUSTRIAL SCENARIOS

▶ COSI

▶ PLUTONIUM MULTIRECYCLING IN PWR

Industrial scenario studies are **similar** to academic ones ...

- Project given strategies
- Propose prospective development of a reactor fleet towards a target reactor fleet
- Show the long-term consequences of a strategy in order to improve it
- Compare different strategies regarding different objectives



But **differ** in significant ways

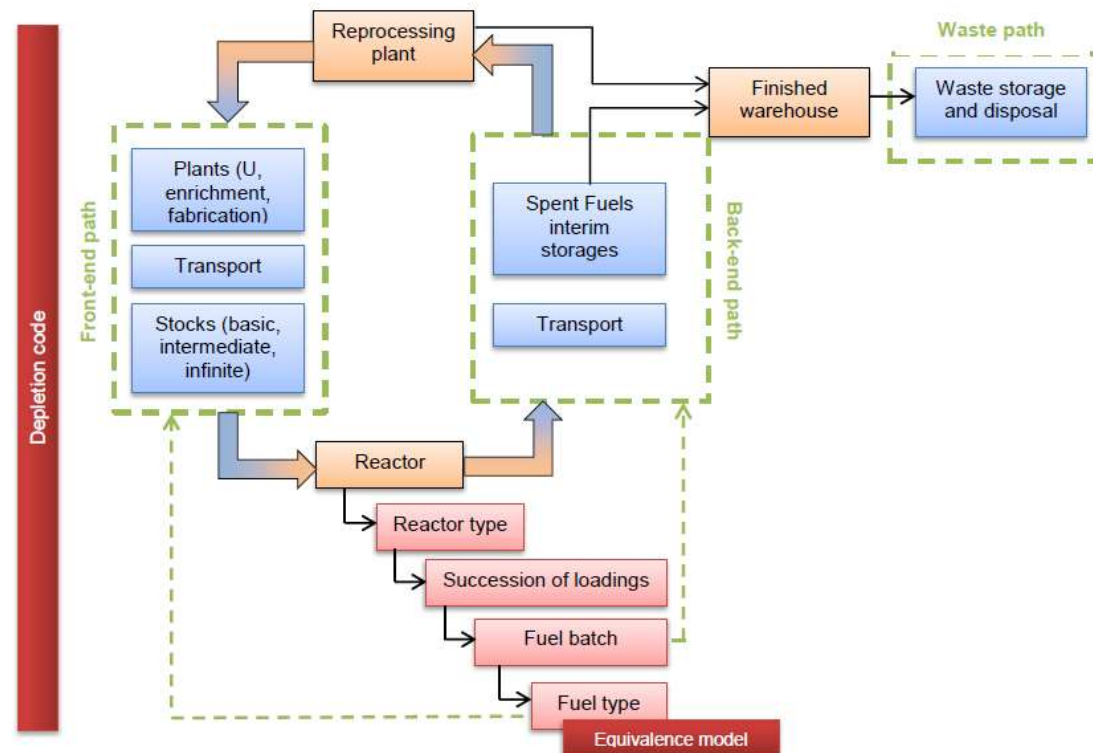
- Build **in collaboration with industrial partners**
- Need **conservative hypothesis** regarding reactor technologies, plants and their capacities etc.
- **Objectives and constraints** consistent with the **current french fleet** and **political goals** regarding the nuclear industry

The code used to built those simulation is **COSI**, a scenario code that simulates the **evolution of nuclear matters flows and inventories** in all of the cycle installations

- Developed since 1980
- Reference code for industrial scenario studies

Technical aspects

- **Irradiation** in reactors simulated with **equivalence models**
- **Depletion** calculations done with **CESAR**
- **Discrete-event simulation**
- Models down to **assembly batch** => linked to the history of recycling spent fuel in France
 - Pu from spent UOX reprocessed into MOX assemblies
 - Spent MOX assemblies accumulate



- French law of waste management – 1991, 2006 [3]

Reference strategy for French nuclear fuel cycle :

- Recycling of Pu in Sodium Fast Reactors (SFR)
- Geological Storage of High Level Nuclear Waste

- Energy planning law: “Programmation pluriannuelle de l’énergie” PPE - 2019 [4]
- Uranium resources are still available and cheap
- SFR deployment is postponed to the second half of 21st century
- Recycling Pu in SFR becomes a long-term strategy
- Research should be conducted on multi-recycling of Pu in PWR
 - with a dedicated type of fuel “MOX2” (CORAIL, ATOLL, MIX, ...)
 - to stabilize Pu and spent fuel (especially MOX2) inventories



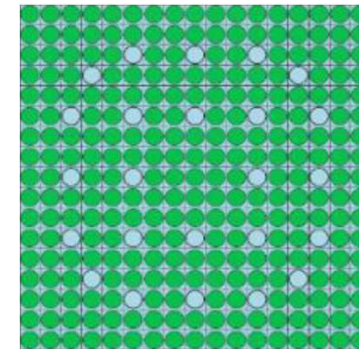
Why not use spent MOX fuel to create new MOX assemblies ?

As Plutonium is used in PWR, its **grade decreases** : the odd isotopes fissionate while the even ones accumulate

- ⇒ Need for **higher Pu content** to ensure criticality, in time, over 12 %
- ⇒ Over that limit, **safety risks** (positive void coefficient)
- ⇒ **Need to design other fuel types, more suited to Pu multirecycling**

One of them is the **MIX fuel**

- ⇒ **Fixed Pu content** (in our case 8%) in a mixture of **enriched Uranium**
- ⇒ Uranium enrichment varies between 2% and 4.2 % to account for the changes in Pu grade



MIX assembly layout

Objective : Pu and spent MIX fuel stabilisation and consumption of MOX fuel

Objective : reach equilibrium of Pu and recycling of all spent MOX fuel by introducing a 100% MIX EPR

2 trajectories for the nuclear fleet in France are studied :

Trajectory Tc :

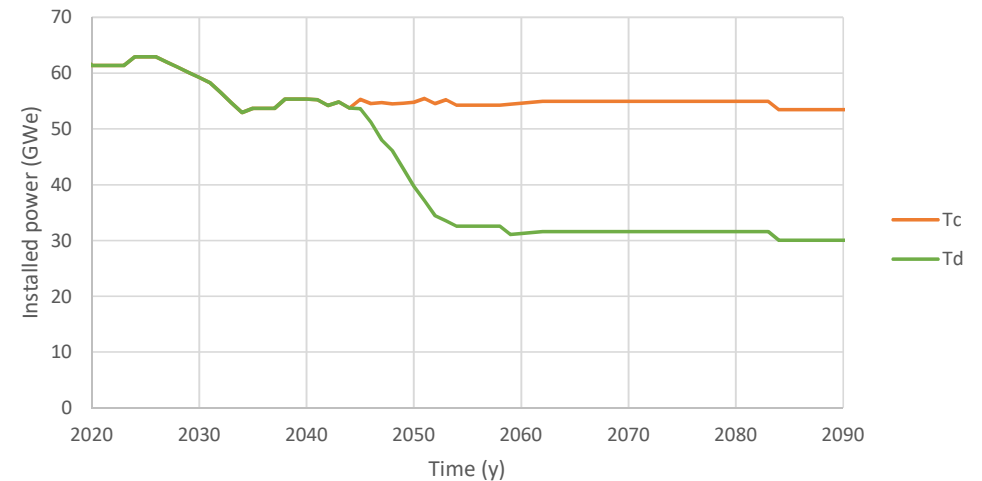
- Installed Power remains constant
- 32 EPR2 (53,44GWe)

Trajectory Td :

- Decrease in the installed Power
- 18 EPR2 (30,06GWe)

Constraints :

- Separated Pu < 55t
- Uranium enrichment in MIX < 4.2 %
- Uranium enrichment in ERU < 5%
- Consistent reprocessing of high Pu content SF



Construction of the scenario :

- MIX fraction to stabilise Pu and SF inventories
- ERU to recycle U from UOX

Current french fleet :

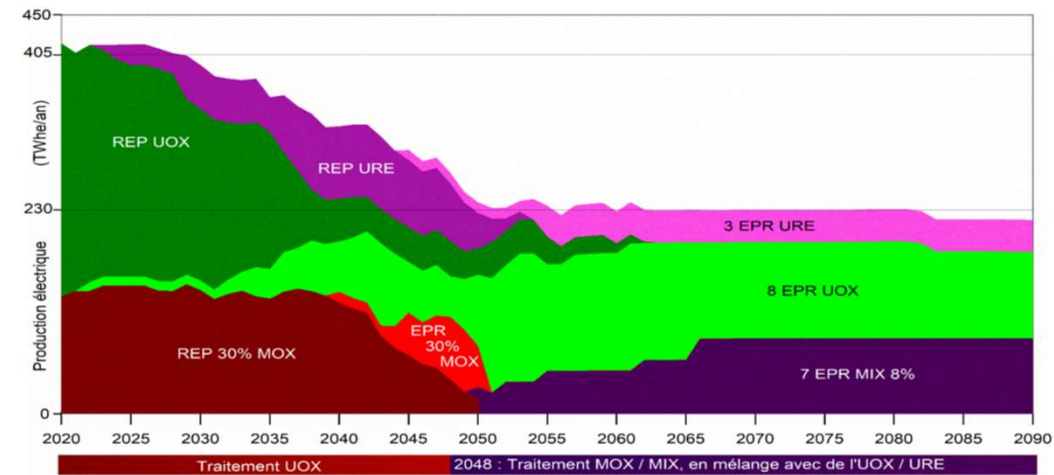
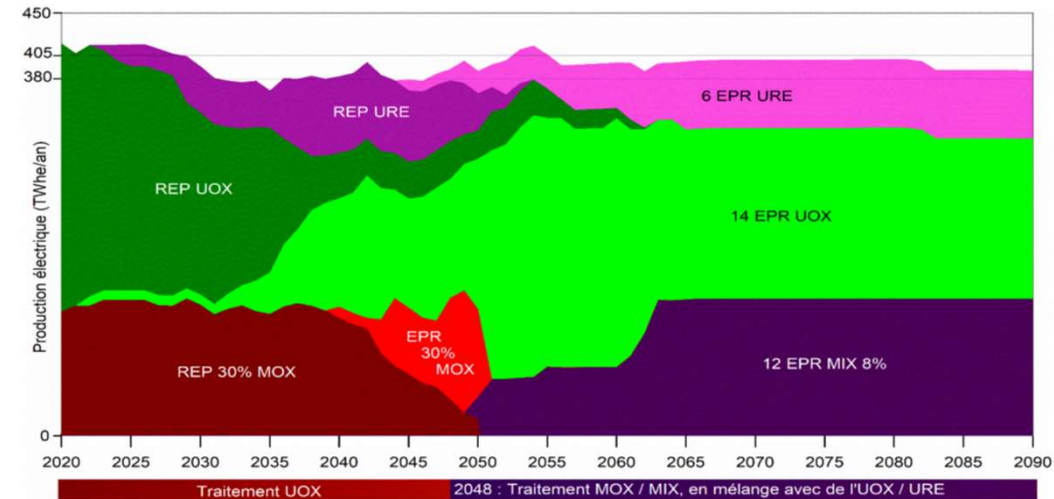
- Model made in collaboration with industrial partners
- Stocks of ressources and waste from the most recent national inventory at time of study
- Flamanville EPR is considered to start in 2022

Reactor hypothesis

- P_{EPR2} : 1670MWe
- Life span : 60 years
- Load factor : 83 %

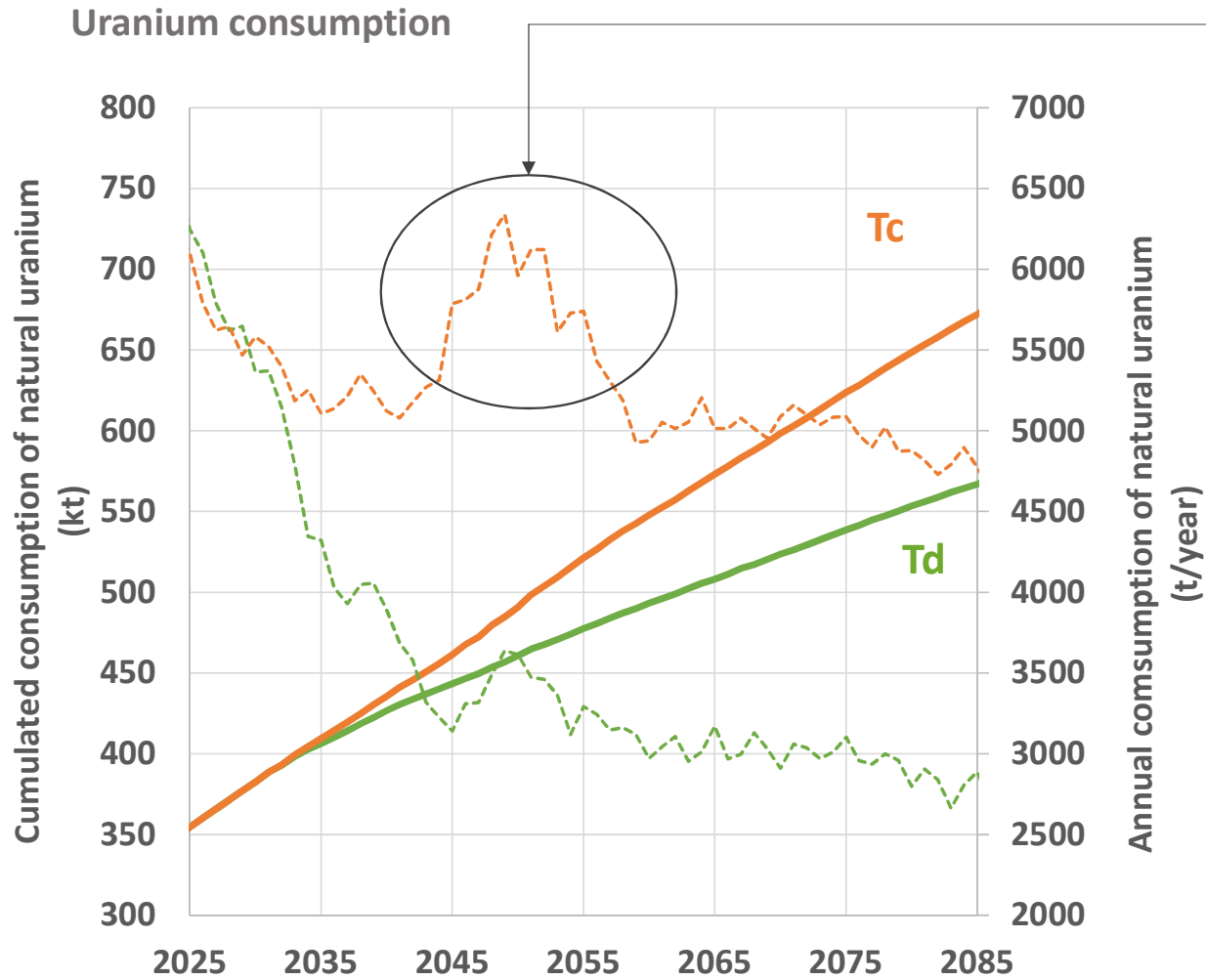
Cycle hypothesis

- Minimal SF cooling time : 5 years
- Fabrication time : 2 years
- Starting date for new cycle plants : 2050
- Plants life span : 50 to 60 years
- Maximum annual spent MOX capacity : 40 t/year in current cycle plants
- No limit for future cycle plants



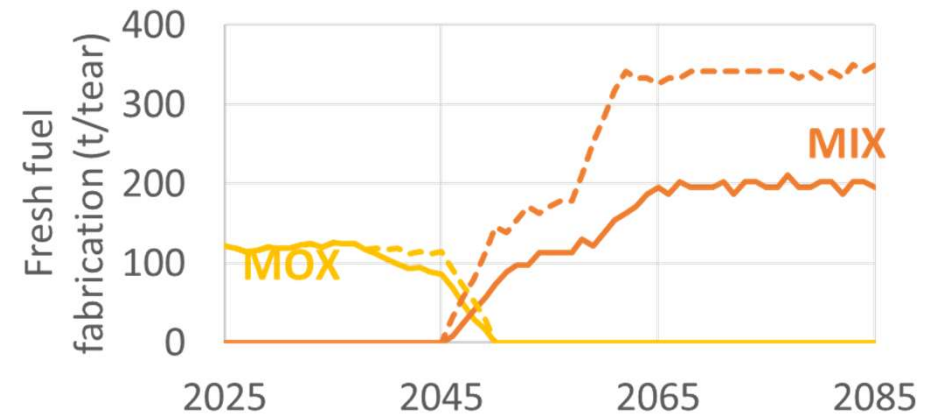
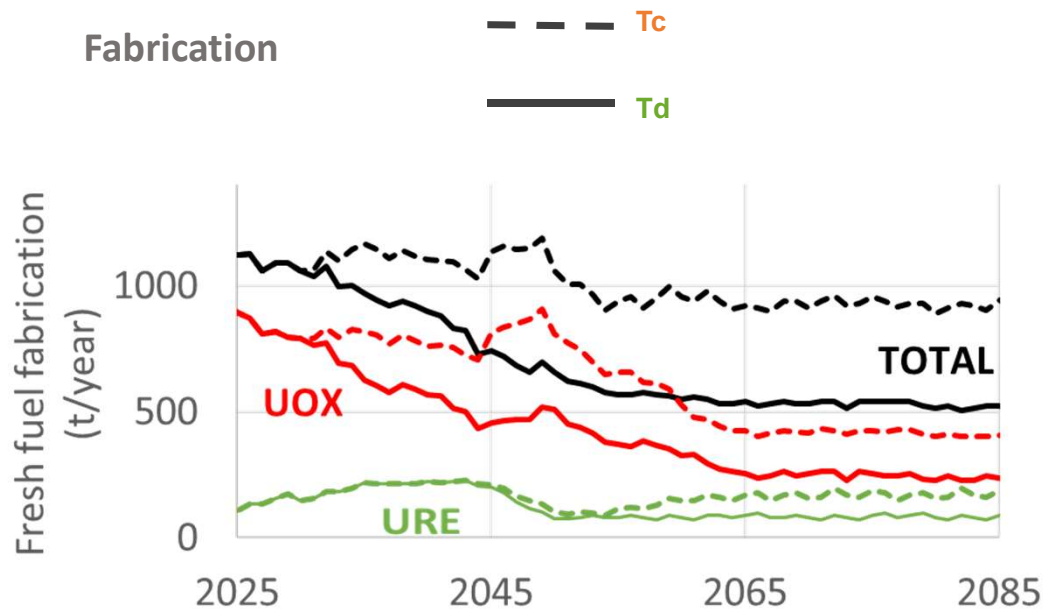
RESULTS

- ▶ UPSTREAM
- ▶ REPROCESSING
- ▶ DOWNSTREAM



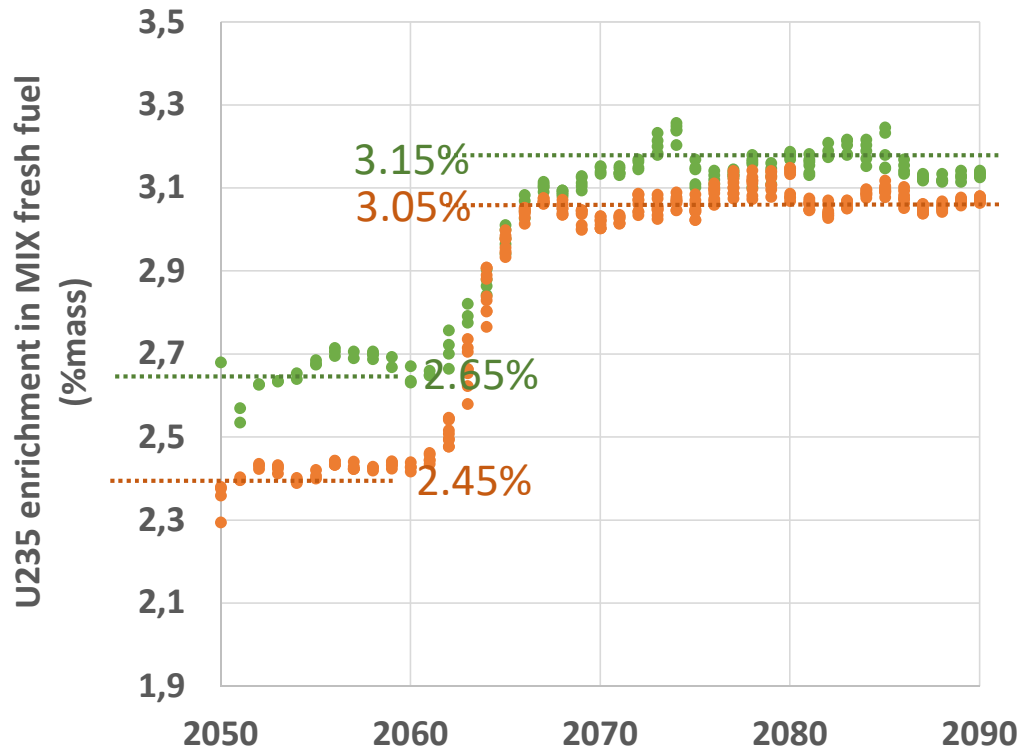
Increase due to the fabrication of new cores, not MIX consuming more ^{235}U than MOX

► Consumption difference is coherent with the number of reactor in each fleet



- ▶ Total fuel fabrication almost twofolds
- ▶ Particularly important MIX fabrication capacity for Tc – reaches 350t/y in less than 20 years

Enrichment

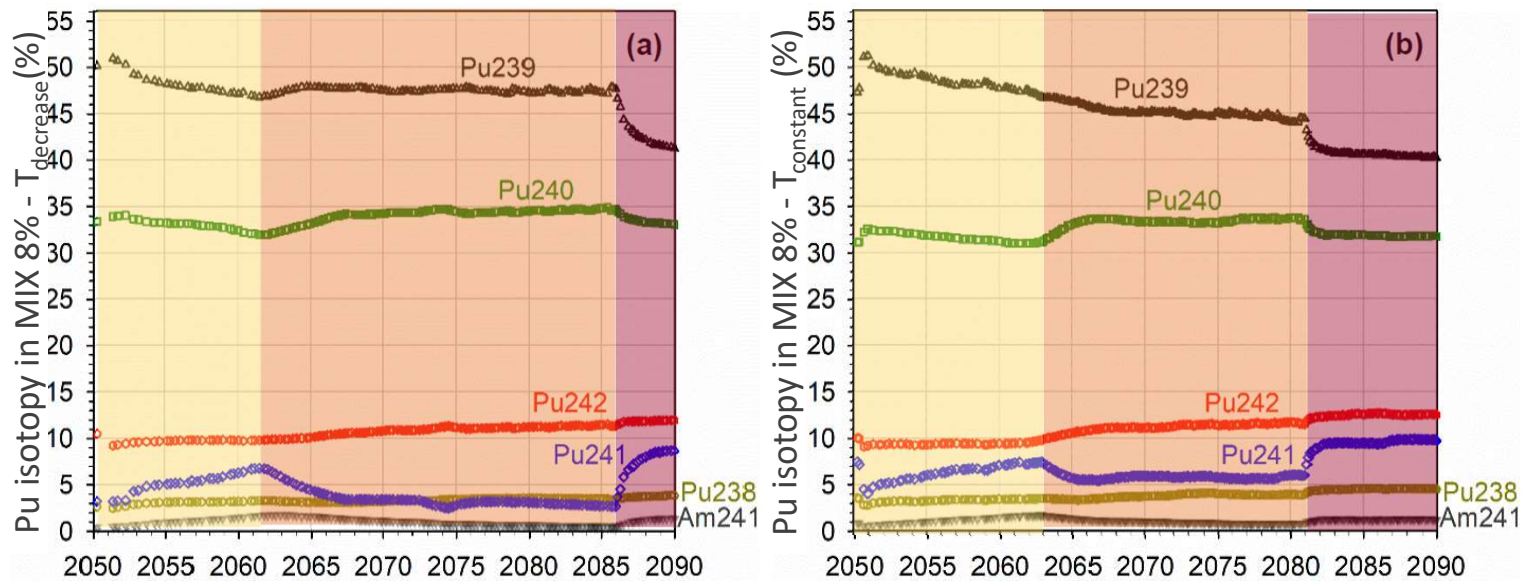


Two **constant enrichment levels** – which respect the limits on ^{235}U content - are identified in both trajectories

The differences between these levels is explained by what limits the reprocessing of spent fuel with high Pu content :

- For **Td** it's the reprocessing capacity of MIX fuel at the end of the transition that tops the reprocessing of MOX at the beginning of the scenario
- For **Tc** it's the maximal cadence of MOX reprocessing, industrially fixed

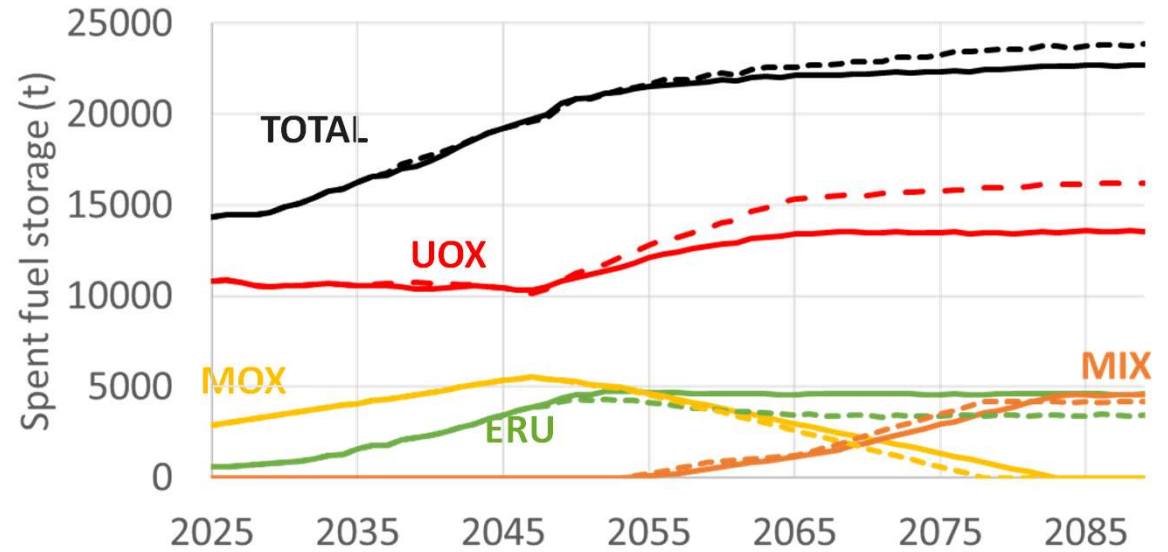
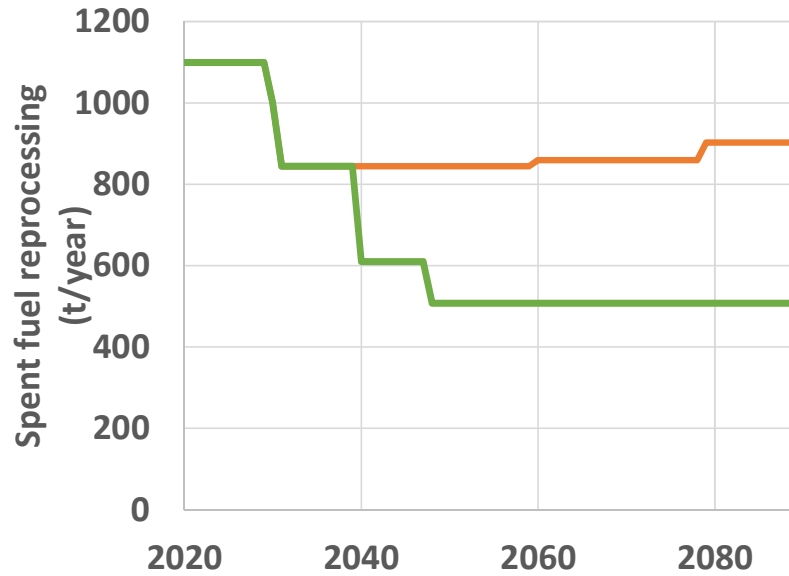
Plutonium isotopy



- ▶ No stabilised isotope
- ▶ Variations related to the mixture of spent fuel at reprocessing, especially regarding ^{241}Pu
 - 1. medium aged MOX
 - 2. recent spent MOX with very old spent MOX
 - 3. MIX

--- Tconstant

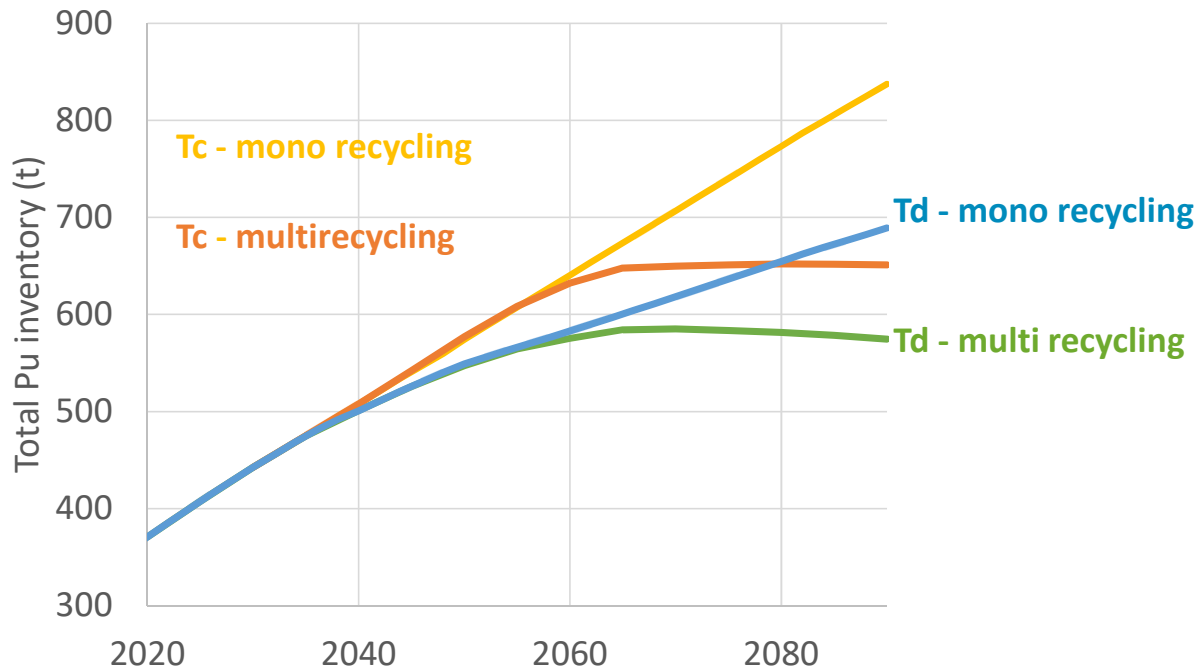
— Tdecrease



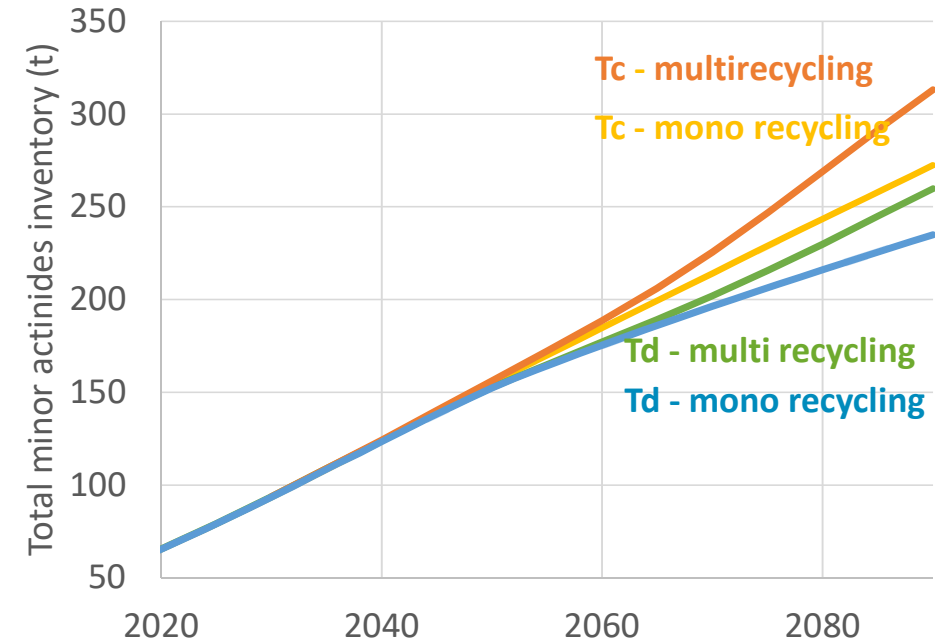
- Reprocessing capacity consistent with the size of the fleet

- In both cases, all spent MOX fuel is reprocessed and the spent fuel inventories are all stabilised
- Higher retreating capacity for **Tc** allows for **earlier consumption of all spent MOX fuel**
- **Stabilisation of all spent fuel at a similar level**

Plutonium and Minor actinides inventories



- Plutonium is stabilised in both cases, and the level of the stabilisation is determined mainly by the size of the fleet



- However, multirecycling in EPR entails a more important production of MA

In a nutshell, at the end of the transition (2090) :

	Mono - recycling	MIX 8%	Mono - recycling	MIX 8%
Fleet composition	14 EPR UOX 6 EPR ERU 12 EPR MIX	14 EPR UOX 6 EPR ERU 12 EPR MIX	8 EPR UOX 3 EPR ERU 7 EPR MIX	8 EPR UOX 3 EPR ERU 7 EPR MIX
Nat U consumption	700 kt + 5.2 kt/y	691 kt + 4.7 kt/y	580 kt + 2.9 t/y	578 kt + 2.7 t/y
Annual reprocessing	720 tHM/y	903 tHM/y	420 tHM/y	508 tHM/y
spent Fuel (tHMI)	Total : 27200 UOX : 8000 URE: 9700 + 135t/y MOX : 9500 + 80 t/y	Total : 23860 UOX : 16 210 URE : 3460 MIX : 4190 MOX : 0 in 2079	Total : 24300 UOX : 8200 URE: 8400 + 81t/y MOX : 7700 + 45 t/y	Total : 22710 UOX : 13550 URE : 4620 MIX : 4540 MOX : 0 in 2084
Plutonium	840 t + 6.5 t/y	650 t	690 t + 3.5 t/y	575 t
Minor Actinides	272 t + 2.9 t/y	310 t + 4.4 t/y	235 t + 1.9 t/y	255 t + 2.9 t/y

Both strategies reach the fixed objectives :

- Pu and SF stabilisation
- Consumption of spent MOX fuel

While respecting industrial constraints :

- Uranium enrichment
- Separated Plutonium
- High Pu content SF capacity controlled

The hypothesis are continuously actualized in collaboration with industrials as more details on reactors and plant technologies (feasibility studies) are known



Thank you for your attention !

Feel free to ask your questions

- [1] Weifeng Zhou. Resilience analysis of nuclear fuel cycle scenarios. PhD. Université de Grenoble, 2020.
- [2] Coquelet-Pascal, C., et al. "COSI6: a tool for nuclear transition scenario studies and application to SFR deployment scenarios with minor actinide transmutation." Nuclear Technology 192.2 (2015): 91-110.
- [3] "Loi no 2006-739 du 26 juin 2006 de programme relative à la gestion durable des matières et déchets radioactifs," 2006. Journal Officiel no 149 du 29 juin 2006.
- [4] Ministère de la transition écologique, "Stratégie française pour l'énergie et le climat, Programmation pluriannuelle de l'énergie 2019-2023, 2024-2028"

General issue : how the French nuclear fuel cycle should evolve in the future ?

Major challenges facing the nuclear industry in the future:

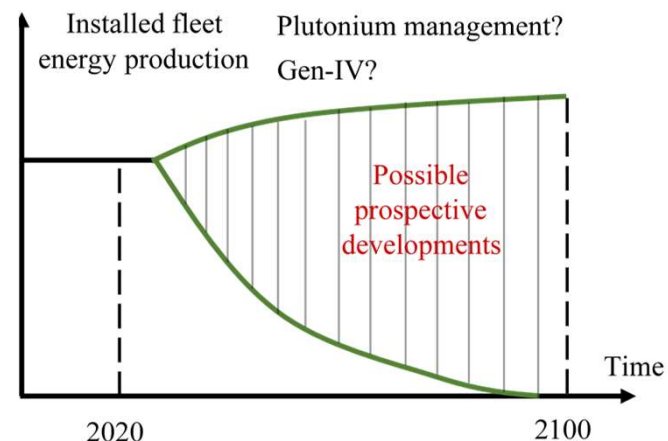
- Ensure a very high safety level;
- Find a reliable solution for nuclear wastes;
- Produce electricity at a competitive price; etc.

Different development strategies may lead to different prospective developments of reactor fleet

- Compatible with challenges?
- What is the impact of a development strategy?

Need for a methodology that:

- Project the given strategies
- Propose prospective development of the reactor fleet towards a target reactor fleet
- Show the long-term consequences of a strategy in order to improve it



[ZHO-20]

Nuclear fuel cycle scenario studies are a tool to model and analyze these possible futures.