framatome

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The CORAIL-A option for recycling plutonium in PWR: overview of the latest investigations at Framatome

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OUTLOOK

- Introduction
- The CORAIL-A concept
- Investigations at the assembly level
- Investigations at the core level
- Conclusions

Introduction

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Introduction (1/3)

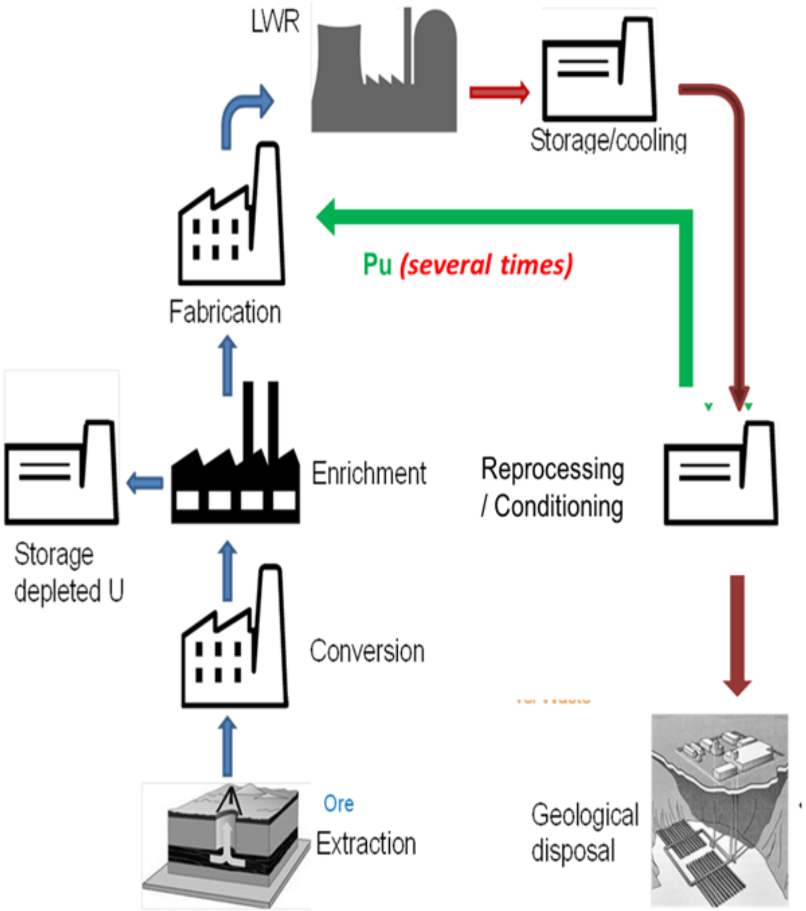
- For achieving the objective of a **long term use of nuclear energy**, the industries together with academics partners are **analyzing several strategies and options**
  - Depending on the strategy, the **reactor and the fuel types** are impacted as well as the overall fuel cycle infrastructures. Therefore, the **feasibility analysis of those strategies** remains an interesting subject for R&D investigations
  - The outcome of those analyses will be **dimensioning for the fuel cycle and may have an impact on reactor design**
- **Beyond the well-established UO2 fuel assembly recycling process through MOX fuel**, energy is still available in the used MOX fuel and an improved use could be considered
- While working on GEN-IV solutions, it has been decided to **investigate a shorter term options based on** the use of **PWR reactor type for reducing irradiated FA**

Framatome contributes with his experience to the analysis by **providing PWR core and fuel investigations for dedicated plutonium multi-recycling options**

Introduction (2/3)

- A **step by step approach is proposed** here to understand the behavior of a **multi-recycling dedicated fuel** (the **Framatome CORAIL-A concept**) as precondition to full 3D core calculations and dynamic scenario studies

- The **respect of the safety criteria, reactor performances as well as the goal of plutonium consumption** (i.e. for stabilizing the inventories in the cycles) is guiding the analysis of Framatome



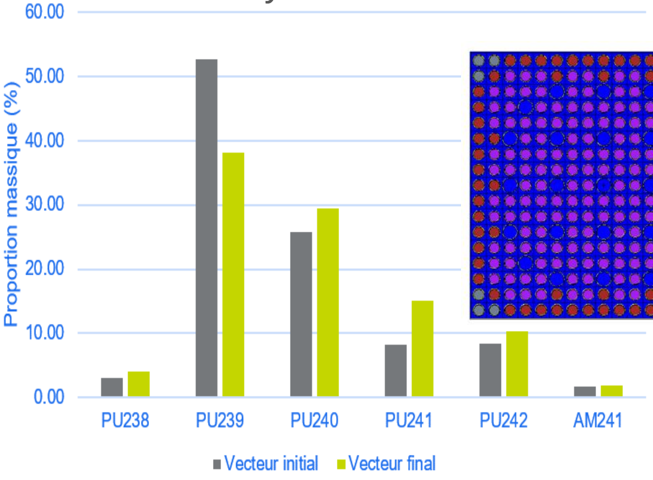
Introduction (3/3)

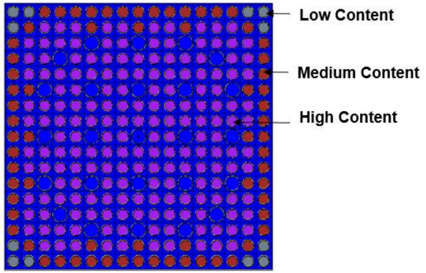
- Several **solutions existent for valorizing the plutonium available in the spent MOX fuel at short term**
- Due to the lower fissile content with respect to the Pu coming from spent UOX fuel, solutions oriented to augment the fissile content in the core are proposed and investigated within a French consortium. These solutions are based on the **addition of U235** are proposed:
    - **At assembly level**:
        - Within the matrix (e.g. used of enriched U235 instated of depleted one) → MIX
        - Within the assembly in dedicated fuel pins → **CORAIL-A**, …
    - **At core level**:
        - Mixed UOX/MOX core loading strategies
    - **At fuel cycle level**:
        - Blending strategies
- The strategy retained will have an impact on the scenarios to be studied

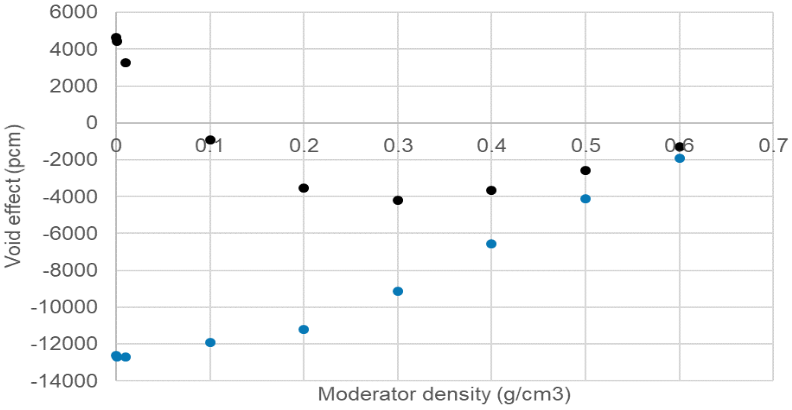
The CORAIL-A concept

MOX Fuel concept

- Actually **Pu is mono-recycled in PWR** in France within **MOX fuel concept** – **no safety-related issues** – large REX on fabrication and utilization
- The investigation over the multi-recycling of Pu in standard MOX fuel assembly design has shown several limitation if energy equivalence compare to UOX is expected for MOX fuel:
  - The amount of fissile Pu isotopes is strongly reduced after the first Pu recycling
  - Safety coefficients becomes less favorable after the first Pu recycling

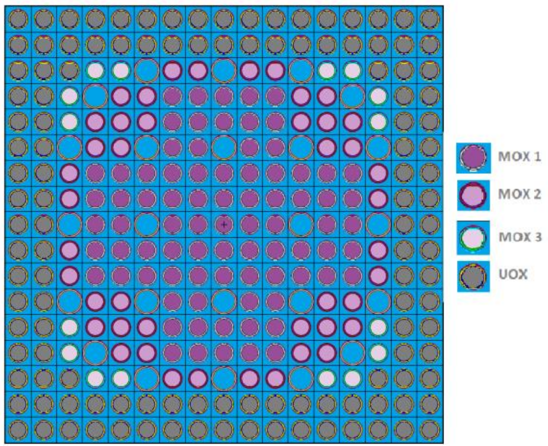






The CORAIL-A concept

- **Needs to development of PWR fuel assembly concepts dedicated to multi-recycling** to maintain energy equivalence when degrading the Pu quality
- **Different concepts exists** and they are under investigation for testing the multi-recycling in REP



124 UOX enriched 4.95%U235 pins

141 MOX pins (3 Pu content zones < 11.5%)

The CORAIL-A concept, proposed by Framatome, considers the **use of UO_2 and MOX fuel rods in the same assembly. Concept criteria are:**

- Reducing the effects at assemblies interface → UOX pins are placed in the periphery
- Flexible concept with respect to the strategy (evolution may be considered regarding Pu quality or reactor performances)
- Possibility to use Gd pins or boron concentration to control the picking factor

This “consolidated design” has been used for starting point of the analyses at lattice and core level and optimized

Investigations at the assembly level

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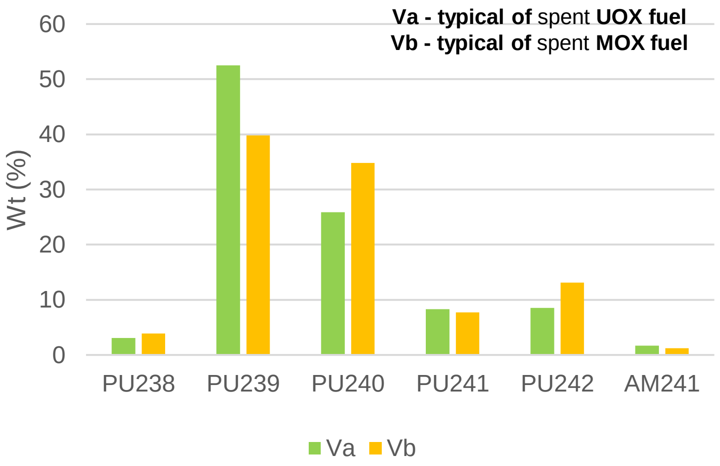
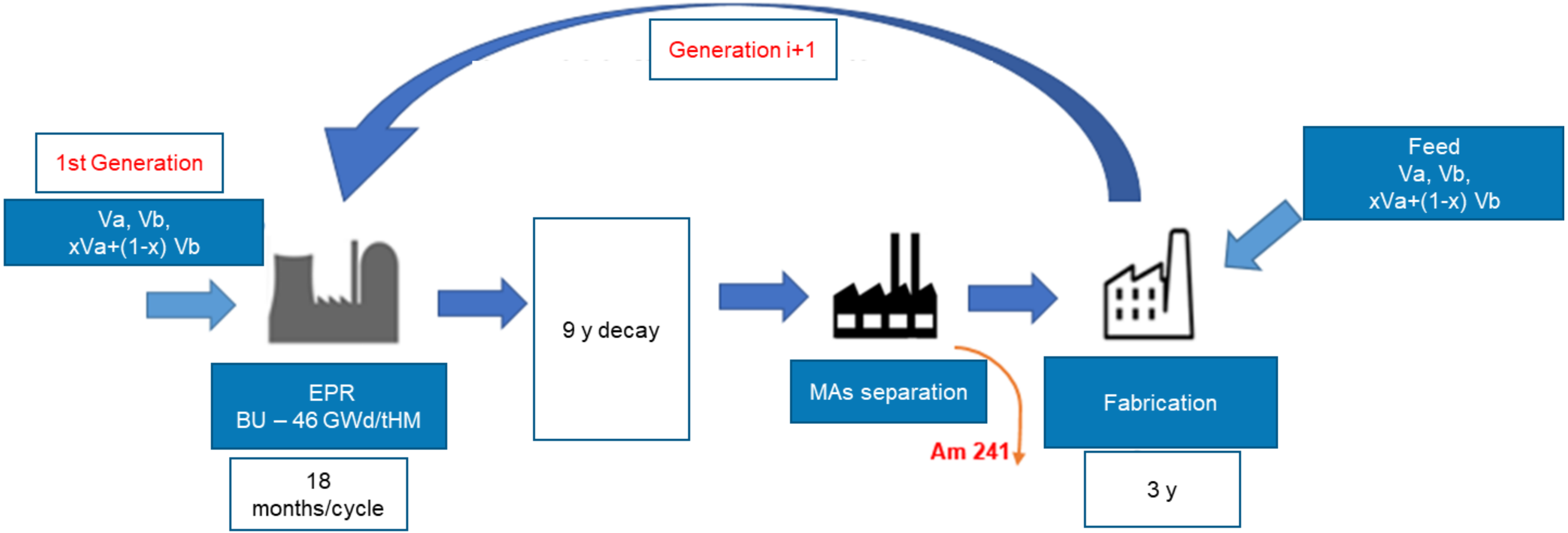
Investigations at the assembly level (1/9)

- The investigation at assembly level have been carried out to understand the **CORAIL-A behavior if different Pu qualities are adopted**
- Two Pu vectors corresponding to **spent UOX** (**Va**) and **MOX** (Vb) fuel stockes have been considered for this study and combined as needed
- **Multi-recycling capability analyzed for several generations** covering the whole cycle (irradiation, cooling, manufacturing)
- **Simplified model for catching tendencies before running scenarios studies**



Investigations at the assembly level (2/9)



Investigations at the assembly level (3/9)

- Selection of Pu **multi-recycling strategy investigation indicators**, related to:
  - **core performances**: kinf vs. BU, Pu quality at discharge
  - **cycle performances**: Pu and U consumptions, Am241 accumulation
  - **safety**: pin power distribution, Doppler and moderator density coefficients -> Pu content in fuel

- In order to take into accout some variability during fuel cycles and scenarios simulations, **several sensitivities** have been carried out:
  - **Isotopic Pu vector** (may changed during the scenario but sjoul remain manageble for the fabrication needs)
  - **Pu content in MOX pins** (keeping a maximum < 15%)
  - **Modification of the assembly concept** (MOX pins location and quantity)
  - **Time between generations**
  - **UOX pin enrichement**

Investigations at the assembly level (4/9)

- Between following generations, the **adjustment of the Pu content is needed in order to cope with Pu quality degradation**
- At assembly level (infinite lattice calculations) an **equivalence model** is considered to allow the Pu content adjustment
- The **choice of the proper equivalent model for representing a system under infinite lattice approximation is crucial also for the scenario simulation** analyses that may use this kind of modelisation for preparing the XS needed by the scenarios codes

- The choice done for the CORAIL-A study, has been:
  - choice of the reference assembly for PWR
  - Identification of the average core BU at end of equilibrium cycle

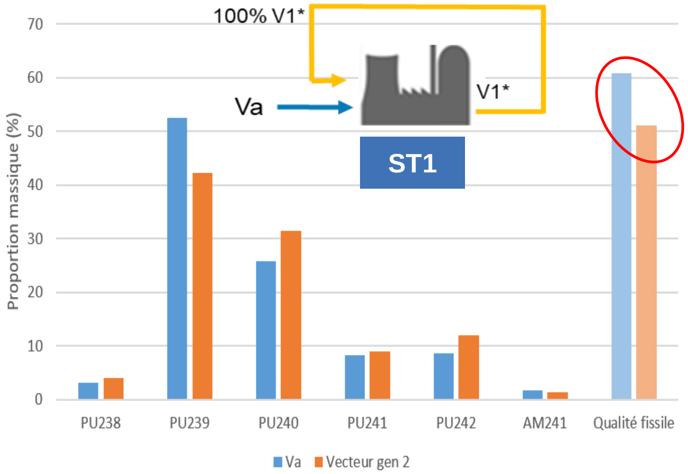
  } **target k∞**
  Average BU
  (34 GWd/tHM - 0 ppm
  boron content)

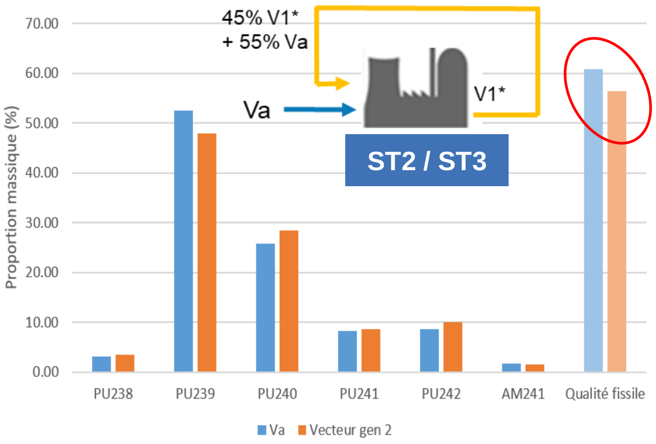
  - Determine the Pu content that allowing to reach the target k∞ at the BU corresponding to the average core BU and 0 ppm boron → **simplified equivalence model**

Investigations at the assembly level (5/9)

Strategy	Vecteur 1st generation	Mixing at n-generation	Pu content adjustment	Concept modification	Time between generations
ST 1	**Va (spent UOX)**	No	Uniform	No	9+3 y
ST 2	Va	**Yes (Va)**	Uniform	No	9+3 y
ST 3	Va	Yes (Va)	**Relative to zones**	No	9+3 y
ST 4	Va	Yes (Va)	Uniform / Relative to zones	*Yes*	9+3 y
ST 5	**55%Va-45%Vb (Vb spent MOX)**	Yes (Va)	Uniform	No	9+3 y
ST 6	**40%Va-60%Vb**	Yes (Va)	Uniform / Relative to zones	No	9+3 y
ST 7	**30%Va-70%Vb**	Yes (Va)	Uniform	No	9+3 y
ST 8	30%Va-70%Vb	Yes (Va)	Uniform	No	**5 + 1 y**

Investigations at the assembly level (6/9)

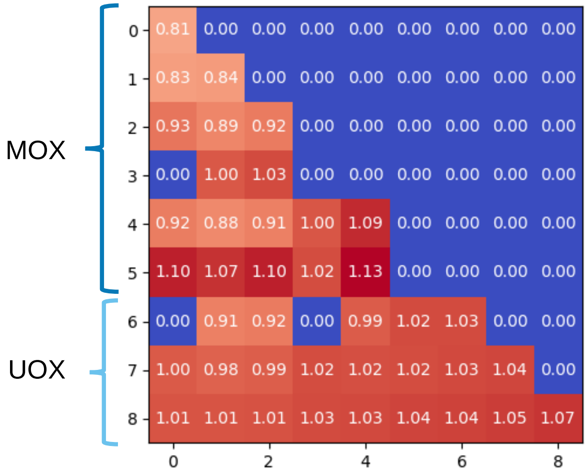


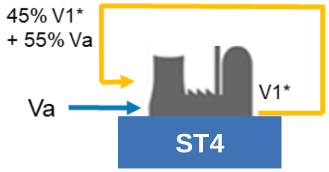


	Pu consumption (kg/ass)	U235 consumption (kg/ass)	Pu content < 15%	Safety coefficients	Pin power peak	N. generations
ST 1	**- 4.92**	**- 2.50**	**X**	√	**X**	**2**
ST 2	**- 4.09** ↓	**- 2.55**	√	√	**X**	**2**
ST 3	**- 4.05** ↓	**- 2.56**	√	√	**X**	**2**

Investigations at the assembly level (7/9)

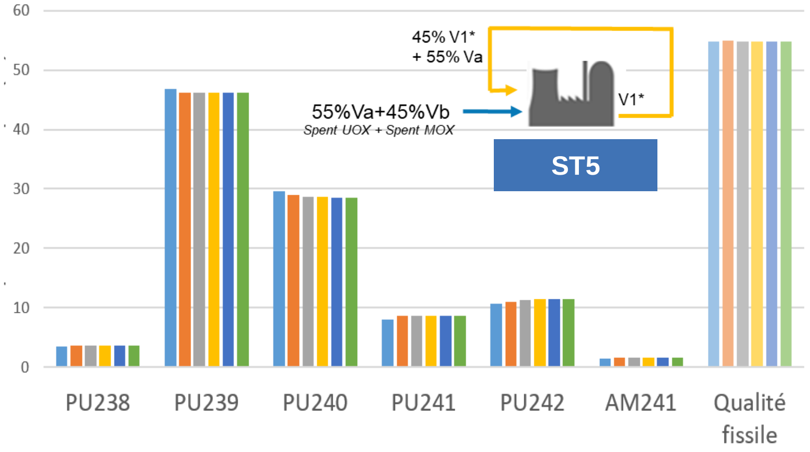
- In order to flat the pin power distribution, on option is to optimise the assembly configuration
- Several options may be tested e.g. **proportion of UOX/MOX pins, MOX zones compositions, UOX enrichement**

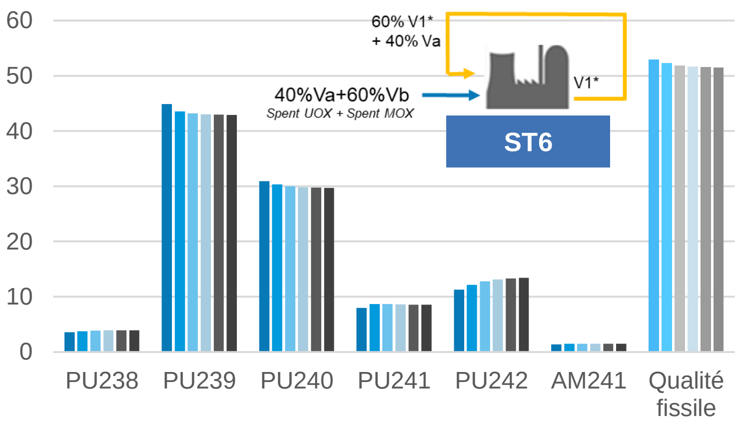


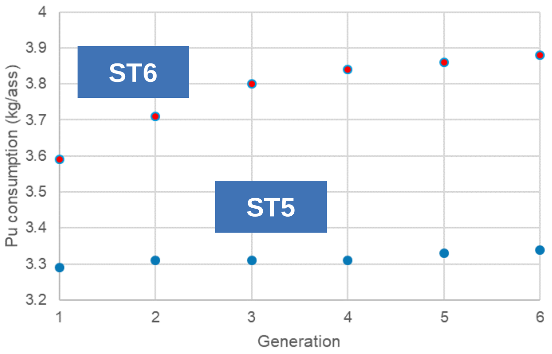


	Pu consumption (kg/ass)	U235 consumption (kg/ass)	Pu content < 15%	Safety coefficients	Pin power peak	N. generations
ST 2	**- 4.09** ↓	**- 2.55**	√	√	X	**2**
ST 3	**- 4.05** ↓	**- 2.56**	√	√	X	**2**
ST 4	**- 3.97** ↓	**- 2.58**	√	√	X	**2**

Investigations at the assembly level (8/9)

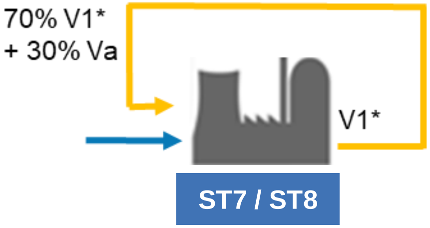


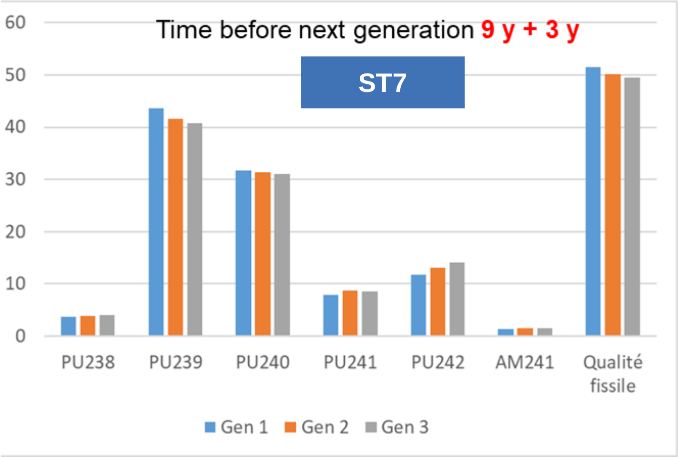


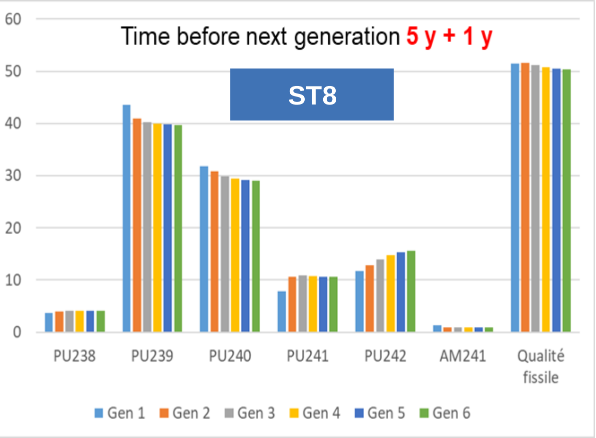


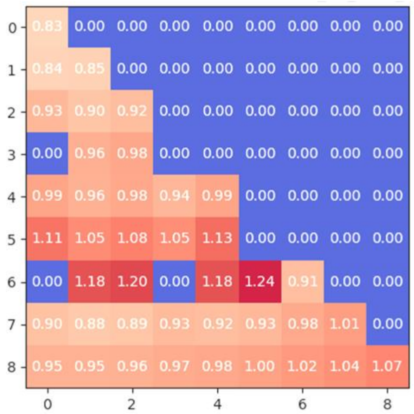
	Pu consumption (kg/ass)	U235 consumption (kg/ass)	Pu content < 15%	Safety coefficients	Pin power peak	N. generations
ST 3	**- 4.05 ↓**	**- 2.56**	√	√	**X**	**2**
ST 4	**- 3.97 ↓**	**- 2.58**	√	√	**X**	**2**
ST 5	**- 3.31**	**-2.62**	√	√	√	**6**
ST 6	**- 3.76 ↑**	**-2.59**	√	√	√*	**6**

Investigations at the assembly level (9/9)









	Pu consumption (kg/ass)	U235 consumption (kg/ass)	Pu content < 15%	Safety coefficients	Pin power peak	N. generations
ST 5	**- 3.31**	**-2.62**	√	√	√	**6**
ST 6	**- 3.76** ↑	**-2.59**	√	√	√*	**6**
ST 7	**-4.01** ↑	**-2.57**	√	√	**X**	**3**
ST 8	**-3.68** ↑	**-2.61**	√	√	√	**6**

Investigations at the core level

Investigations at the core level (1/3)

- The assembly investigations are used for designing the fuel assembly concepts and provide first sensitivities but **core level analyses are mandatory to investigate the behavior of those fuel types under representative 3D core conditions**
- **Two core loading strategies** have been investigated as **representative of different phases of the scenarios** (transition / stabilisation). For both core loading the same CORAIL-A FA configuration is used
- The **safety coefficients** (Doppler, moderator density coefficients, boron coefficients, kinetictics parameters, shutdown margins, etc.) **have been evaluated** for obtainig loading strategies that respect the criteria
- The two cases are:
  - **Full CORAIL-A loadign strategy (FULL)**
  - **Partial CORAIL-A loadign strategy (PART)**
- For each strategy the Pu performances have been analysed as well

Investigations at the core level (2/3)

- Heterogeneous loading strategy for the equilibrium cycle is reached

	FULL	PART
Core configuration	**1st cycle: 92 CORAIL-A** **2nd cycle: 92 CORAIL-A** **3rd cycle: 57 CORAIL-A**	**1st cycle: 16 Gd8, 24 Gd12, 52 CORAIL-A** **2nd cycle: 16 Gd8, 24 Gd12, 52 CORAIL-A** **3rd cycle: 16 Gd8, 24 Gd12, 16 CORAIL-A** **4th cycle : 1 Gd12 (central FA)**
Cycle length (EFPD*)	474	473
Moderator density coefficient (pcm / °C)	-12.7	-10.6

** Equivalent Full Power Day*

Investigations at the core level (3/3)

Isotopes	Pu Vector (input)	Pu Vector (output)		
		FULL	PART	
			CORAIL-A	UOX
PU238	3.4	3.9	3.8	3.3
PU239	**46.8**	**37.4**	**37.8**	**51.1**
PU240	29.7	29.8	30.1	23.2
PU241	8.0	14.7	14.5	14.9
PU242	**10.6**	**12.7**	**12.4**	**7.1**
AM241	1.5	1.6	1.5	0.6

FULL: the Pu mass balance is negative (-264 kg/cycle)
PART: the Pu mass balance is positive (+137 kg/cycle)

Conclusions

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Conclusions

For achieving the objective of a **long term use of nuclear energy**, a French consortium are **analyzing, from Pu management perspective, several strategies and options that allow the transition from current PWR fleet to future technologies**

Before all, the options considered need to respect all the safety criteria. In addition, the **short term solution do not have to impact the transition to long term solutions** based on innovative reactor concepts (e.g. FRs)

The Pu multi-recycling in REP is investigated with respect to the **Framatome CORAIL-A concept However, there are other solutions under investigation**

The investigation at **assembly level have been carried out to understand the CORAIL-A behavior** if different Pu qualities are adopted. **This simplified model allow catching tendencies before core 3D full investigations and scenarios studies**

In particular, the **options investigated at assembly level (blending strategy, assembly optimization, time between generation, …) may allow to stabilize the Pu vector during generations**

Representative **3D core investigations on full and partial CORAIL-A core loadings have been carried out. The FULL core loading is** the only option **able to reduce the Pu inventory** without providing an accumulation of Am241 framatome

Thank you
for your attention