TWoFCS:
A new tool for the simulation of different nuclear fleets at equilibrium

DE LA RECHERCHE À L'INDUSTRIE

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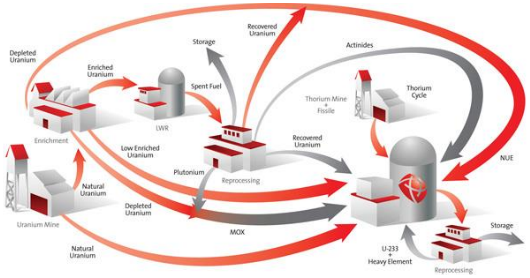
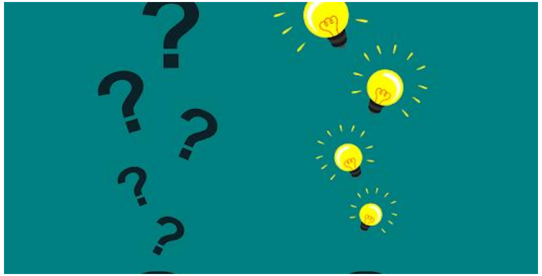
Context

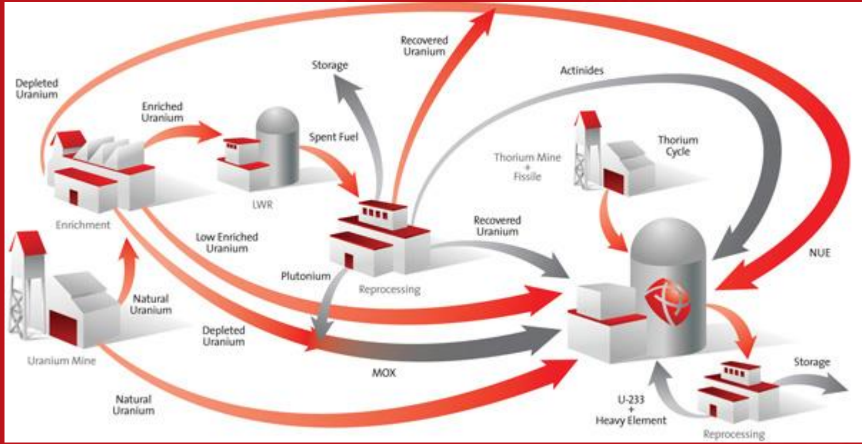


Methods

Results

Conclusion





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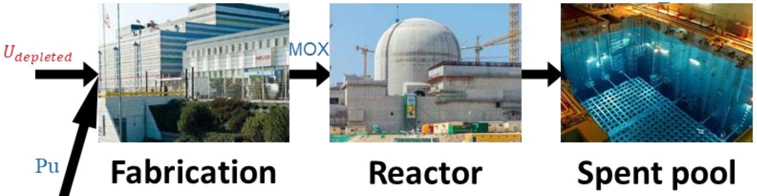
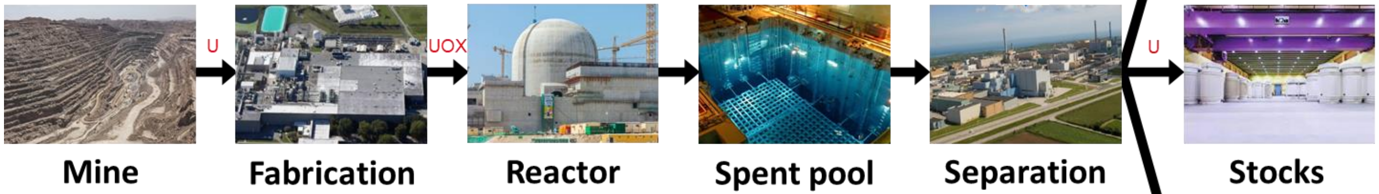
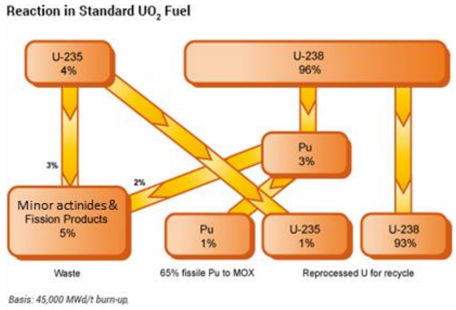
FRENCH CURRENT NUCLEAR FUEL CYCLE

Plutonium *mono-recycling* in PWR-MOX

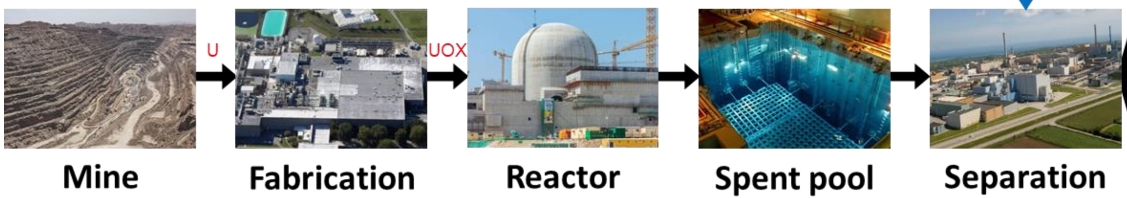


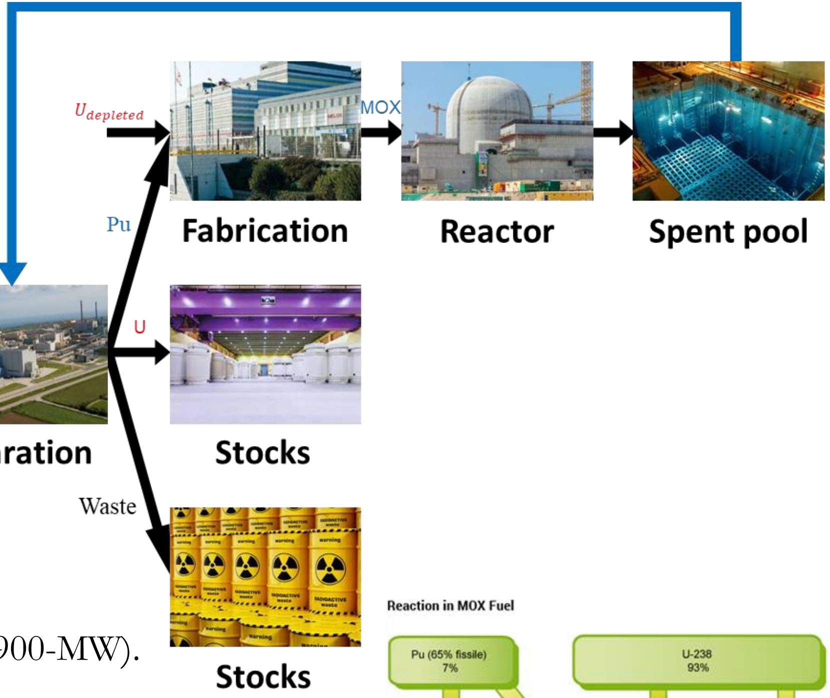


- Current French fleet:
  - 56 reactors with 90% UOX total assemblies
- Current French strategy:
  - Plutonium mono-recycling in PWR-MOX
  - 22 PWR with 30% MOX ⟶ 10% MOX total assemblies
- Spent MOX French strategy:
  - Temporary storage



Plutonium ***multi-recycling*** in PWR-MOX2

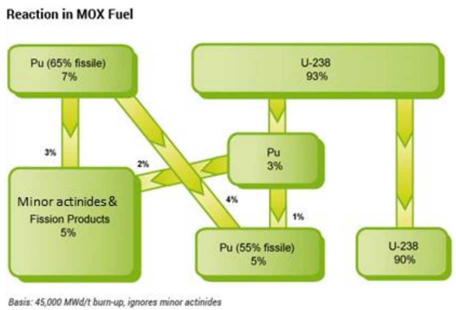




PPE 2020 measures:

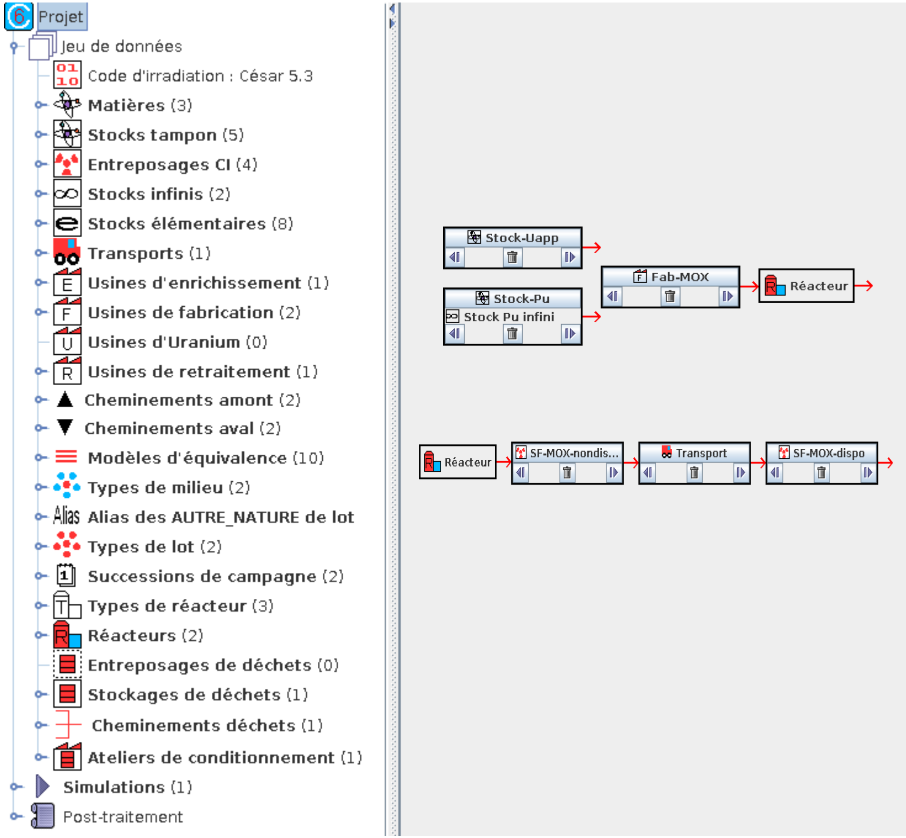
- Max 50% nuclear share in electricity mix in 2035.
- Any nuclear site stopping completely (shutdown of 14 reactors 900-MW).
- Moxing of 1300-MW reactors.

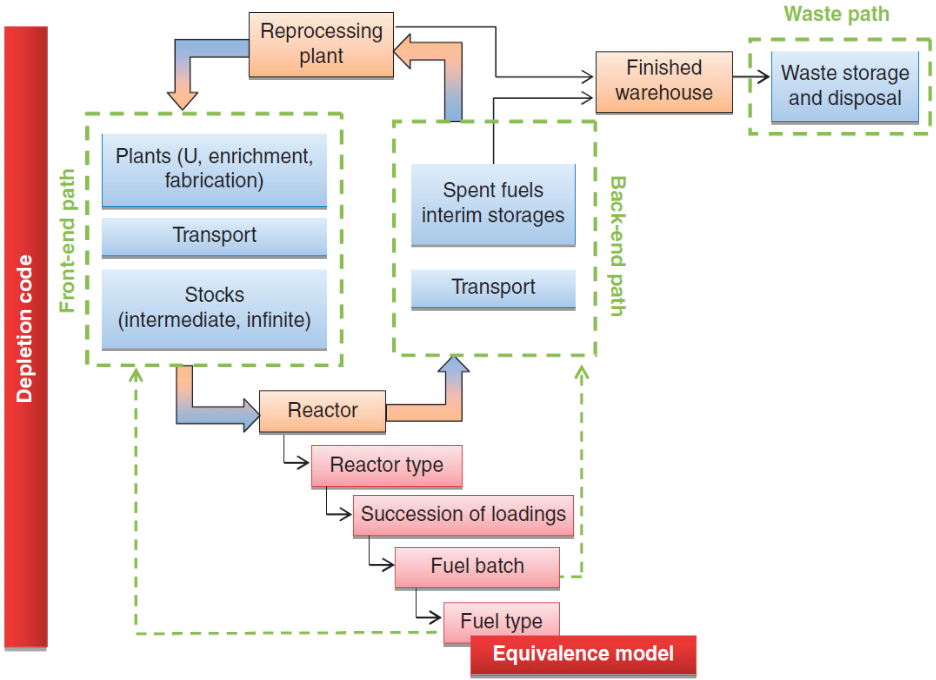
- Studies on fuel ***multi-recycling*** in existing reactors (MIX, ERU and Corail).



PPE-Executive summary (ecologie.gouv.fr)

COSI6 DYNAMIC SCENARIO CODE





COSI

- Developed from 1985 by CEA
- COSI6 version written in JAVA
- Weak point: find equilibrium configuration

[COSI6: a tool for nuclear transition scenario studies (C. Coquelet-Pascal 2017)]

EQUILIBRIUM STUDY PRINCIPLES

- Direct prediction of output isotopic composition from input isotopic composition + burnup;
- Equilibrium solution has no dependencies on time
- The use of equivalence and irradiation meta-models

→ fast calculation time

- Equilibrium code can be used to stabilize the Pu in the cycle:

$$Consumption = Production \qquad \sum x_i\, C_i = \sum x_i\, P_i\, \lambda_i$$

i : reactor
x_i: reactor fraction
C_i: Pu mass entering the reactor (t/y)
P_i: Pu mass leaving the reactor (t/y)
λ_i: mass loss during reprocessing

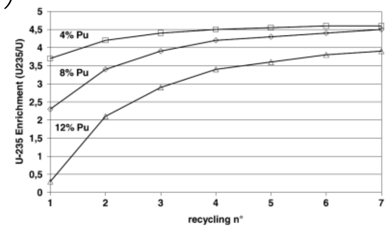
- A simplified way to take into account the Pu isotopic composition in term of reactivity is the Pu grade or quality as indicator:

$$g = \frac{m(^{239}Pu) + m(^{241}Pu)}{\sum_{j=238}^{242} m(^{j}Pu) + m(^{241}Am)}$$

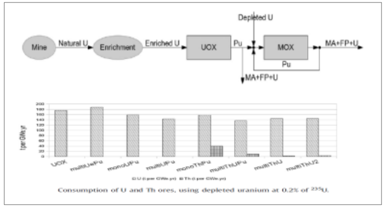
SEPAR
- Developed from 2018 by CEA/SPRC/LE2C
- Written in C++ (≈ 5k lines of code)
- Developed to find equilibrium configuration

LITERATURE REVIEW SYNTHESIS AND SEPAR

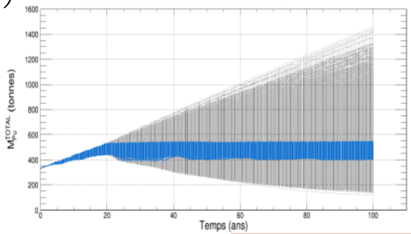
1) G. Youinou article 2005



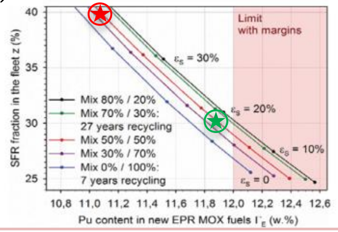
2) M. Ernoult article 2014



3) F. Courtin PhD thesis 2017



4) G. Martin article 2018



Methods:

1) Hand calculation
2) Neutronic–iterative method
3) By trials with dynamic code
4) Pu equilibrium algorithm

SEPAR

Literature hints:

- Step by step approach
- Optimization
- Wide modularity approach

Areas of improvement:

- Guarantee absolute equilibrium
- Enhance automation
- Improve modularity
- Strengthen precision
- Increase calculation rapidity

Characteristics:

- Isotopic/inventory equilibrium
- Automation
- Modularity
- Precision?
- Extreme calculation rapidity
- Systematic approach

Methods

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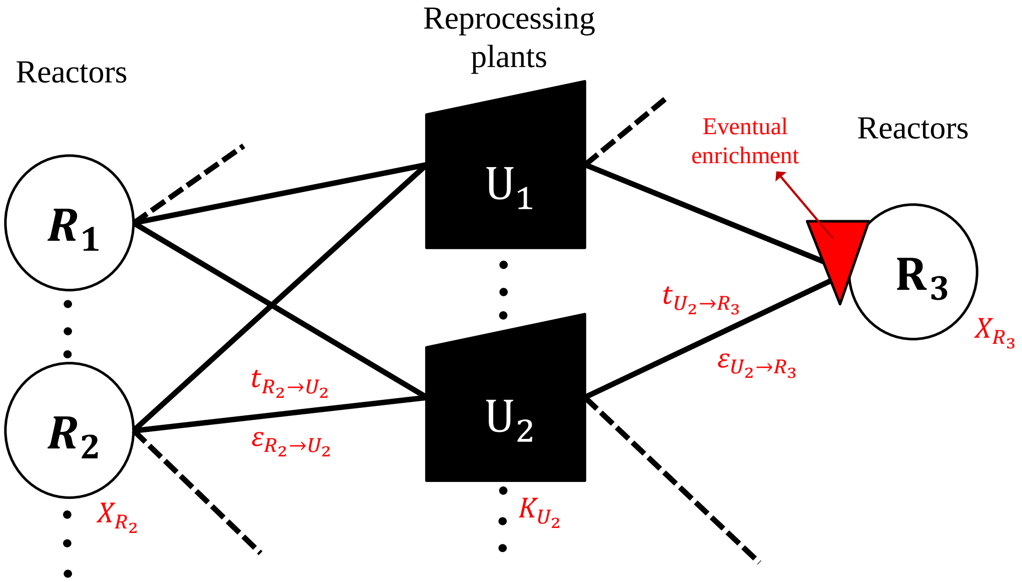
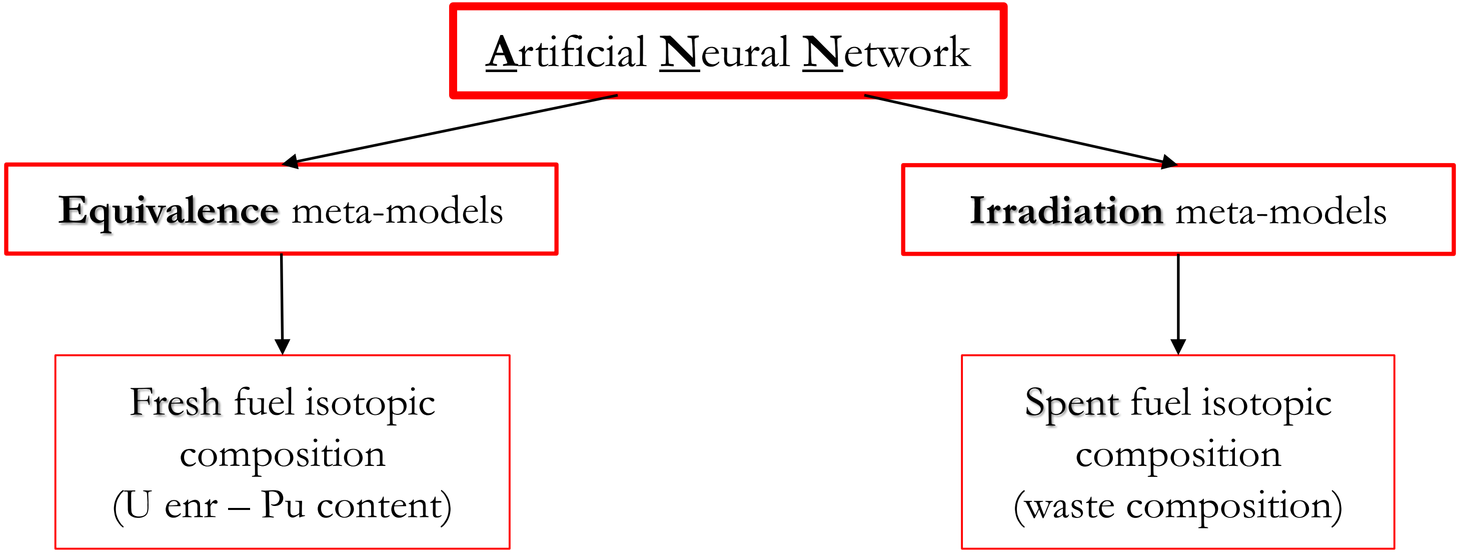
SEPAR: **S**imulateur d'**E**quilibres de **P**arcs **A**vancés de **R**éacteurs

- Find the fleet composition at equilibrium
- Model heavy nuclei evolution using Artificial Neural Network



- X → fuel batch fractions
- K → treatment function
- t → transfer time
- ε → transferred material flux fraction

SEPAR – PREDICTION OF ISOTOPIC COMPOSITION



ANN working steps:

1) Create a fuel library → huge amount of APOLLO2 neutronic calculations, for a wide range of isotopic composition, input and outputs are stored;
2) Training of the ANN on input and output isotopic composition;
3) ANN ready for fast predictions.

SEPAR – SIMPLIFIED BALANCE EQUATIONS

2 isotopes system:

$$\begin{cases} \dfrac{dm_p}{dt} = -\lambda_p m_p \\ \dfrac{dm_i}{dt} = -\lambda_i m_i + B_{pi}\lambda_p m_p \end{cases}$$

solution →

$$m_i(t) = \underbrace{B_{pi}\frac{\lambda_p}{\lambda_i - \lambda_p} m_p^0 (e^{-\lambda_p t} - e^{-\lambda_i t})}_{\text{Parent nuclei accumulation}} + \underbrace{m_i^0 e^{-\lambda_i t}}_{\text{Daughter nuclei decay}}$$

Reactor (R2) -> Reprocessing (U2)

$$m_i(t_{R_2\to U_2}) = B_{pi}\frac{\lambda_p}{\lambda_i - \lambda_p} m_p^0 (e^{-\lambda_p t_{R_2\to U_2}} - e^{-\lambda_i t_{R_2\to U_2}}) + m_i^0 e^{-\lambda_i t_{R_2\to U_2}}$$

Reprocessing (U2) -> Reactor (R3)

$$m_i(t_{U_2\to R_3}) = B_{pi}\frac{\lambda_p}{\lambda_i - \lambda_p} m_p^{0\prime} (e^{-\lambda_p t_{U_2\to R_3}} - e^{-\lambda_i t_{U_2\to R_3}}) + m_i^{0\prime} e^{-\lambda_i t_{U_2\to R_3}}$$

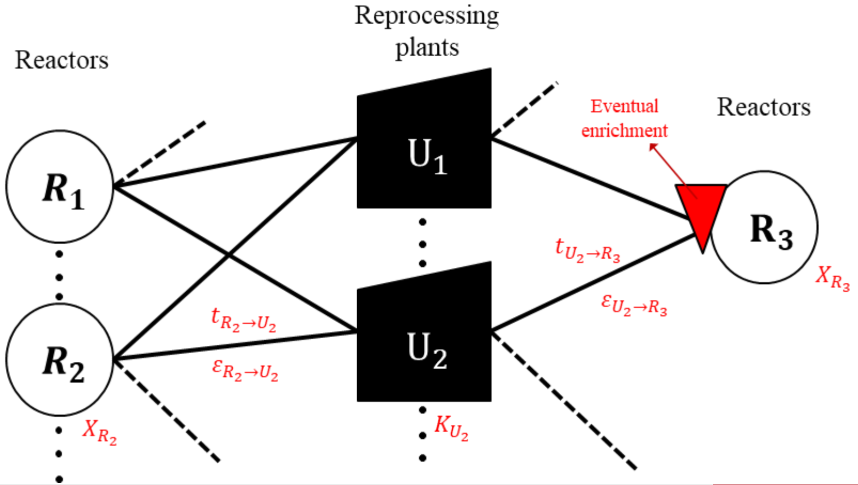
t: transferred time

$\lambda = \ln(2)/t_{1/2}$: decay constant

B: branching factor

p_i: precursor

i: isotope



Results

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SEPAR - INPUT/OUTPUT

INPUTS:

- Reactor type and Fuel batch descriptions:
  - Final burnup
  - Reloading factor
  - Core mass
  - Equivalent full power days
  - Load factor
  - Net yield
- Fuel library data (for training NN)
- Links between: fuel batches ⟷ reprocessing facility
- Cooling – Reprocessing time
- Power installed capacity

SEPAR →

EQUILIBRIUM RESULTS:

- Fleet composition (batch fraction)
- Natural uranium consumption
- Fuel fabrication capacity
- Fuel reprocessing capacity
- Isotopic composition of the fresh fuel
- …

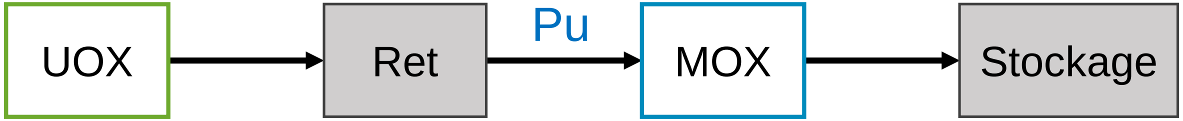
Example based on French-like nuclear installed capacity = 61.2 GW

GENIII PWR reactors (UOX, MOX, ERU, MIX)	
Thermal power (MWth)	4592
Electrical power (MWe)	1653
Full core mass (t)	129
Burnup (GWday/t)	55
EFPD (day)	515
Load factor	0.83
Fuel fractioning	3
UOX enrichment (%)	4.58
Enrichment tail (%)	0.2
Cooling time (y)	10
Fabrication time (y)	2

Framatome GENIII reactor characteristics

SEPAR case 1: UOX-MOX Plutonium mono-recycling

MOX fuel: Pu in spent UOX fuel is extracted and recycled into new MOX fuel (Pu content < 12%)



Plutonium annual flux = Φ_{Pu} = 10.56 t

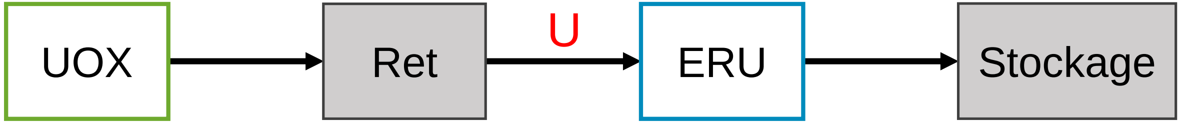
Fresh MOX Pu vector

Isotopes	SEPAR
^{238}Pu	0.028895
^{239}Pu	0.517862
^{240}Pu	0.272503
^{241}Pu	0.087053
^{242}Pu	0.084895
^{241}Am	0.008828
PuCi	0.112034

Results	UOX reactor	MOX reactor
Reactor fraction	0.897	0.103
Number of reactor	33.2	3.8
Nat. U consumption (t/y)	7209.5	0.0
Fuel fabric. capacity (t/y)	848.5	88.0
Fuel reproc. capacity (t/y)	848.5	0.0

SEPAR CASE 2: UOX-ERU URANIUM MONO-RECYCLING

ERU: Enriched Reprocessed Uranium fuel



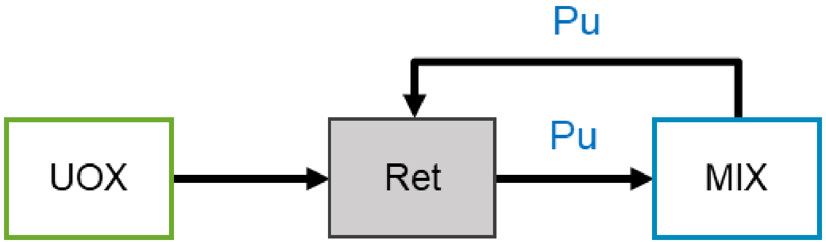
U vector before enrichment

Isotopes	SEPAR
^{234}U	0.000201
^{235}U	0.008081
^{236}U	0.006798
^{238}U	0.984921

Results	UOX reactor	ERU reactor
Reactor fraction	0.899	0.101
Number of reactor	33.3	3.7
Nat. U consumption (t/y)	7215.0	0.0
Fuel fabric. capacity (t/y)	842.0	94.5
Fuel reproc. capacity (t/y)	842.0	0.0

SEPAR CASE 3: UOX-MIX PLUTONIUM FULL MULTI-RECYCLING

MIX fuel: assemblies with fixed plutonium content (8%) supported by enriched uranium



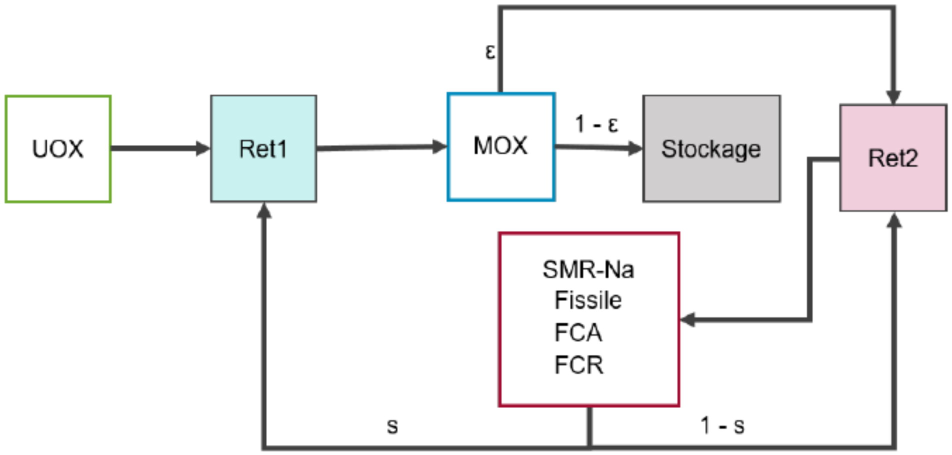
Plutonium annual flux = Φ_{Pu} = 27.85 t

Fresh MIX Pu vector

Isotopes	SEPAR
^{238}Pu	0.037850
^{239}Pu	0.358794
^{240}Pu	0.271273
^{241}Pu	0.085696
^{242}Pu	0.237707
^{241}Am	0.008690
PuCi	0.080000

Results	UOX reactor	MIX reactor
Reactor fraction	0.639	0.361
Number of reactor	23.6	13.4
Nat. U consumption (t/y)	4940.8	2779.7
Fuel fabric. capacity (t/y)	599.4	371.0
Fuel reproc. capacity (t/y)	599.4	371.0

SEPAR CASE 4: UOX-MOX-SMR(NEW-ASTRID)



K. Tirel article 2020

Reactors	UOX	MOX	SMR-Na
Thermal power (MWth)	4590	4590	400
Electrical power (MWe)	1650	1650	160
Full core mass (t)	129	129	19.2
Burnup (GWday/t)	50	46	65
EFPD (day)	468	431	225
Load factor	0.83	0.83	0.90
Fuel fractioning	3	3	4
Cooling time (y)	5	5	5
Fabrication time (y)	2	2	2

Fresh MOX Pu vector

Isotopes	SEPAR
^{238}Pu	0.022927
^{239}Pu	0.487713
^{240}Pu	0.294205
^{241}Pu	0.079473
^{242}Pu	0.107623
^{241}Am	0.008059
PuCi	0.112964

Results	%
Pu content in MOX	11.30
UOX	79.16
MOX	15.84
SMR-Na	5
ϵ	70
s	100

SMR-Na 5 → Fixed Power fraction

Conclusion

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"Equilibrium codes do not substitute dynamic code, but they are complementary to them!"

Four exercises conclusion:
- SEPAR is actually working
- Separ can model different cycle option in a rapid, modular and precise way
- Separ is the first step to reach equilibrium with a dynamic code

Method validation:
- Validate SEPAR on different cycles with COSI
- Validation needed for simple fuel cycles, complex cycles and GEN IV reactors

SEPAR

New field exploration:
- General interest on equilibrium code
- Continuous scientific investigation on different fields (transmutation)

Conception optimization:
- Possibility to add on SEPAR the calculations we want, using its C++ modular nature
- Neural network meta-modeling
- Equation system resolution
- …

FUTURE WORKS

Perspectives short term

- SEPAR/COSI validation
- Further post-treatment development in SEPAR (Pu-MA production, etc…)
- Work comunication : Paper, Workshop
- GEN IV and in particular MSR cycle
- Other developments on SEPAR
- Preliminary work on technical/economic indicators
    - Collaboration with DMRC
    - Internship on economic calculation in COSI (N. Thiollière from IMT)

      -> first economical development in SEPAR

Perspectives long term

- Other developments on SEPAR
- Application to transmutation