Electronuclear scenarios with PWRs and SFRs Status and management of Plutonium

CS IN2P3 - February 2022

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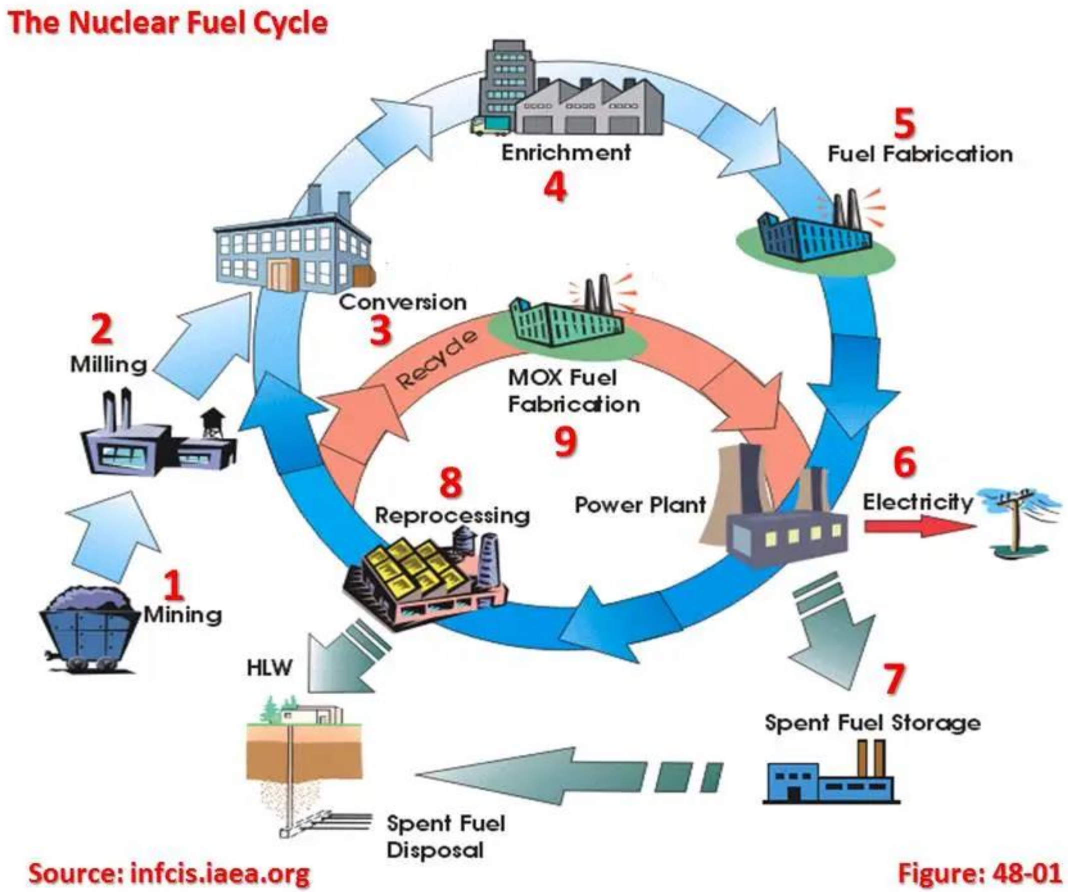
Collaborators : X. Doligez (IJCLab), N. Thiollière (Subatech)

Plan of the presentation

1. The fuel cycle
   a. French fuel cycle
   b. Management and status of Pu
2. Methods for Scenario studies
   a. How to do a scenario study
   b. Simulating a trajectory
   c. Managing uncertainties
3. Multirecycling Pu in PWR
   a. Physics
   b. Multirecycling with MOXEUS
   c. Multi-recycling in PWR a barrier to future SFR deployment?
4. Contribution of SFRs for plutonium management
   a. Symbiotic scenarios
   b. Fleet full of Gen4 reactors
   c. Impact of only few SFRs
5. Conclusions and Perspectives

Annex : Human resources and collaborations

1. A.The fuel cycle : a French Example

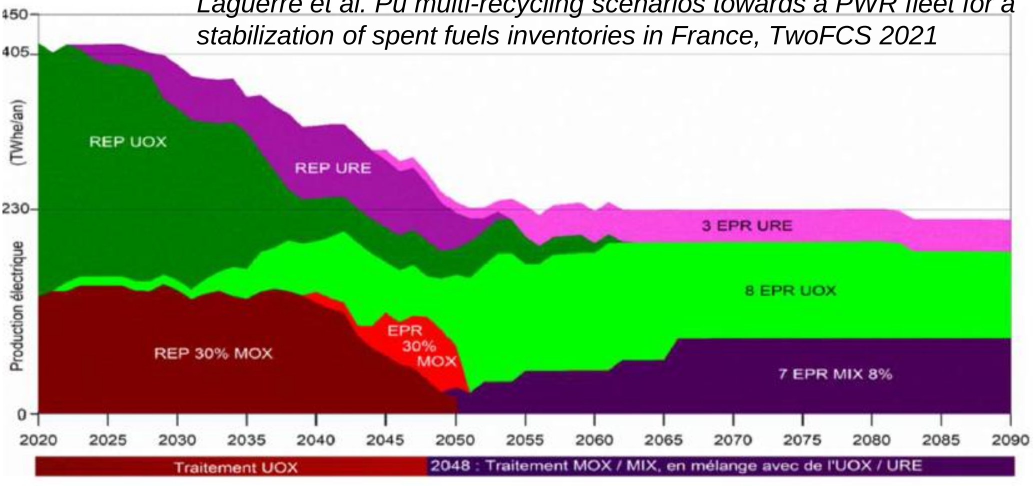


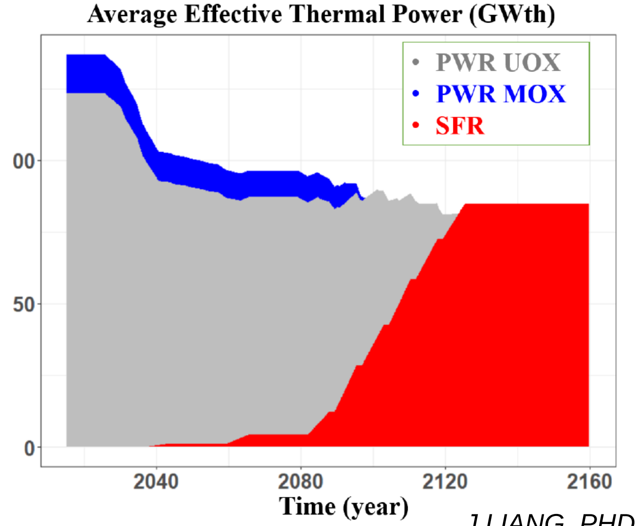
- Nuclear reactor at the center of the center of the fuel cycle
- Interaction between different reactors (place, time) through the cycle

Scenarios = fuel cycle studies

1. a. The fuel cycle : a French Example

Laguerre et al. Pu multi-recycling scenarios towards a PWR fleet for a stabilization of spent fuels inventories in France, TwoFCS 2021





J.LIANG, PHD 2021

Long Time studies :

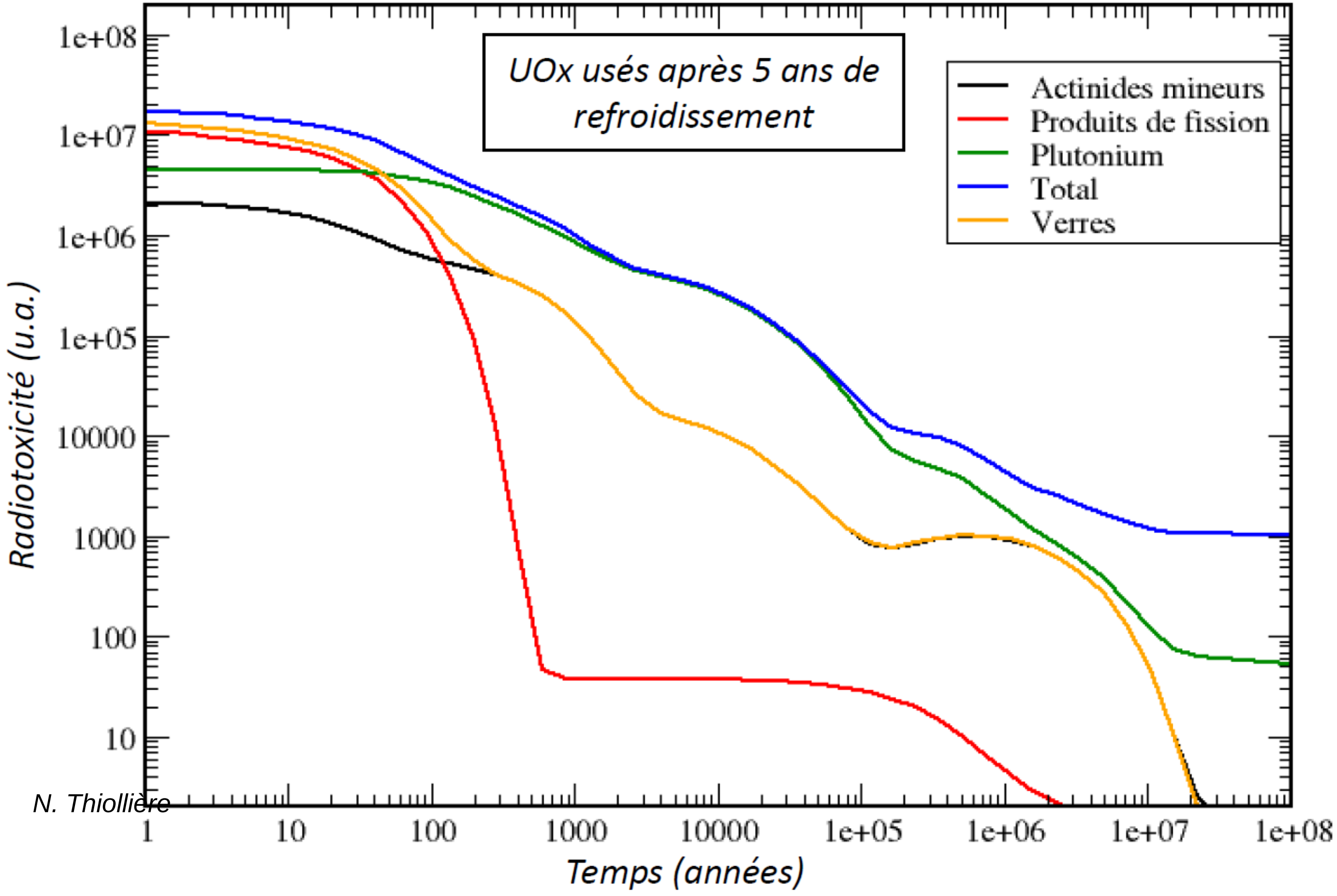
- New installation : at least 10y between decision and start
- Lifetime of an installation : 30 to 60 y
- Time span of an transition : 50 to 200 y

Large scale studies

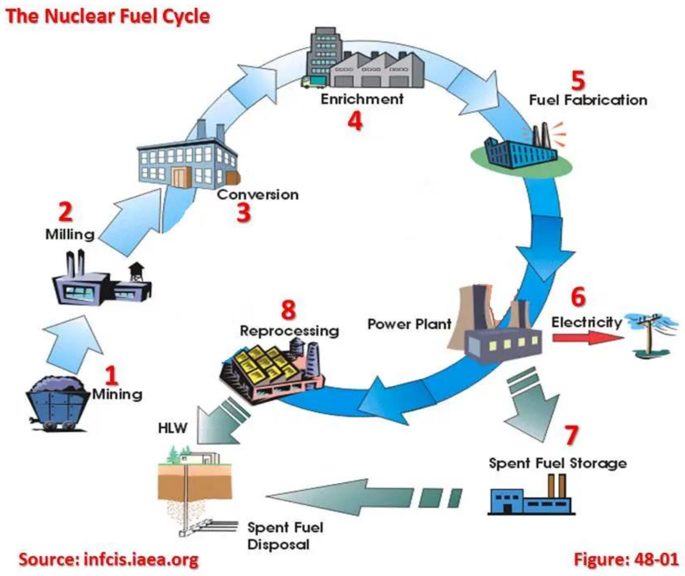
- 10s of reactors
- 100s to 1000s of fuel to be created and irradiated

1.b Management and status of Pu

Open Cycle :



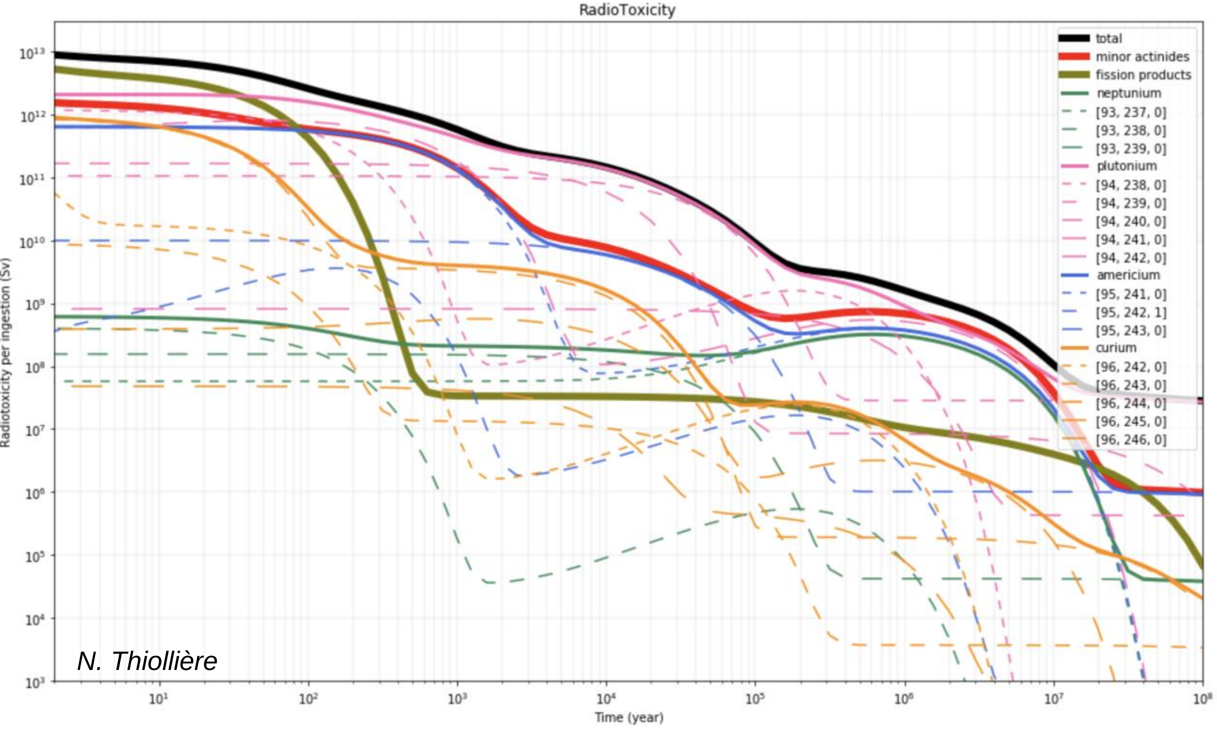
Radiotox of nuclear materials in Spent UOX fuel



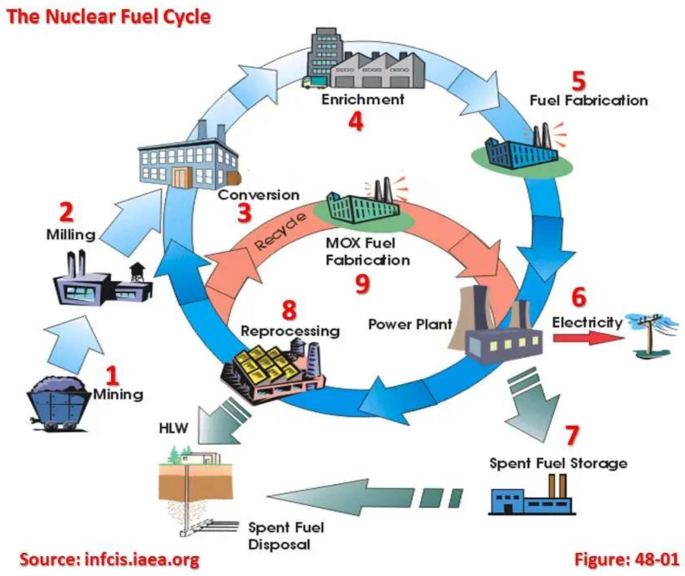
- Waste to be watched during around 1 My
- Pu main contributor to radiotox and decay heat from ~100 to 1 My

1.b Management and status of Pu

Current strategy : mono-recycling



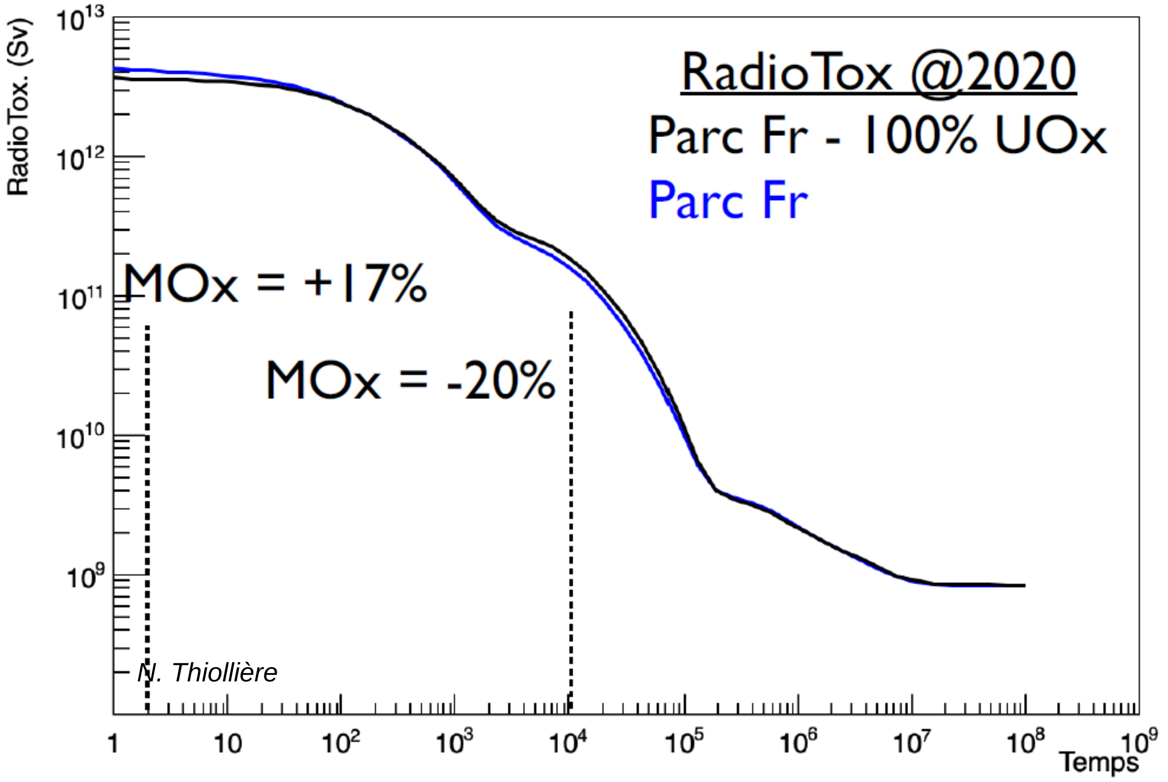
Radiotox of nuclear materials in nuclear fleet in 2015

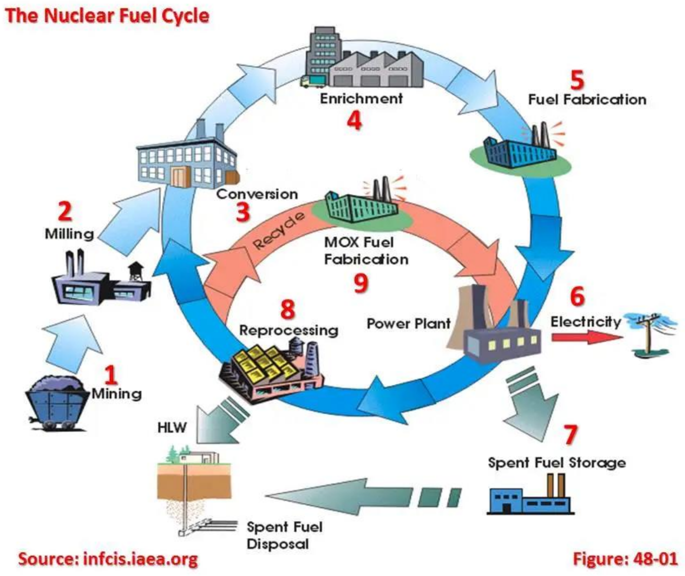


- "radioactive waste is radioactive material for which no further use is planned or envisaged“
- Pu not waste any more => wastes far easier to manage
- Pu : fissile in majority
- 7 and 8 UOX for 1 MOX
  - ➢ less storage needed

1.b Management and status of Pu

Current strategy : mono-recycling





But

- Increase of complexity of the cycle
- Safety limits the recycling of Pu

➢ Only 1 recycling is done

- One recycling have limited impact on global intentories
- Surplus of MA produced

➢ Mono-recycling does not solve Pu question, a long term use is needed

1.b Management and status of Pu

Options for long term Pu management

1. Reference until recently : SFRs
   - more than 1000 t needed to start the fleet
2. Direct to waste
   - Less TRU as possible with current tech
3. New reference : multi Pu in PWR
   - Need innovative fuel management in PWR
4. Other Innovative reactors
   - Need system level studies to fix concept
5. Any other innovative option

2. Management and status of Pu

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Scenario Studies

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System+Scenario Studies

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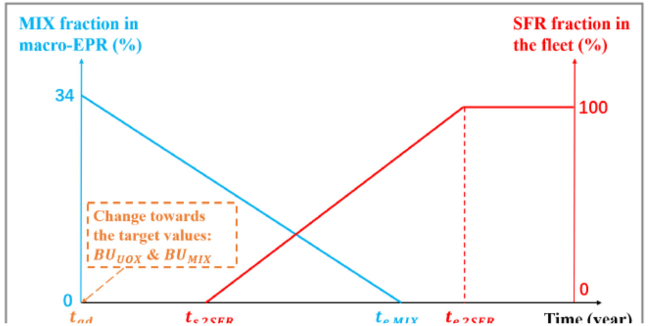
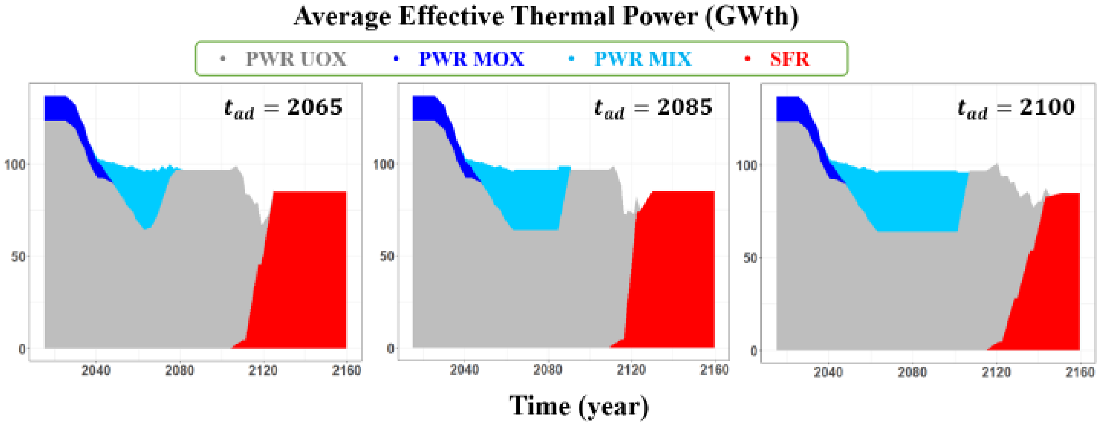
3. Scenario studies

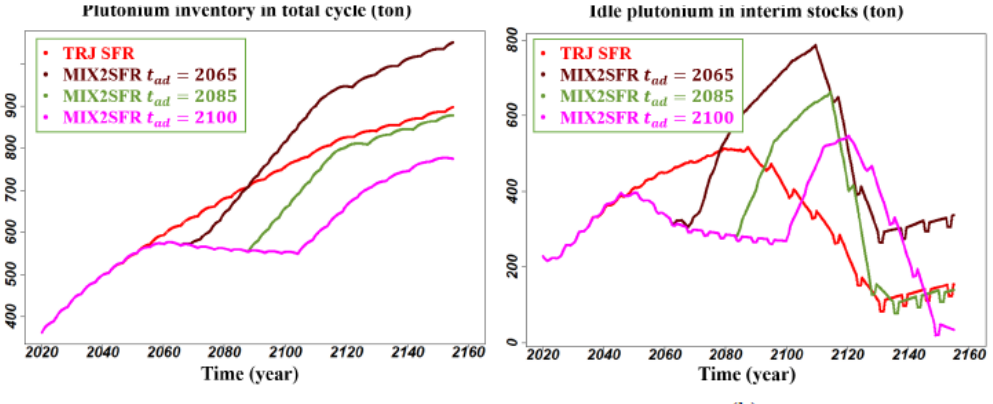
a. How to do a scenario study

1. A question of scientific interest
2. Choose framework (time horizon, technologies, constraints, …)
3. Choose strategy of interest
4. Simulate trajectories
5. Analyze the trajectories
6. Answer the question

Can we switch quickly from MIX to SFRs?







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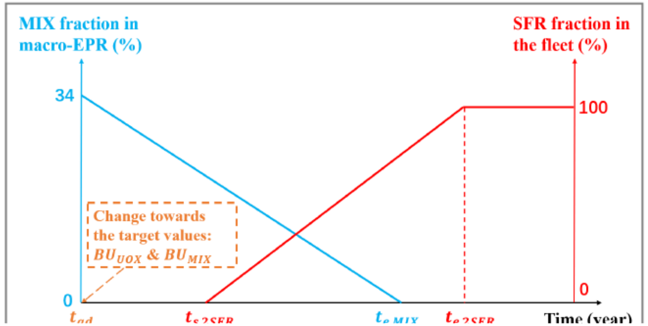
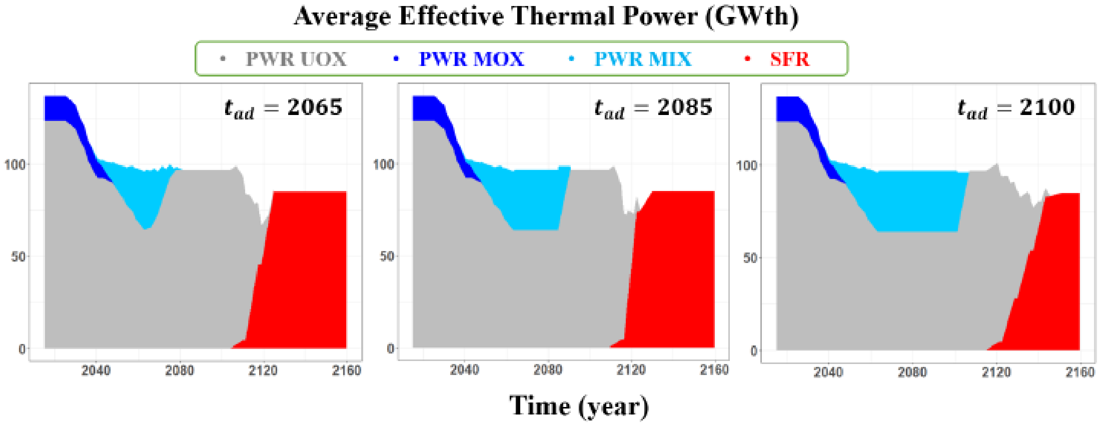
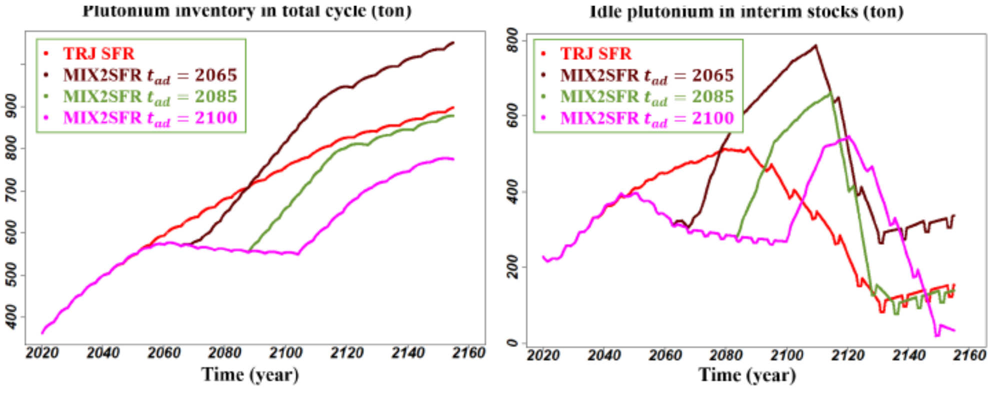


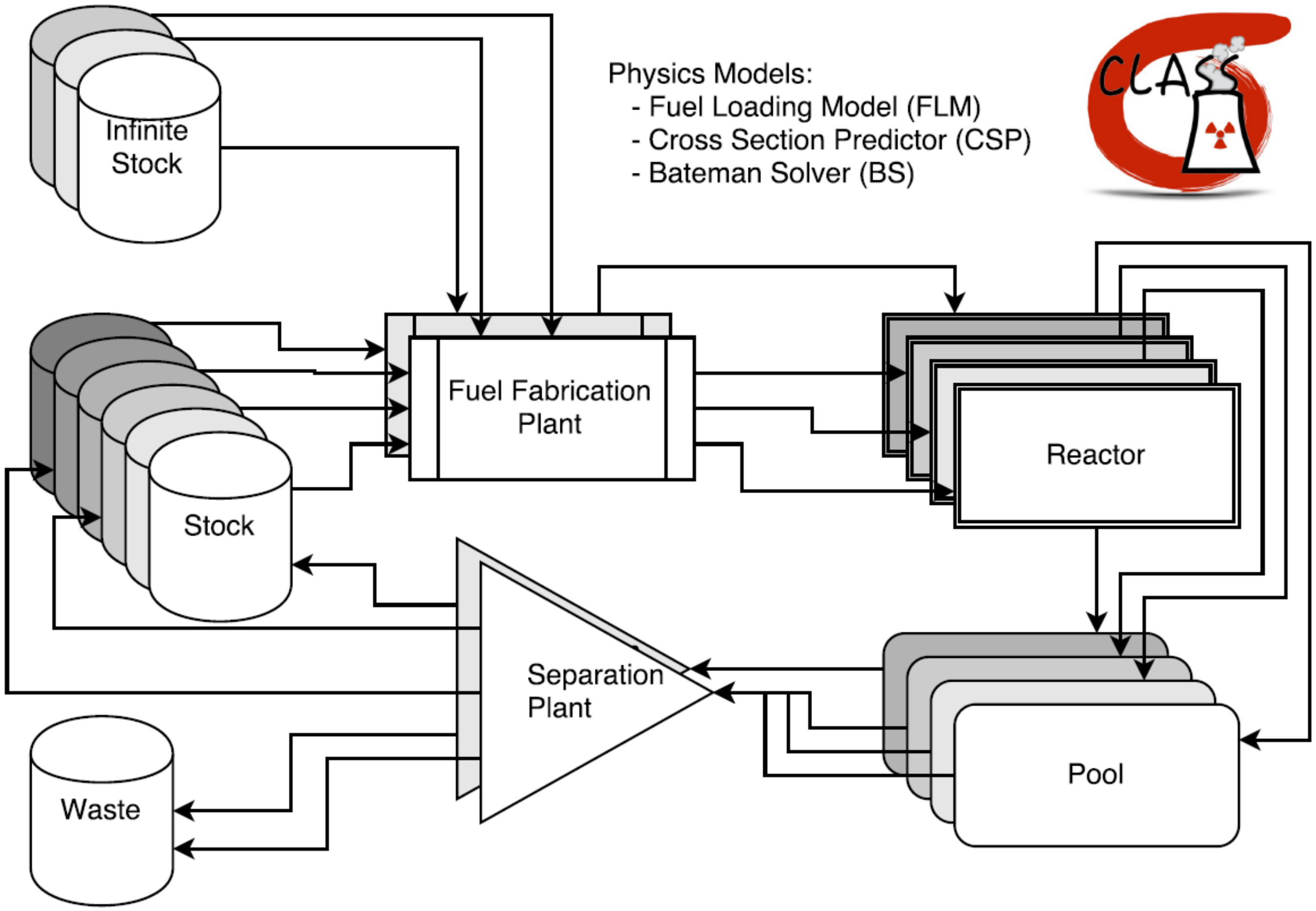




3. Scenario studies

b. Simulating a trajectory

- CLASS for **C**ore **L**ibrary for **A**dvanced **S**cenario **S**imulation
- collection of C++ classes that describes the installations of a nuclear fleet.
- two main complex models:
  - Build new Fuel
  - Fuel evolution under irradiation
- Mine and waste storage not modeled : only material flux and inventories
- Use of Machine-Learning for quick non-linear meta-models



3. Scenario studies

c. Managing uncertainties

questions about situations in the distant future with complex systems that do not yet exist :

➢Lots of uncertainties

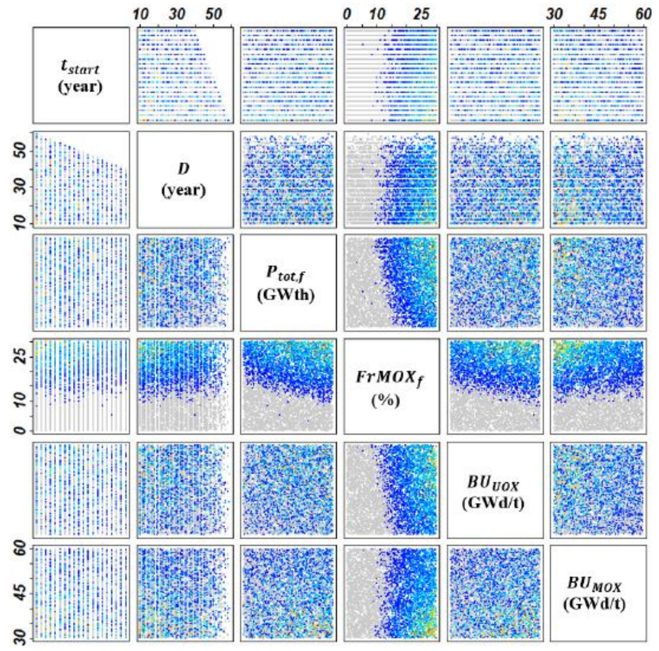
- Base Data (nuclear data, processes)
- Future Operational parameters
- Expert prediction for technologies
- Simplified modeling
- Model biases

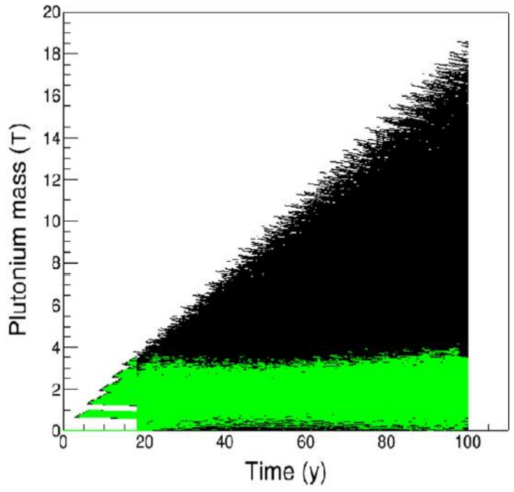
3. Scenario studies

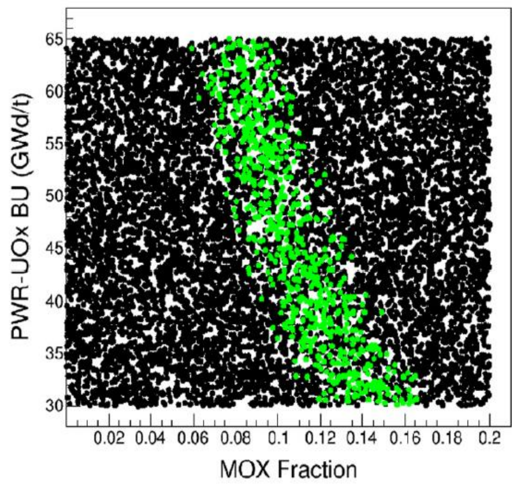
c. Managing uncertainties

Dealing with uncertainties on future operational parameters : GSA

- operational parameters considered no longer most probable value but range of possible values
- Large random sampling : exploration
- Correlations, Statistical analyses
- Sobol sensitivity indices
- Selection of trajectories of interest and projection in input spaces





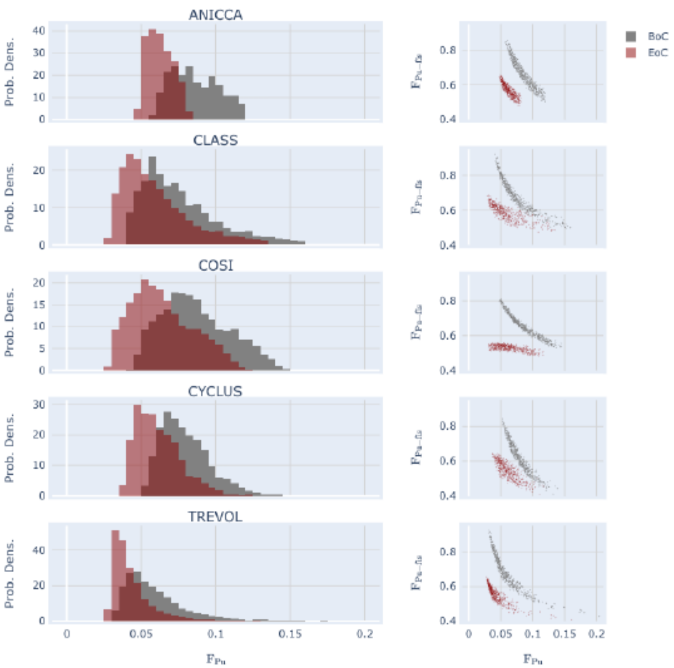


3. Scenario studies

c. Managing uncertainties

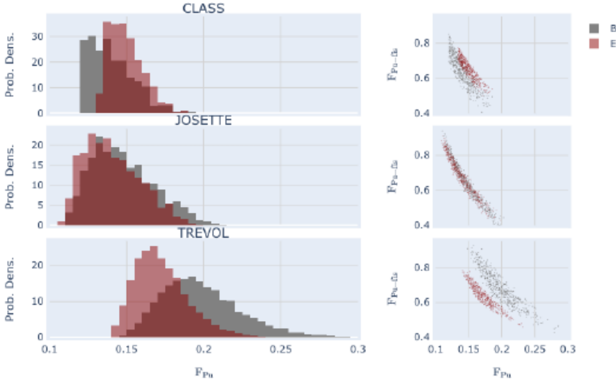
FIT (Functionality Isolation Test) international project driven by IN2P3

- first test : a fuel loading model (FLM) vs "fixed fraction" (FF)
- two fuel fabrication models will be compared within the same simulator



PWRs

Code	$E(F_{Pu}^{FLM}(BoC))$	$\sigma(F_{Pu}^{FLM}(BoC))$	E_1
ANICCA	0.086	0.016	0.19
CLASS	0.076	0.025	0.33
COSI6	0.087	0.023	0.26
CYCLUS	0.079	0.016	0.20
TR_EVOL	0.060	0.024	0.40



SFRs

	BoC		
code	Mean	STD	E_1
CLASS	0.140	0.014	0.10
JOSSETTE	0.148	0.020	0.14
TR_EVOL	0.199	0.026	0.13

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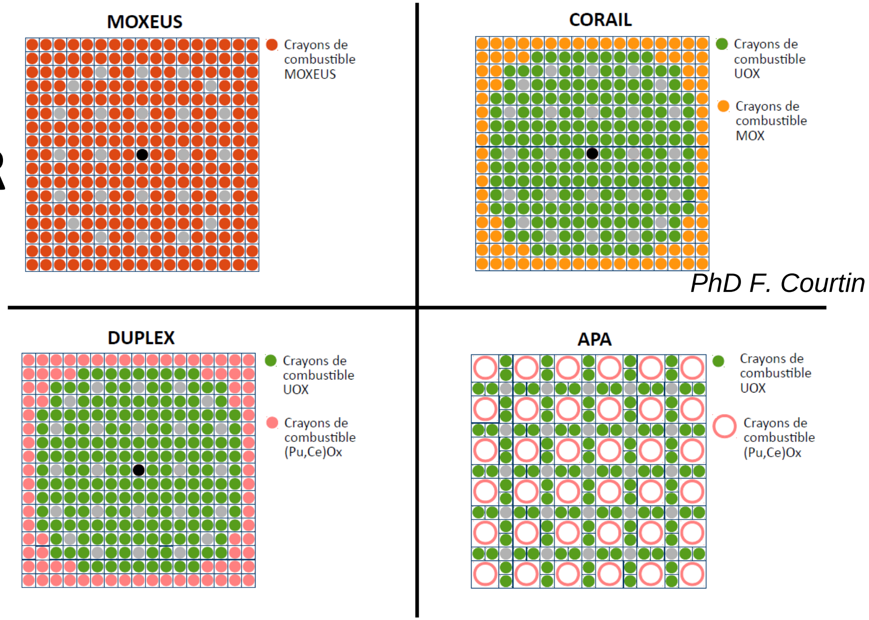
4. Multirecycling Pu in PWR

a. Integrating the physics of Pu recycling in PWR

Looking for physics based constraint to define the CLASS models :

- Neutronic studies inspired by the methods developed for the GSA
- Assembly level studies : safety coefficients, control parameters
- Isotopy effect mainly due to increase of Pu content for reactivity
- Void coefficient drive the max Pu content (importance of Boron)



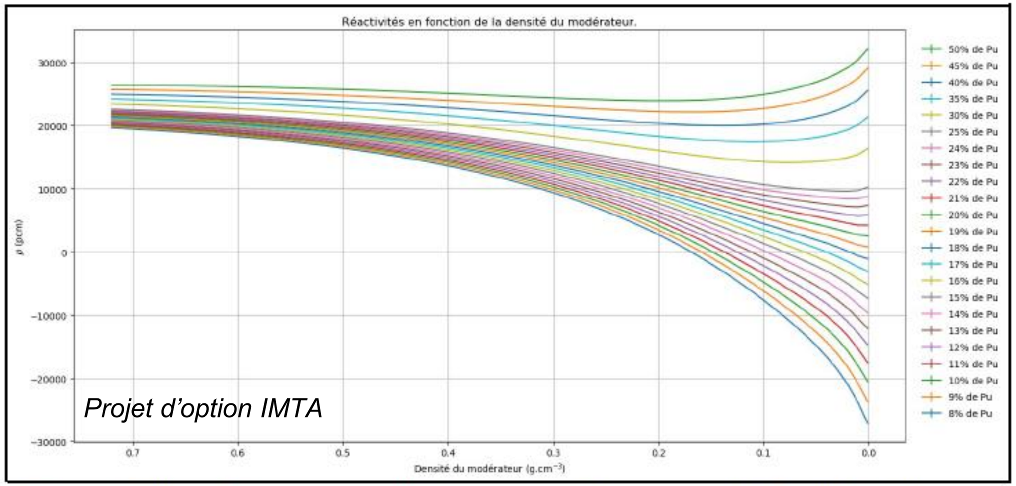


Figure 15 : Réactivités en fonction de la densité du modérateur pour plusieurs %ages de Pu total

4. Multirecycling Pu in PWR

a. Integrating the physics of Pu recycling in PWR

MOX in PWR => heterogeneous cores :

➢We need core scale

- Coupling CLASS with DONJON
- New BuildFuel Model looking at power form factor
- Question of loading patterns

(cf talk of X. Doligez this morning)

Tableau 6.8 Écarts relatifs sur les inventaires déchargés entre des calculs effectués avec PMC et avec DONJON5 dans les cas UOx et MOX1, 2, 3* et 4*.

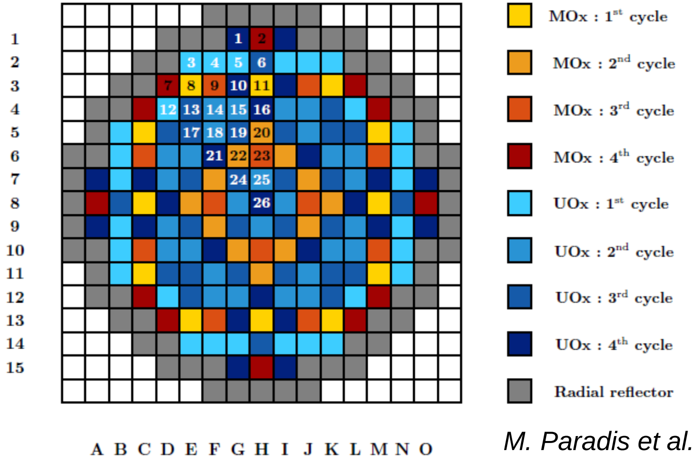
M. Guillet et al.

(a) isotopes de l'uranium et du plutonium.

Combustible	^{235}U	^{238}U	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
UOx : 4.01%	-11.0	-0.2	13.9	0.7	-1.1	4.5	10.5
MOX1 : 6.38%	-5.7	-0.3	-0.3	-1.1	-2.4	0.5	1.1
MOX2 : 7.68%	-5.6	-0.3	-0.2	-2.0	-1.5	0.3	0.7
MOX3* :11.12%	-4.6	-0.3	-0.2	-1.3	-2.3	1.9	0.8
MOX4* : 8.72%	-1.7	-0.0	1.4	-19.2	1.2	-0.4	0.5

(b) isotopes de l'américium et du curium.

Combustible	^{241}Am	^{242m}Am	^{243}Am	^{243}Cm	^{244}Cm	^{245}Cm
UOx : 4.01%	-2.2	-0.3	19.0	15.4	28.1	34.5
MOX1 : 6.38%	-5.6	11.9	5.6	7.1	13.3	20.6
MOX2 : 7.68%	-7.0	-4.9	4.5	8.4	12.3	19.2
MOX3* :11.12%	-3.8	-6.4	3.9	12.1	12.9	18.7
MOX4* : 8.72%	2.3	15.7	-0.6	-2.7	-1.8	0.6



M. Paradis et al.

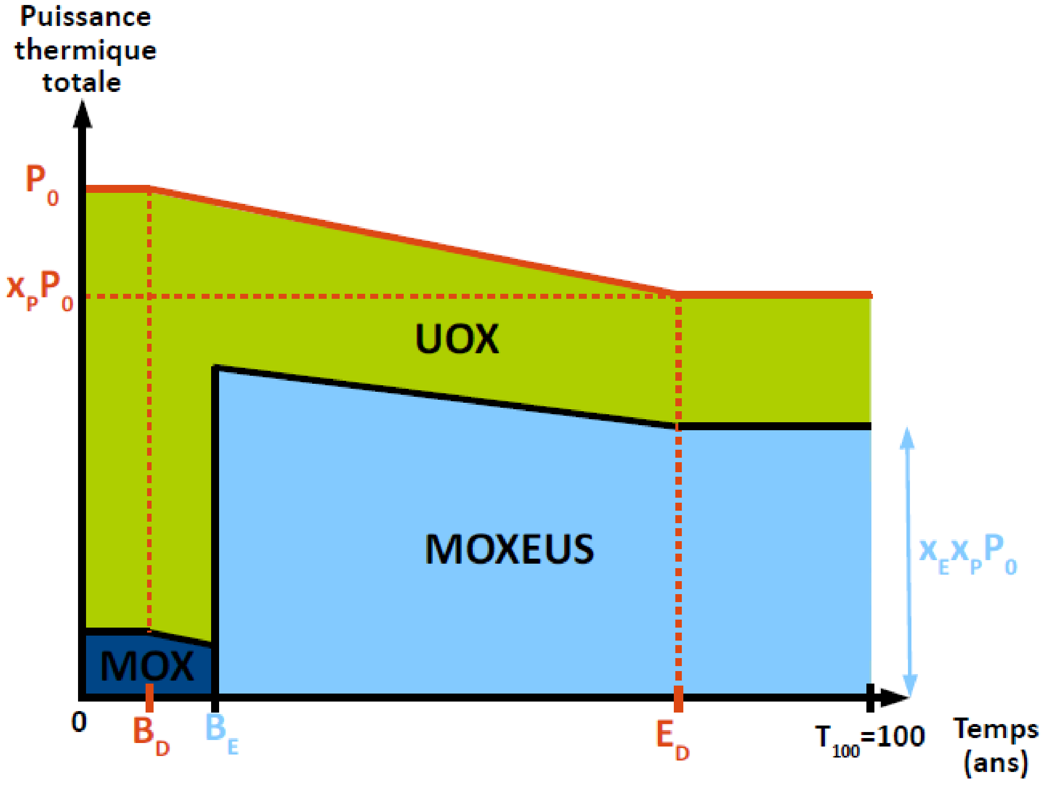
4. Multirecycling Pu in PWR

b. Scenarios for multirecycling Pu in PWRs

PhD F. Courtin

Is it possible to stabilize in the long term the total amount of plutonium contained in the cycle and the waste accumulated in a PWR-only fleet ?

Nom	Description	Gamme de valeurs
BU_U	Burn-up du REP UOX	[30, 65] GWj/t
BU_E	Burn-up du REP MOXEUS	[30, 65] GWj/t
x_E	Fraction de la puissance totale dédiée au REP MOXEUS	[0, 1]
w_{Pu}^{MAX}	Teneur maximale en Pu dans le combustible MOXEUS	[0.8, 0.13]
T_c^U	Durée de refroidissement du combustible UOX usé	[3, 10] ans
T_c^E	Durée de refroidissement du combustible MOXEUS usé	[3, 10] ans
E_D	Fin de la décroissance de la puissance	[20, 100] ans
x_P	Rapport des puissances thermiques totales finale et initiale	[0.01, 1.0]
G_s	Stratégie de gestion des stocks de plutonium	LiFo, FiFo



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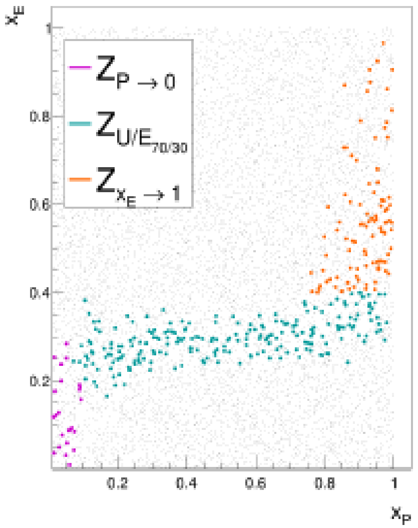
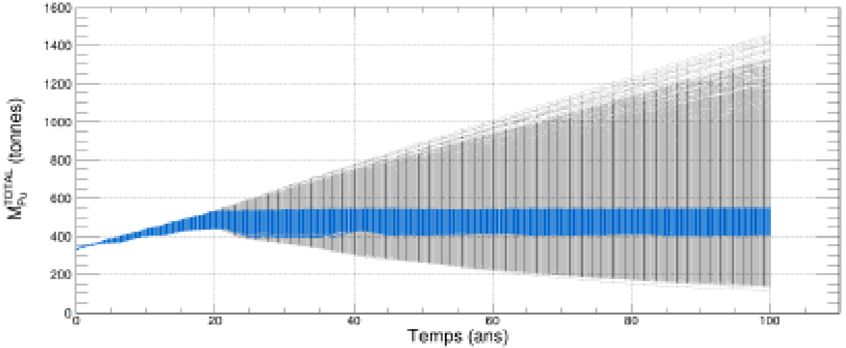
Stratégie	Indice	$M_{Pu}^{TOTAL}(t = 100 \text{ ans})$ Indice / Erreur	$M_{Pu+AM}^{TOTAL}(t = 100 \text{ ans})$ Indice / Erreur
LiFo	$\hat{S}_{BU_U}$	0.032 / 0.024	0.033 / 0.021
	$\hat{S}_{x_E}$	0.825 / 0.005	0.648 / 0.013
	$\hat{S}_{x_P}$	0.097 / 0.024	0.260 / 0.019
	$\hat{T}_{BU_U}$	0.032 / 0.001	0.032 / 0.001
	$\hat{T}_{x_E}$	0.875 / 0.024	0.691 / 0.017
	$\hat{T}_{E_D}$	0.014 / 0.001	0.030 / 0.001
	$\hat{T}_{x_P}$	0.131 / 0.005	0.300 / 0.010
FiFo	$\hat{S}_{BU_U}$	0.036 / 0.021	0.034 / 0.020
	$\hat{S}_{x_E}$	0.820 / 0.007	0.650 / 0.012
	$\hat{S}_{x_P}$	0.110 / 0.021	0.260 / 0.018
	$\hat{T}_{BU_U}$	0.033 / 0.001	0.032 / 0.002
	$\hat{T}_{x_E}$	0.860 / 0.022	0.690 / 0.017
	$\hat{T}_{E_D}$	0.013 / 0.001	0.030 /0.002
	$\hat{T}_{x_P}$	0.140 / 0.005	0.300 / 0.001





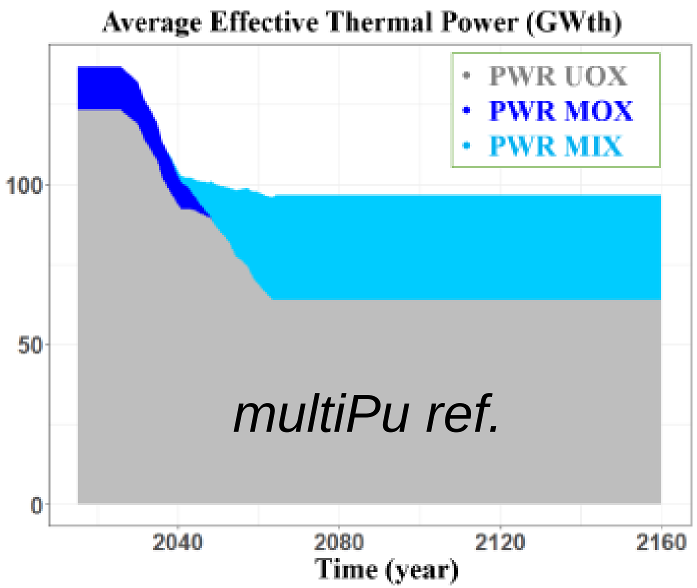
Three groups of trajectories can be distinguished:

- nuclear phase-out (x_P close to 0)
- very high fraction of MOXEUS (x_E > 0.5)
- intermediate situations with lower fractions of MOXEUS and a power around 30% of the current power.

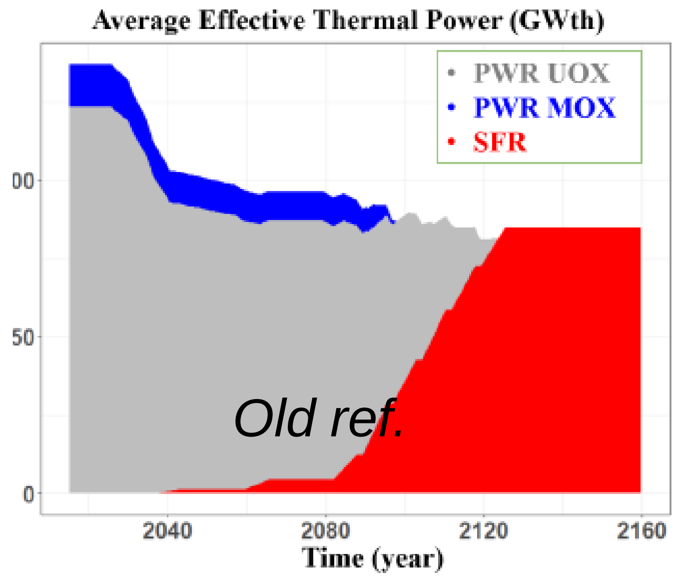
4. Multirecycling Pu in PWR

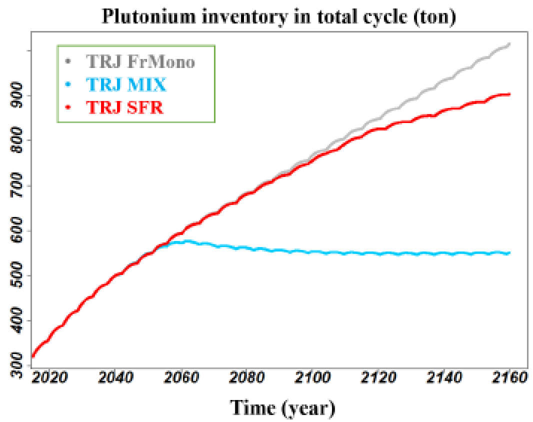
PhD J. Liang

c. multi-recycling of Pu in PWR a barrier to future SFR deployment?



Vs





- ➢ Without adaptation : not enough Pu

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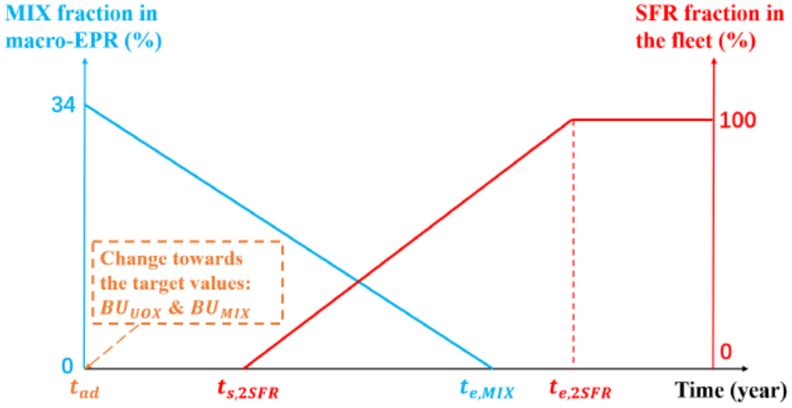

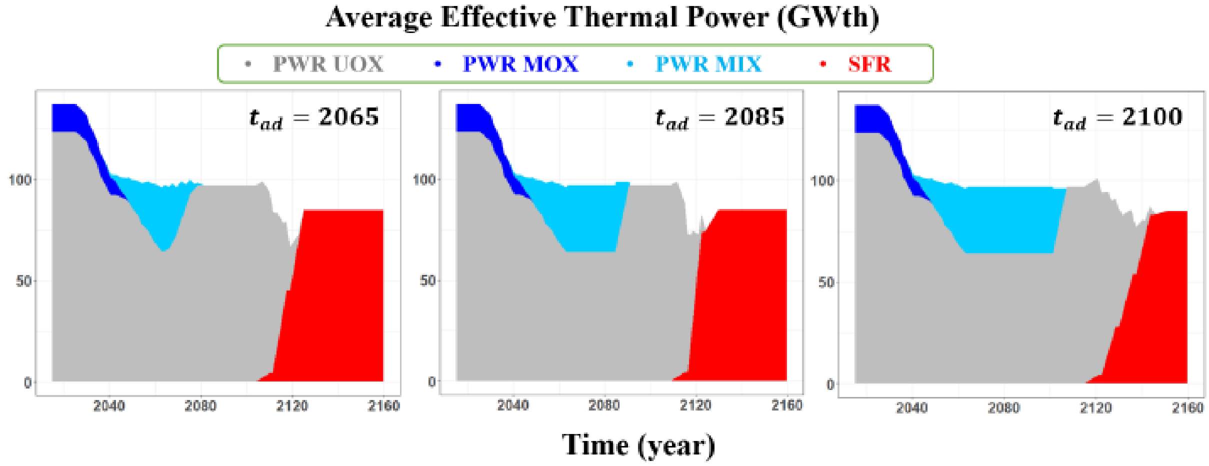

t_{ad}	$t_{e,MIX}$	$t_{s,2SFR}$	$t_{e,2SFR}$	BU_{UOX}	BU_{MIX}	Output ($t_{e,2SFR}$)
2065	2078	2114	2120	31.9	41.7	2120
2085	2088	2113	2120	33.8	43.4	2120
2100	2101	2118	2140	48.6	54.4	2140
(Unit)	year	year	year	GWd/t	GWd/t	year

adapt early enough => starting MIX not a barrier for SFRs

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5. Contribution of SFRs for plutonium management

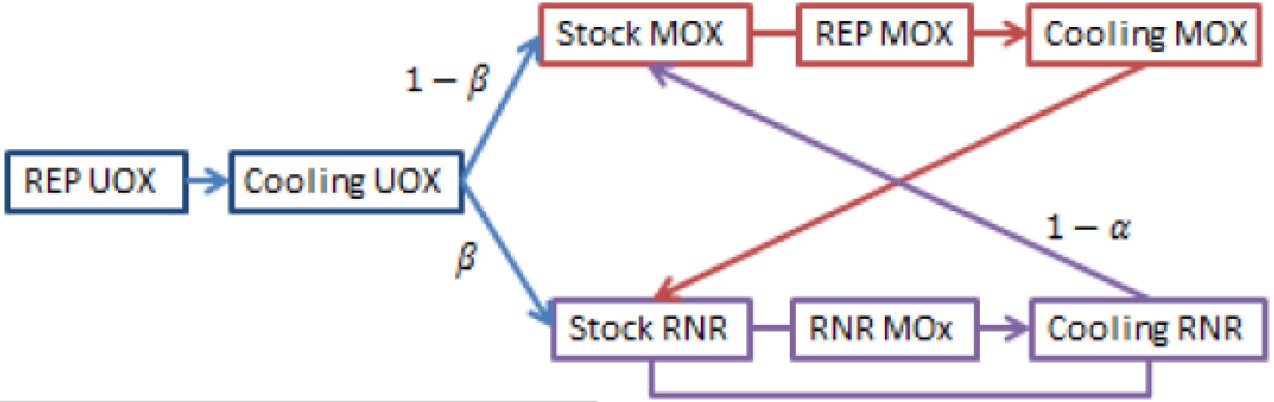
a. Symbiotic scenarios between PWRs and SFRs

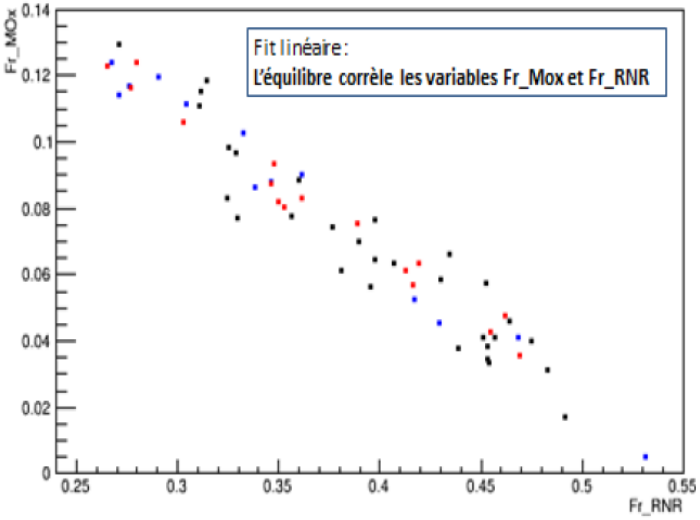
- Steady-state fleet
- PWR and SFR
- Pu stabilisation

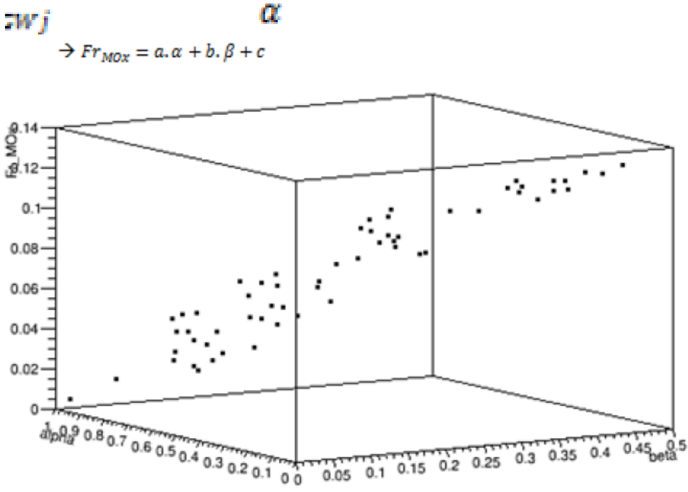
➢ More than 25% SFR

➢ Equilibrum space defined

➢ But not dense nor convex







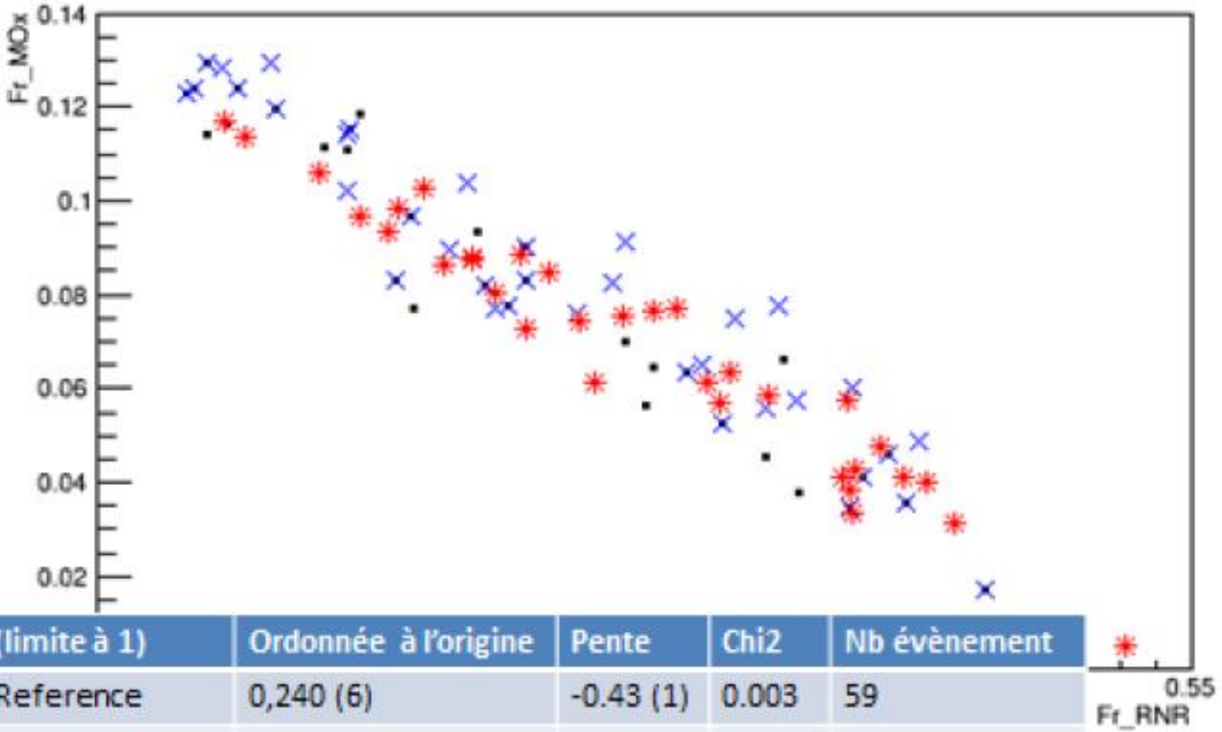
PERMIS, Doligez

5. Contribution of SFRs for plutonium management

a. Symbiotic scenarios between PWRs and SFRs

- Perturbation loose equilibrum
- But equilibrum space stay the same

➢Never far from a equilibrium solution



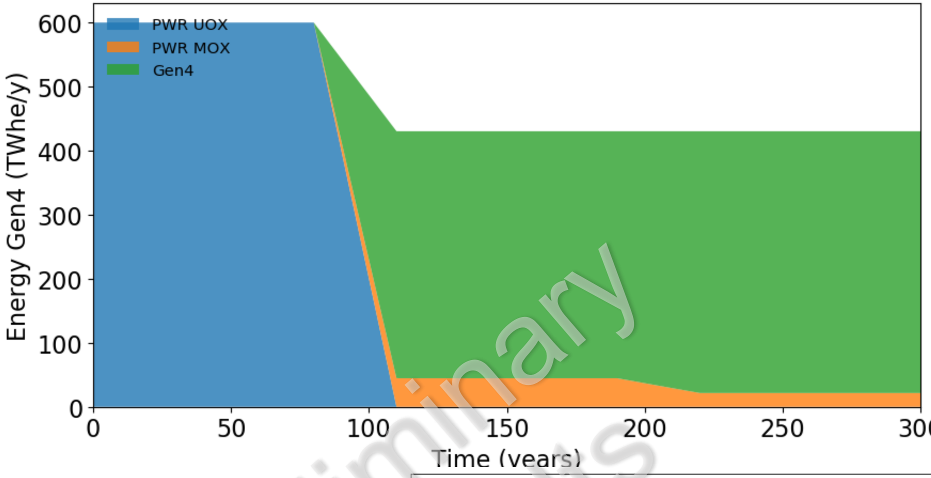
(limite à 1)	Ordonnée à l'origine	Pente	Chi2	Nb évènement
Reference	0,240 (6)	-0.43 (1)	0.003	59
Bruit blanc	0,236 (6)	-0.42 (2)	0.004	61
Systématique	0,227 (7)	-0,40 (1)	0.001	33

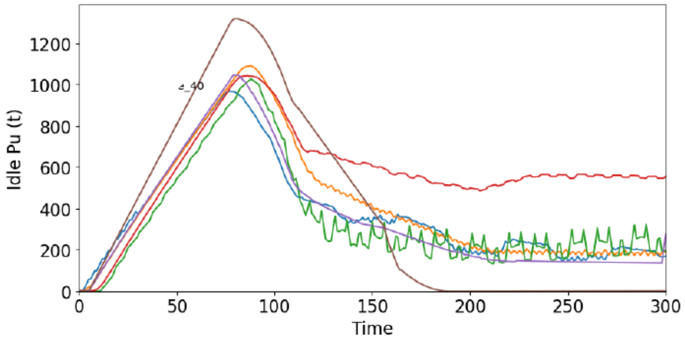
PERMIS, Doligez

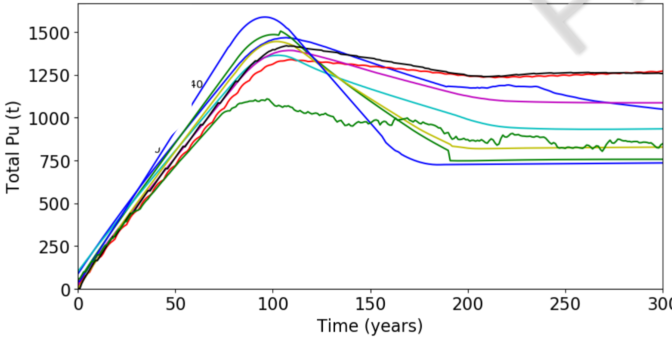
5. Contribution of SFRs for plutonium management

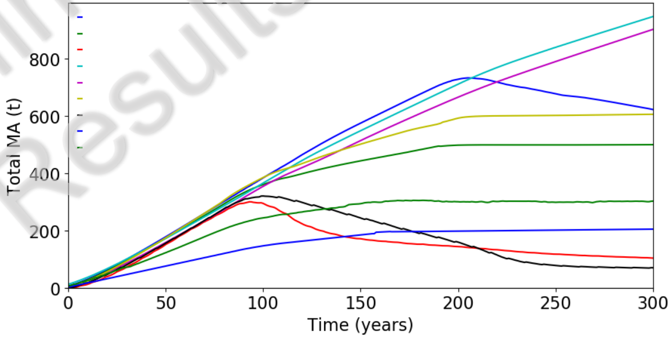
a. Pu management with 100% Gen4 fleet

- Goal : stabilize TRUs
- a large number of fast neutron reactor concepts
- Grouping similar result groups more strategies than Gen4 designs





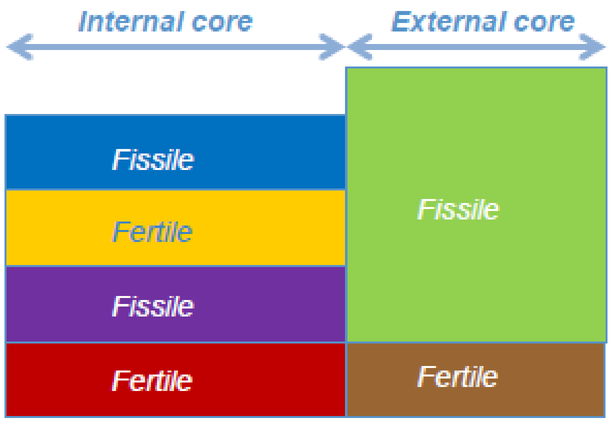




5. Contribution of SFRs for plutonium management

c. Impact of only few SFRs for Pu management

- Highly heterogenous core
  - Dedicated multi-zone models
  - BuildFuel using k and power distribution
  - Irradiation model with XS per zone + flux per zone



Sectional view of ASTRID-like reactor

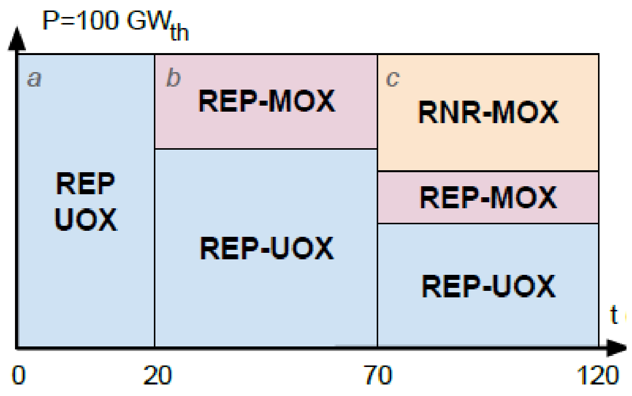
- Highly heterogenous

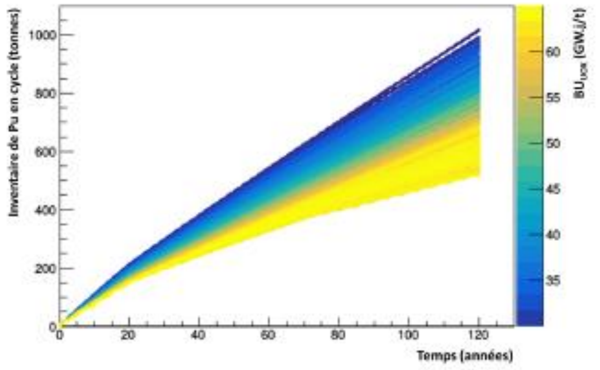
		^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
Isogénérateur	Monozone	3,0%	1,1%	1,2%	5,2%	2,4%
	Multizone	0,30%	0,10%	0,17%	0,47%	0,22%
Incinérateur	Monozone	3,0%	1,8%	0,85%	5,5%	1,4%
	Multizone	0,84%	0,58%	0,34%	0,19%	0,19%

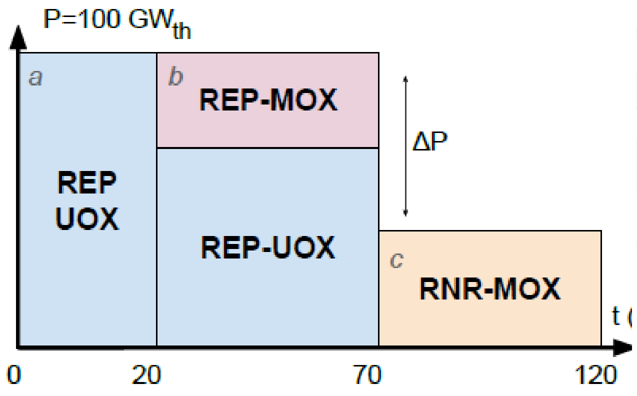
5. Contribution of SFRs for plutonium management

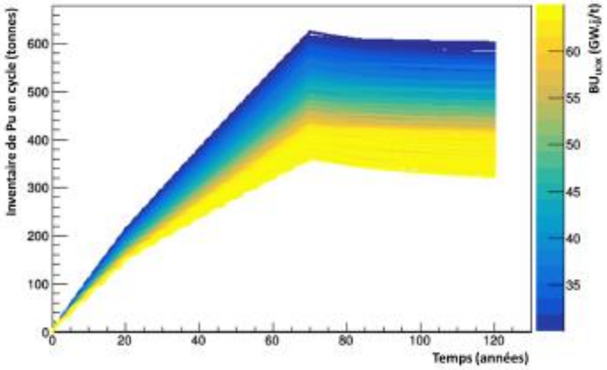
c. Impact of only few SFRs for Pu management

- the stabilization of plutonium inventories is never reached without stopping the PWRs
- main factors for Pu inventory the cycle remain the behavior of PWRs









6. Conclusions

Overview

- Group implanted in national and international collaborations
- Focus on differences sources of uncertainties to quantify and suggest alternative modeling
- Specific focus on models that better representation of the physics and could be use to
- Behavior of PWR and the management of their fuel dominate the effect on transition towards future reactors and even the operation of these reactors if fleet keep large amount of PWR

6. Conclusions and perspectives

Perspectives

- Develop more precise model to evaluate bias of models
- New Methods to select strategies of interest
- Intermiedling of uncertainties of different kind
- Interdisciplinary collaboration with sociology, economics and techno-eco

Annex 1 : Human resources and collaborations

Subatech

- Nicolas THIOLLERE, MCF

Recent Temporary Staff

- F. Courtin (PhD)=>CEA
- B. Mouginot (CDD) => Framatome
- B. Leniau (CDD)

IJCLab

- Xavier DOLIGEZ, CR
- Marc ERNOULT, CR

Recent Temporary Staff

- L. Tillard (PhD) => Orano
- J. Liang (PhD)=> **China General Nuclear Power Group** (CGN)
- A.A Zakari-Issoufou (CDD)
- M. Guillet (MRes) => EDF
- M. Pararids (CDD)

Annex 2 : Collaborations

National

- NEEDS:
  - DOSE : 2013
  - COMPRIS : 2014-2015
  - PERMIS : 2016-2017
  - PISE : 2018- 2019
  - CINEASTE : 2020-2022
- IRSN : 2013-2019
- CEA: 2018-
- Other ad-hoc : Orano, EDF

International

- PICS with Madison-Wisconsin : 2015-2018
- **Technical Workshop on Fuel Cycle Simulation : 2016-**
- FIT project : 2016-
- Ecole polytechnique Montréal : 2017-
- NEA/WPFC/EGAFCS : 2017-