Technical Workshop on Fuel Cycle Simulation 2021

Coupling reactor design and scenario calculations: a new methodology applied for scenario optimization

DE LA RECHERCHE À L’INDUSTRIE

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Introduction

Utility of using reactor design as a parameter in scenario calculations

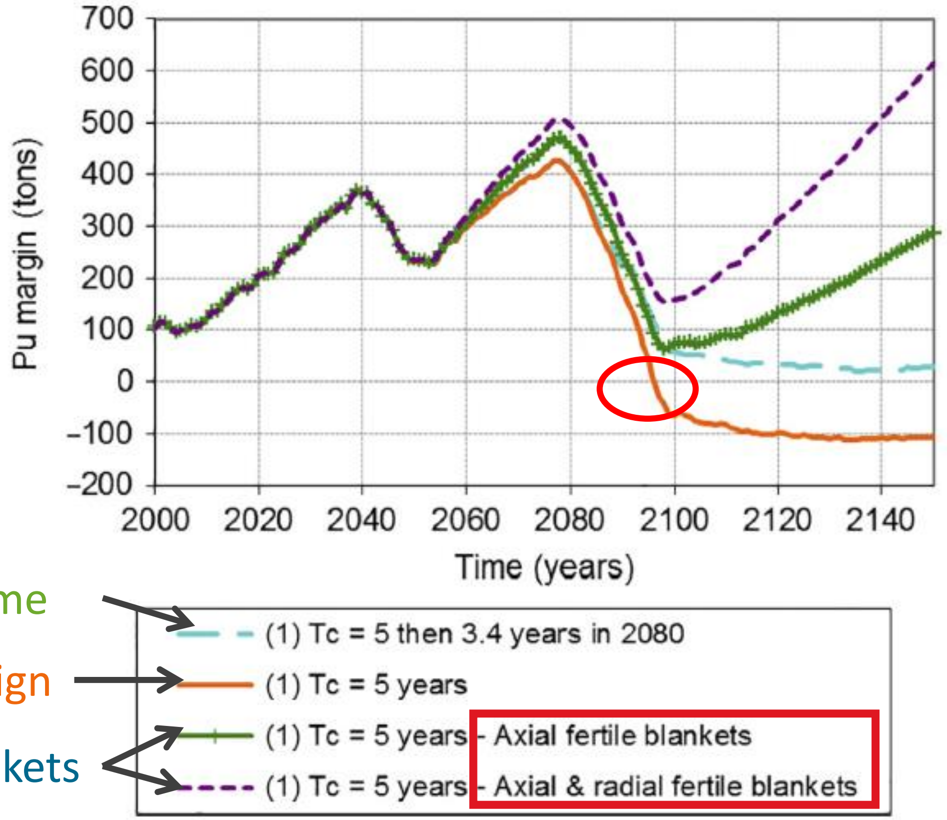
- Example: transition PWR fleet ➔ mixed PWR – SFR fleet ➔ 100% SFR fleet

PWR = Pressurized Water Reactor
SFR = Sodium-cooled Fast Reactor

In this example, the **initial SFR design** leads to a lack of plutonium in 2090.

Possible solutions:

- **Changing the cooling time**
- **Addition of breeding blankets**



Flexible reactor design

↓

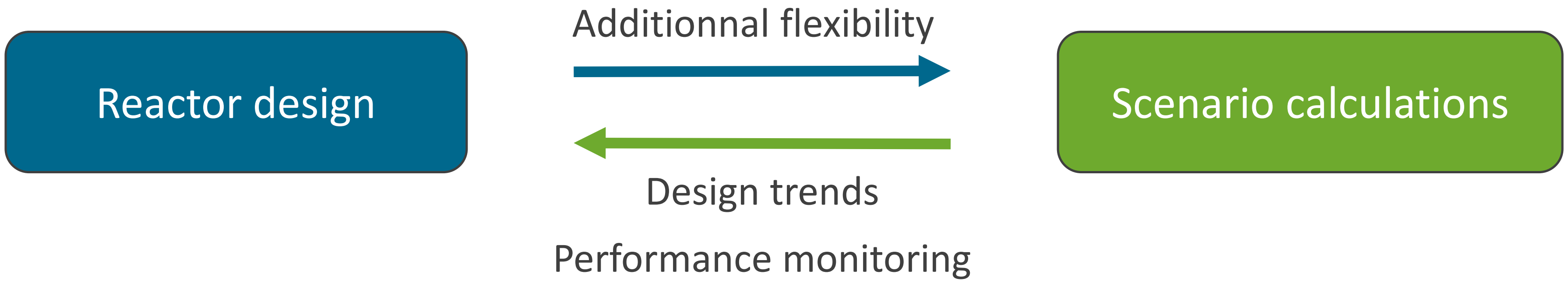
More viable trajectories !

C. Coquelet-Pascal, M. Tiphine, G. Krivtchik, D. Freynet, C. Cany, R. Eschbach et C. Chabert, *COSI6: A Tool for Nuclear Transition Scenario Studies and Application to SFR Deployment Scenarios with Minor Actinide Transmutation,* Nuclear Technology, 192:2, 91-110, DOI: 10.13182/NT15-20, 2015.

Why coupling reactor design and scenario calculations

Some reasons why coupling reactor design and scenario calculations is interesting:

- Flexible reactor design can give more options for a scenarist to make a trajectory work ➔ possibility to unlock new trajectories
- Reactor settings tuned by the scenarist can be used as guideline by the designer
- Reactor performance monitoring over its lifetime is achievable thanks to the data of loaded fuel composition during the simulation


Reactor design

Additionnal flexibility

Scenario calculations

Design trends

Performance monitoring

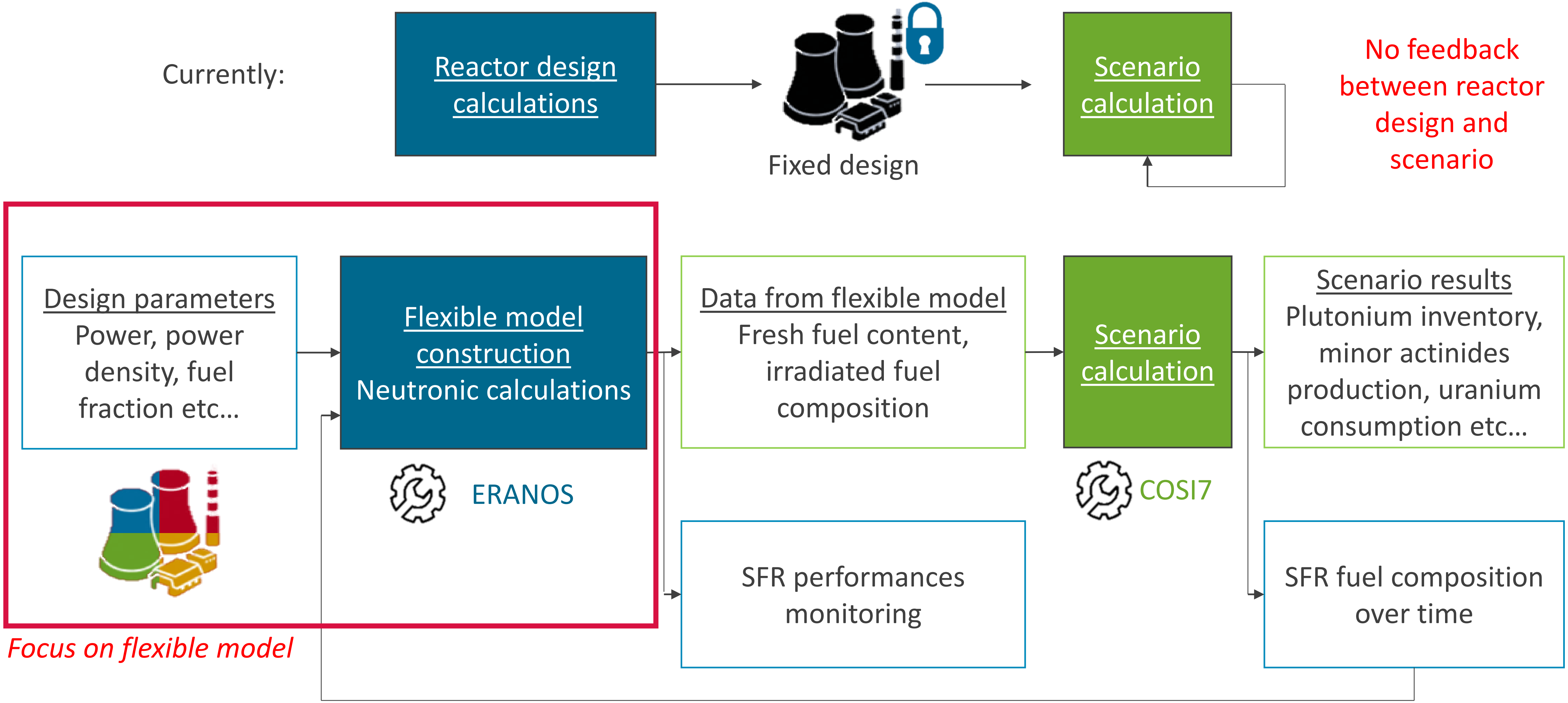

Flexible design

We chose to work with Sodium-Cooled Fast Reactors (SFR) here as CEA has gathered a lot of experience with SFR and there is currently no definitive design in France

Presentation content

Methodology

Theorical coupling



Currently:

Reactor design calculations

Fixed design

Scenario calculation

No feedback between reactor design and scenario

Design parameters
Power, power density, fuel fraction etc…

Flexible model construction
Neutronic calculations

ERANOS

Data from flexible model
Fresh fuel content, irradiated fuel composition

Scenario calculation

COSI7

Scenario results
Plutonium inventory, minor actinides production, uranium consumption etc…

SFR performances monitoring

SFR fuel composition over time

Focus on flexible model

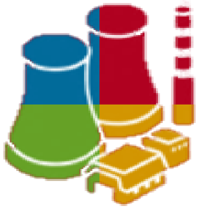
SFR flexible model

Inputs from scenario

Plutonium isotopy in fresh fuel

Design parameters

Power	MWth	100	4500
Power density	W/cm^3	50	350
Fuel fraction	%	35	45
Irradiation time	EFPD	600	2400
Ax. Breeding blankets thickness	cm	0	30
Rad. Breeding blankets thickness	cm	0	30



SFR flexible model

Outputs for scenario

Plutonium content in fresh fuel

Irradiated fuel composition

Performance monitoring

Burn-up

Maximum power density

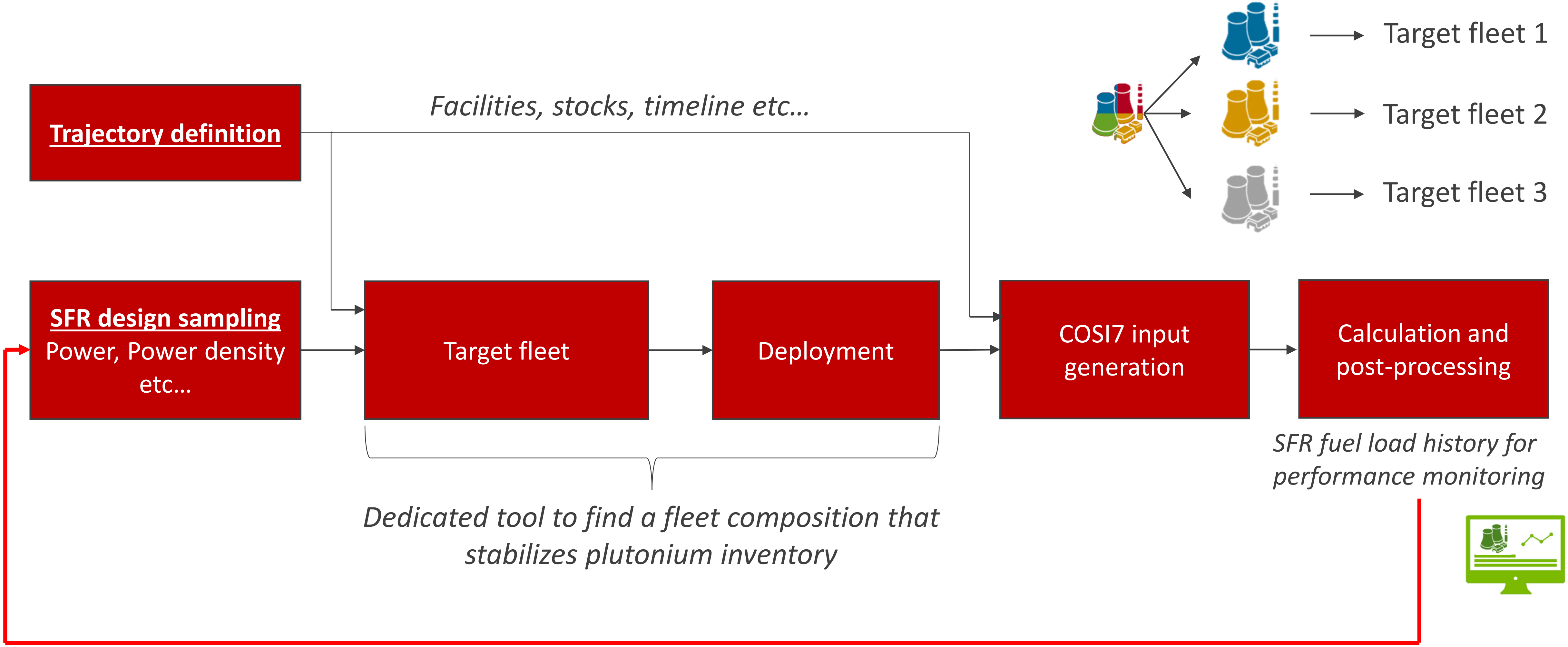
DPA max

Void coefficient

Doppler coefficient

- SFR flexible model = set of Artificial Neural Networks (ANN) built from a database generated with the determinist code ERANOS

Coupling



Trajectory definition

Facilities, stocks, timeline etc…

Target fleet 1

Target fleet 2

Target fleet 3

SFR design sampling
Power, Power density etc…

Target fleet

Deployment

COSI7 input generation

Calculation and post-processing

SFR fuel load history for performance monitoring

Dedicated tool to find a fleet composition that stabilizes plutonium inventory

Possibility to integrate an optimization loop

Application case

Application case: reaching plutonium stabilization

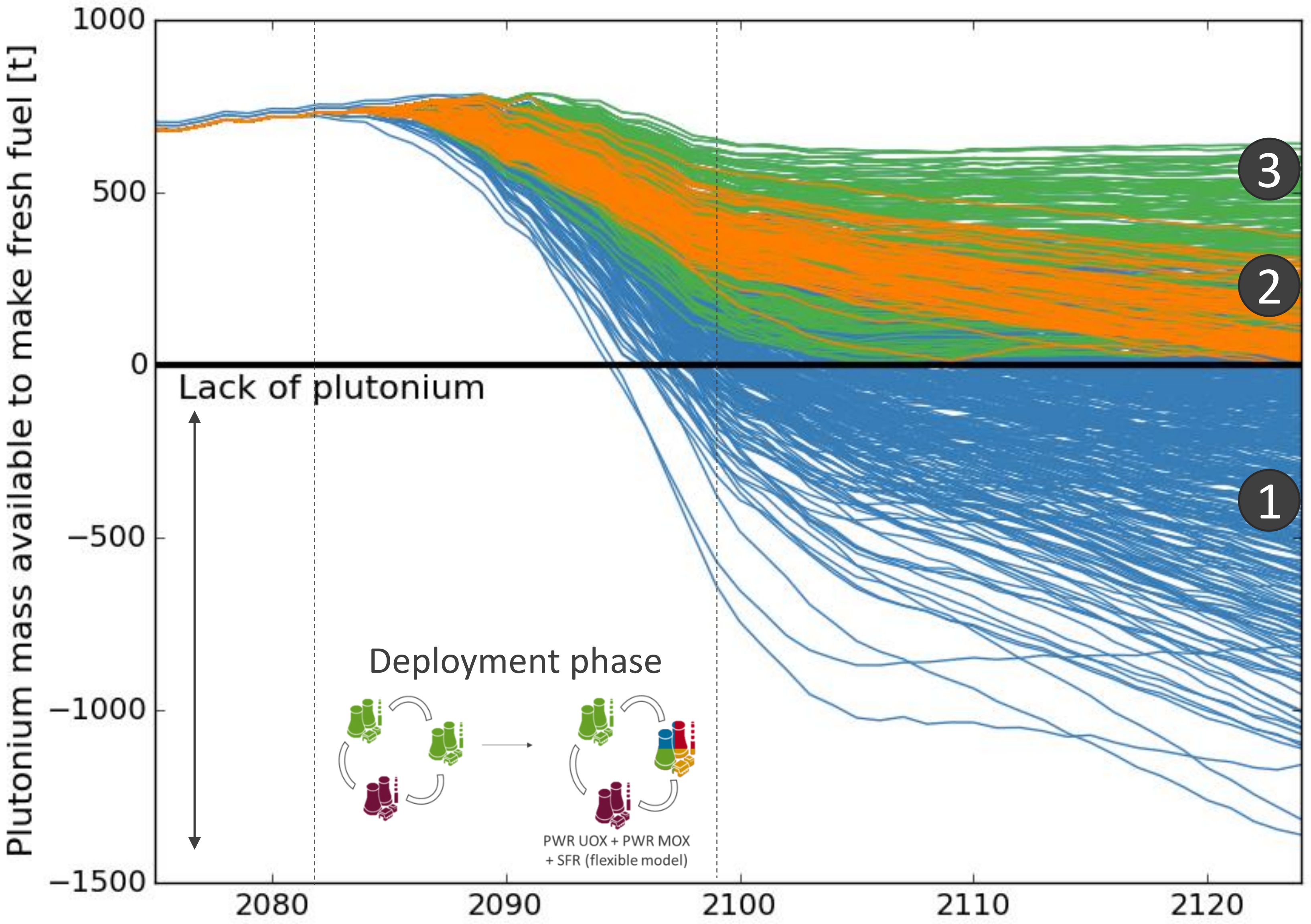
700 SFR designs sampled in the ANN definition domain

Hypotheses:

- Electricity production = 420 TWhe (constant)
- Time related:
  - Minimum 5 years cooling time for irradiated fuel
  - 2 years aging time during fresh fuel fabrication
- Initial stocks based on the French National Radioactive Waste Management Agency (ANDRA)
- Plutonium repartition:
  - Good grade plutonium is given preferentially to PWR MOX to ensure a plutonium content < 12%
  - SFR takes preferentially plutonium from irradiated PWR MOX fuels, UOX fuels and finally SFR MOX fuels.

Objective: highlight all the trajectories that lead to plutonium stabilization and compare them

Plutonium availability and viable trajectories



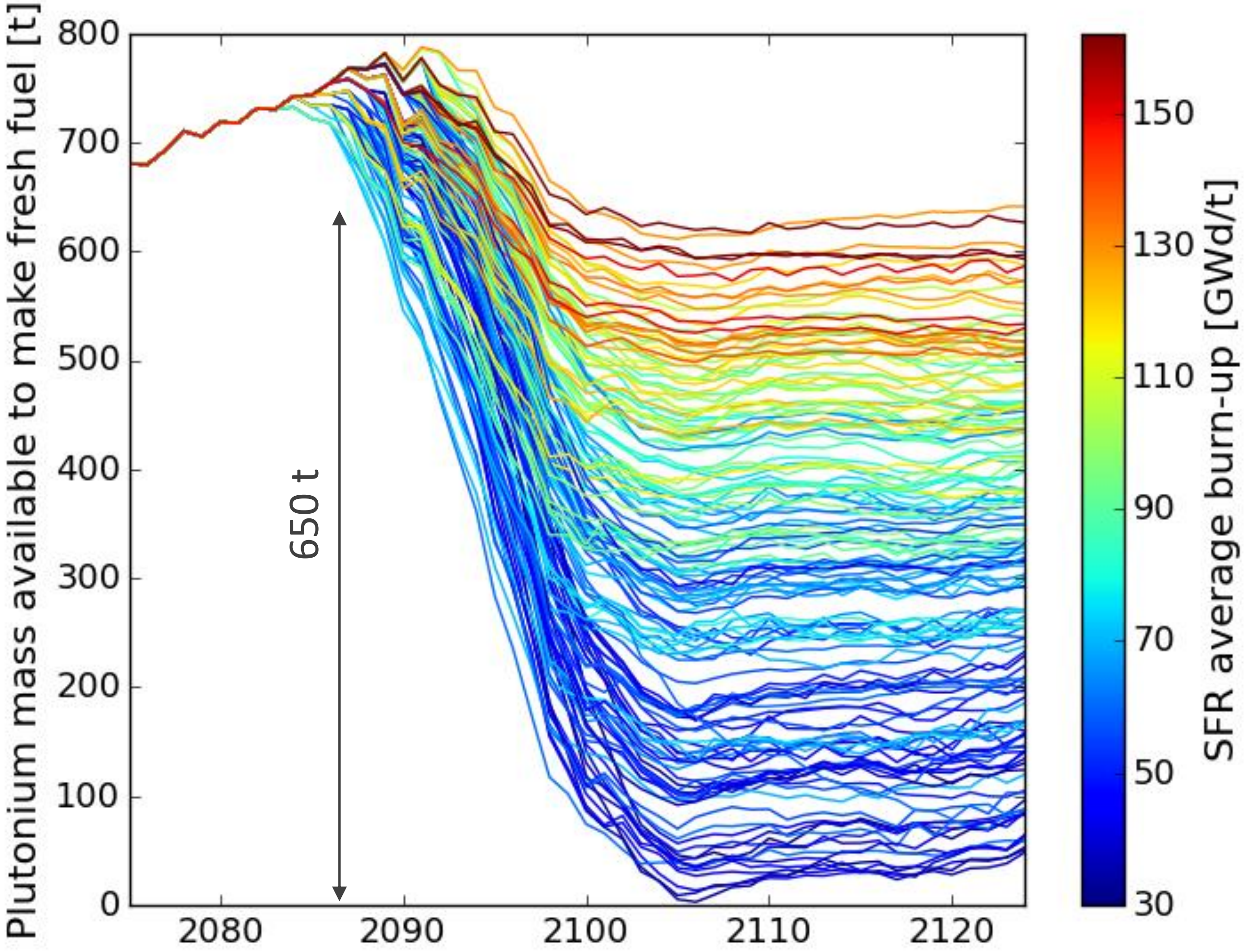
3. Fleets that have reached stability

2. Fleets that does not require external source of plutonium yet, but will do

1. Fleets that require external source of plutonium

Among the 700 SFR designs sampled, **150 lead to viable trajectories**

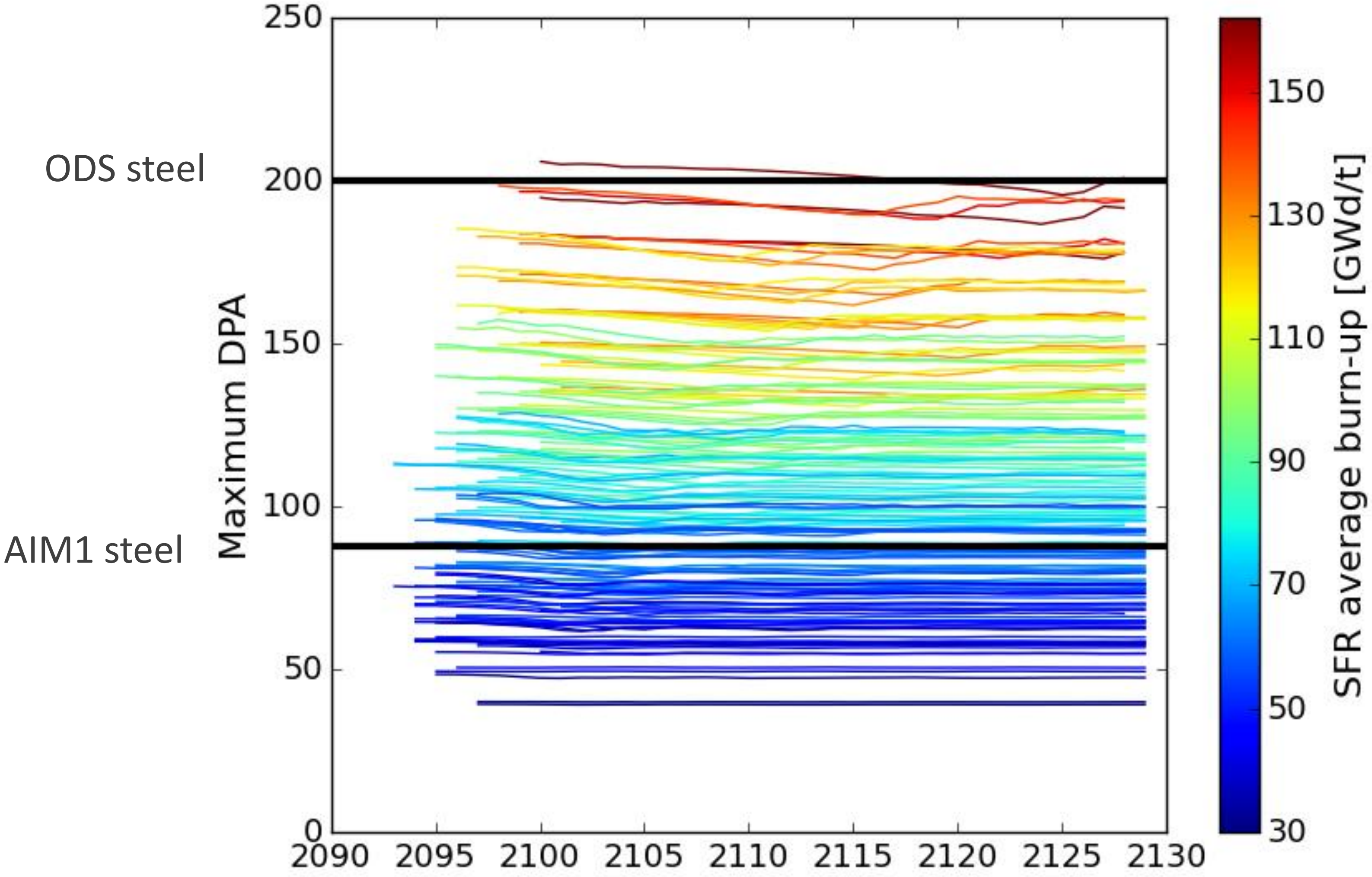
Viable trajectories



- Trend: **the higher the average SFR burn-up, the higher the plutonium mass available in cooled irradiated fuels**
- **Burn-up ∝ Power density * Irradiation time**
- The higher the power density, the lower the number of fuel assemblies
- The higher the irradiation time, the lower the reload frequency

- **Higher burn-up** ➔ plutonium available ↑, **easier transition towards a 100% SFR fleet**
- **Lower burn-up** ➔ less irradiated fuels stored, **relieve pressure on storage**

Example of SFR performances monitoring: maximum DPA



- Maximum DPA received almost constant over time for a given burn-up ➔ plutonium isotopy has almost no effect on DPA
- The higher the burn-up, the higher the maximum DPA ➔ expected as the fuel is exposed to higher neutron fluence
- Thanks to this kind of monitoring, design choice can be made. Here, if we want to use AIM1 steel, it is mandatory to choose an average burn-up arround 50 GWd/t
- In the case of ODS steel, all viable trajectories but one respect the safety criteria

Conclusions

Conclusions

- Using a flexible model of reactor within a scenario calculation is interesting because:
    - It **adds a lever** to make a trajectory work for the scenarist
    - It gives **design guideline** directly from scenario calculations
    - It enables **performance monitoring** for the reactor

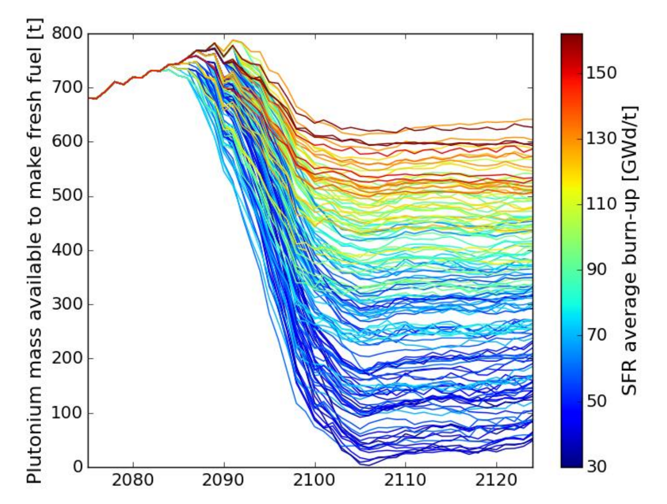
- A new methodology has been developped that relies on the use of **flexible reactor model** in scenario calculation code.

- An application case has been presented and consists in the theoretical evolution of the current French fleet toward a PWR – SFR mixed fleet that stabilizes the plutonium inventory.

    - Among the 700 sampled SFR designs tested, 150 lead to viable trajectories
    - Regarding trajectory viability, the **SFR average burn-up has the main influence** and is defined by the SFR **power density** and **irradiation time**. When the SFR works at high burn-up, the plutonium mass available is high, at the cost of the storage needed for irradiated fuels. It would nevertheless facilitate the transition toward a 100% SFR fleet
    - Maximum DPA monitoring has been shown as an example of performance monitoring and brings information about material that is to be used according to the burn-up chosen.

- Such methodology should be useful for resilience and robustness analysis of scenarios as it would be possible to find SFR designs that bring flexibility to a trajectory in front of changes of assumptions or objectives.

Thank you for your attention



BACK UP

SFR sampling

Sampling method: One At a Time (OAT)

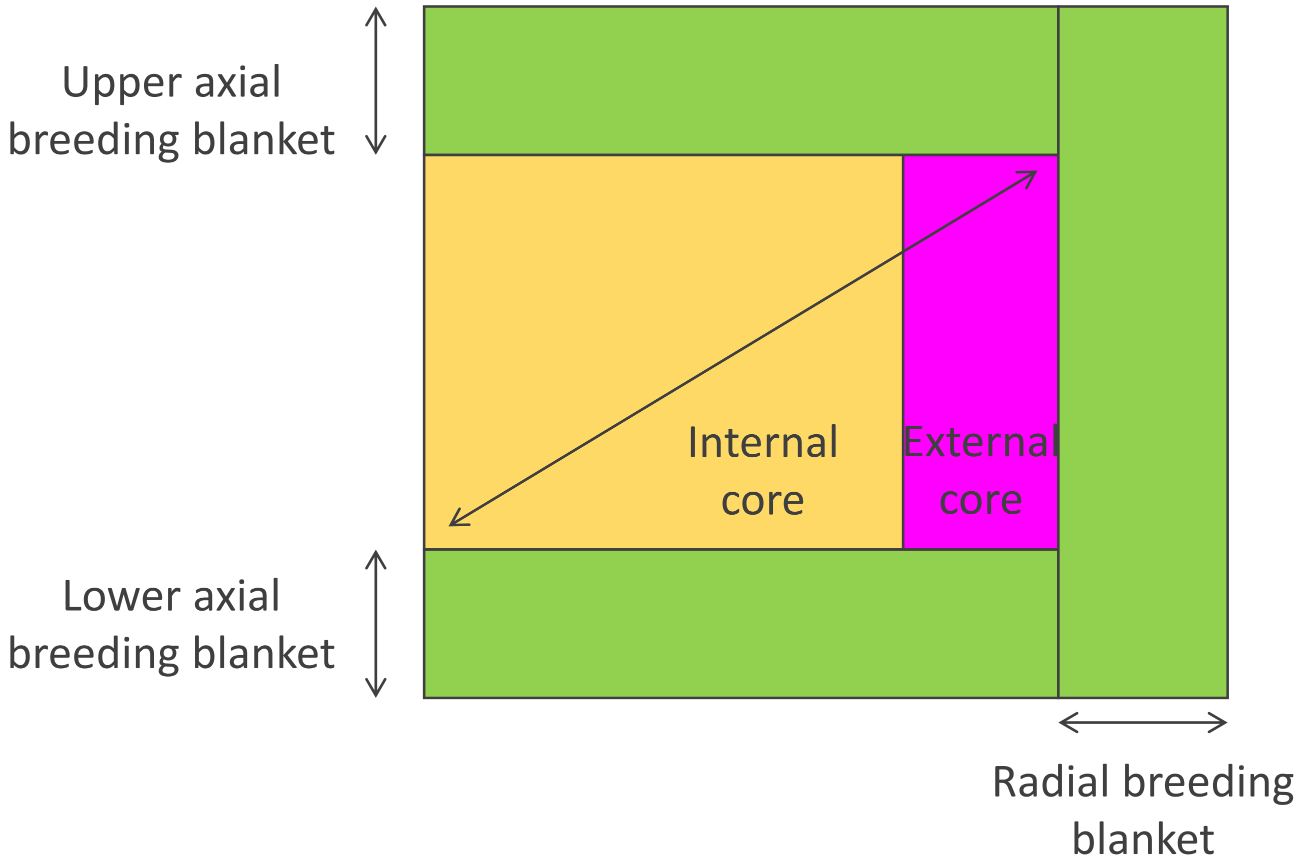
- Power [MWth] : 1000 – 2000 – 3000 – 4000
- Power density [W.cm^{-3}] : 100 – 150 – 200 – 250 – 300
- Irradiation time [EFPD] : 800 – 1200 – 1600 – 2000
- Fuel fraction [%] : 37 – 40 – 43
- Fertile blankets (axial and radial) [cm] : 0 – 10 – 20

SFR model used

- SFR base model = V2B core
- Volume changes done with constant aspect ratio (H/D)
- Tool: ERANOS
- Cross section library: JEFF 3.1

Power	MWth	100	4500
Power density	W/cm³	50	350
Fuel fraction	%	35	45
Irradiation time	EFPD	600	2400
Ax. Breeding blankets thickness	cm	0	30
Rad. Breeding blankets thickness	cm	0	30

RZ model



Methodology used to determine a fleet that stabilizes plutnoium inventory

- Plutonium mass balancing

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

- Stabilization of plutonium isotopy + use of « plutonium grade »

$$\boldsymbol{g} = \frac{m(^{239}Pu) + m(^{241}Pu)}{\sum_{i=238}^{242} m(^{i}Pu) + m(^{241}Am)} \qquad g = \frac{\sum x_i P_i G_i}{\sum x_i P_i}$$

Réacteur i

x_i : Reactor i fraction in the fleet

C_i : Plutonium mass consummed annually by reactor i [t/an]

P_i : Plutonium mass produced annually by reactor i [t/an]

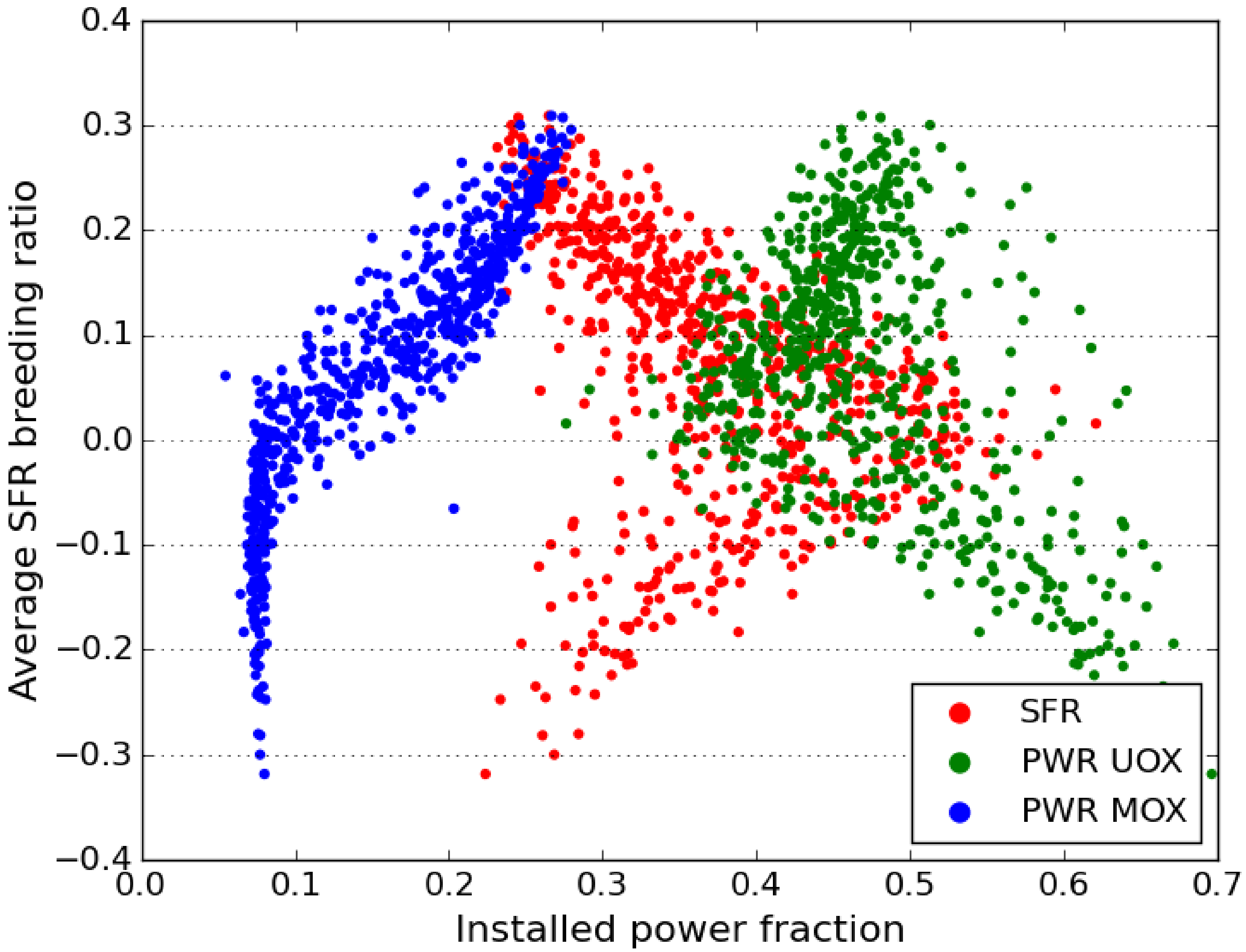
G_i : Plutonium grade in reactor i irradiated fuel

Linear functions of plutonium grade g

Final fleet composition is obtained by solving these equations

G. Martin et C. Coquelet-Pascal, « Symbiotic equilibrium between Sodium Fast Reactors and Pressurized Water Reactors supplied with MOX fuel », *Ann. Nucl. Energy*, vol. 103, p. 356-362, may 2017

Fleets that stabilize plutonium inventory according to the SFR used



- For each SFR design sampled, a fleet composition that **ensure plutonium stabilization** is found thanks to a **static analysis**

- Fleets diversity:
  PWR UOX fraction : [30% - 70%]
  PWR MOX fraction : [5% - 25%]
  SFR fraction : [25% - 60%]

Different fleet composition for each SFR design