REACTOR SIMULATIONS FOR SAFEGUARDS WITH THE MCNP UTILITY FOR REACTOR EVOLUTION CODE

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Outline

1. Introduction
2. MURE code
   - MURE code
   - MURE-CHARS extension
3. Examples of reactor simulation
   I. Validation of the code and PWR simulation
   II. On-load reactors
      - CANDU simulation
      - PBR simulation
   III. FBR simulation
   IV. Research reactor simulation
4. Conclusion and outlooks

Need of reactor simulation

- We promote practical and concrete measures in order to pursue nonproliferation.
- Some useful information can be obtained by simulation:
  - How many kilograms of plutonium are generated?
  - How much time will it take to achieve it?
  - What is the practical refueling plan?

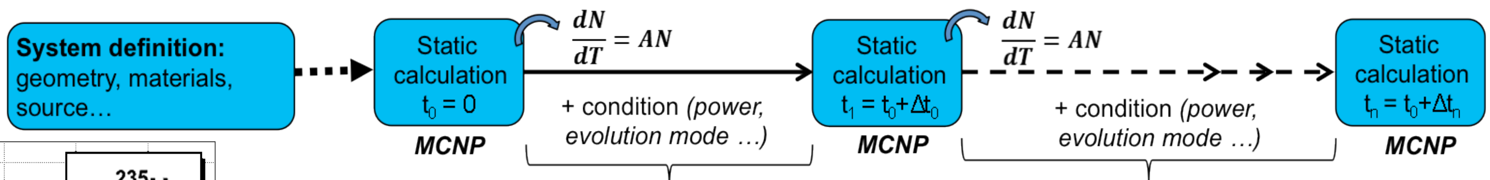
➢ To seek them, a reactor simulation code could help testing proliferation scenarios.

➢ Such code should be customized according to the needs of users.

MURE could provide valuable information in order to help IAEA to meet its surveillance goal.

MURE code

- MURE (MCNP Utility for Reactor Evolution)*: C++ interface for MCNP and subsequent burnup calculation.
- High expandability: various types of reactors, fuels, refueling schedule. Suitable for scenario studies.
- Providing useful outputs: criticality, neutron flux, inventory, reaction rates (fission, capture, …)

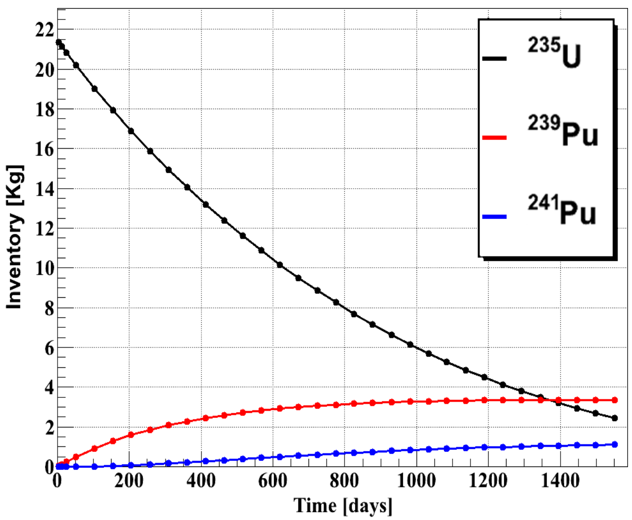


Evolution of materials: solving the differential coupled equations of Bateman:

$$\frac{\partial N_i}{\partial t} = \underbrace{-\lambda_i N_i + \sum_j \lambda_j^{j\to i} N_j}_{\text{Decay}} + \underbrace{\sum_{j'} N_{j'} \langle\sigma_{j'}\rangle^{j'\to i}\langle\phi\rangle - N_i \sum_{\forall r} \langle\sigma_i\rangle^{(r)}\langle\phi\rangle}_{\text{Neutron-induced reactions}}$$

$\langle\phi\rangle^{MCNP}$: Normalization to thermal power

Evolution process of MURE code



Ex. Core inventory evolution

* http://www.oecd-nea.org/tools/abstract/detail/nea-1845

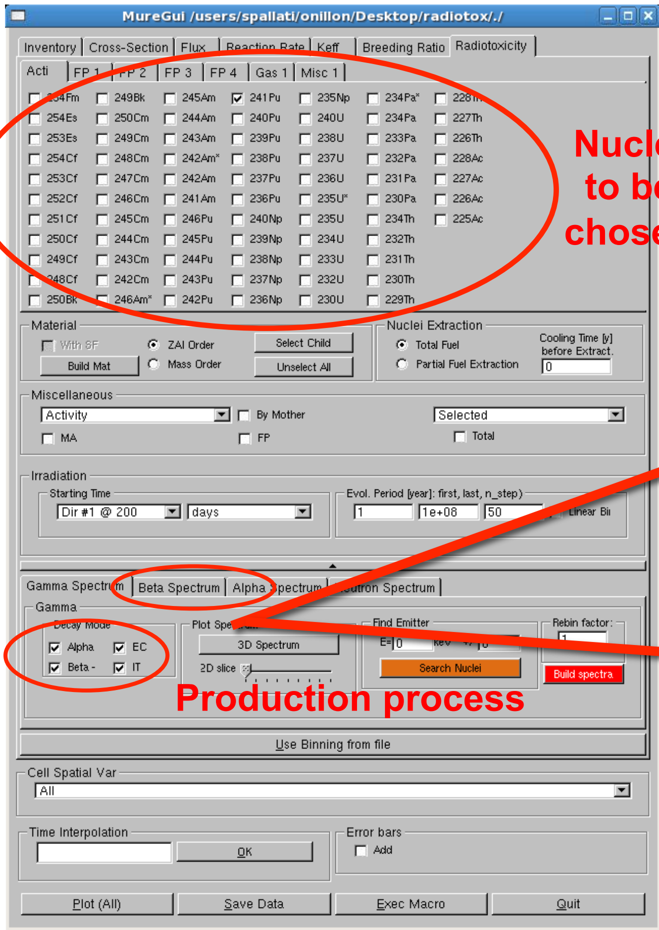
CHARS: CHaracterization of Radioactive Sources

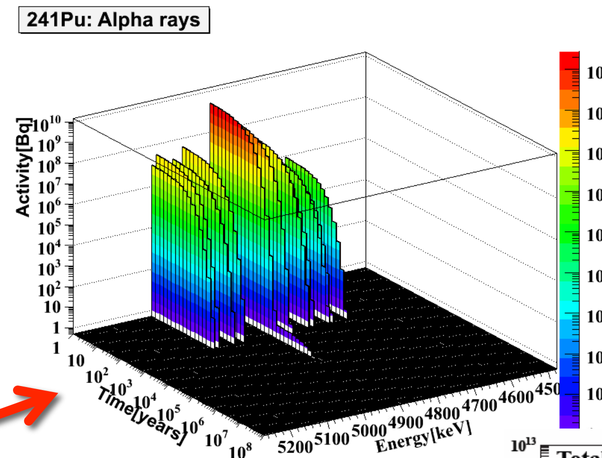
Coupled to the MURE code:

- produces spent fuel composition info. for any geometry
- generates α,β,γ,n spectra for any spent fuel

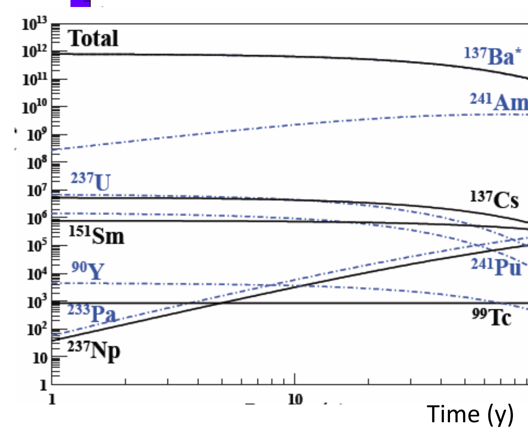
Coupled to Graphical User Interface MureGui:

- Access to data generated during the fuel evolution: Fluxes, Decay spectra, Inventories, Reaction Rates



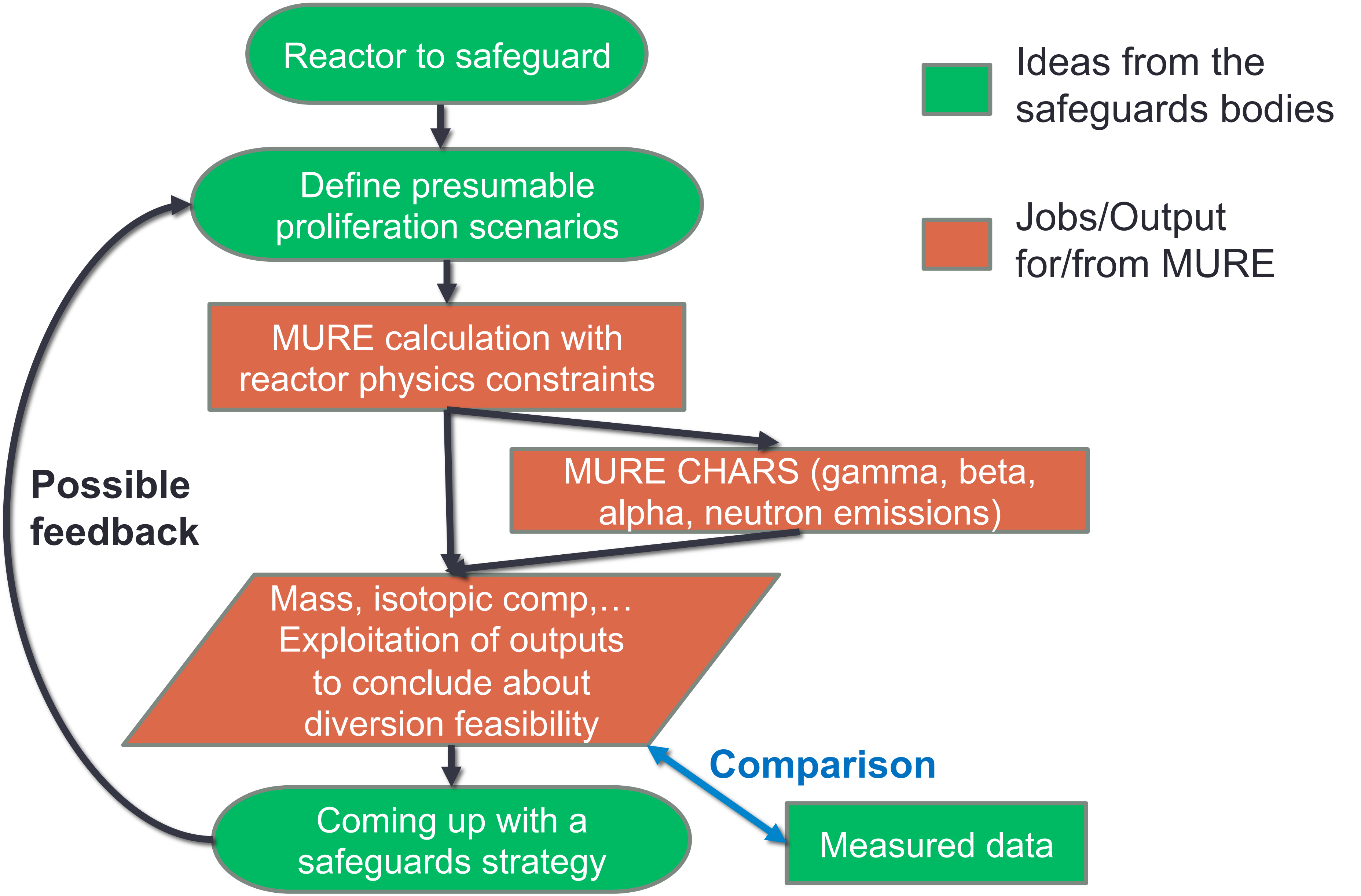


Spectra of alpha ray emitted from Pu-241



Container of Intermediate Level Long Lived Wastes

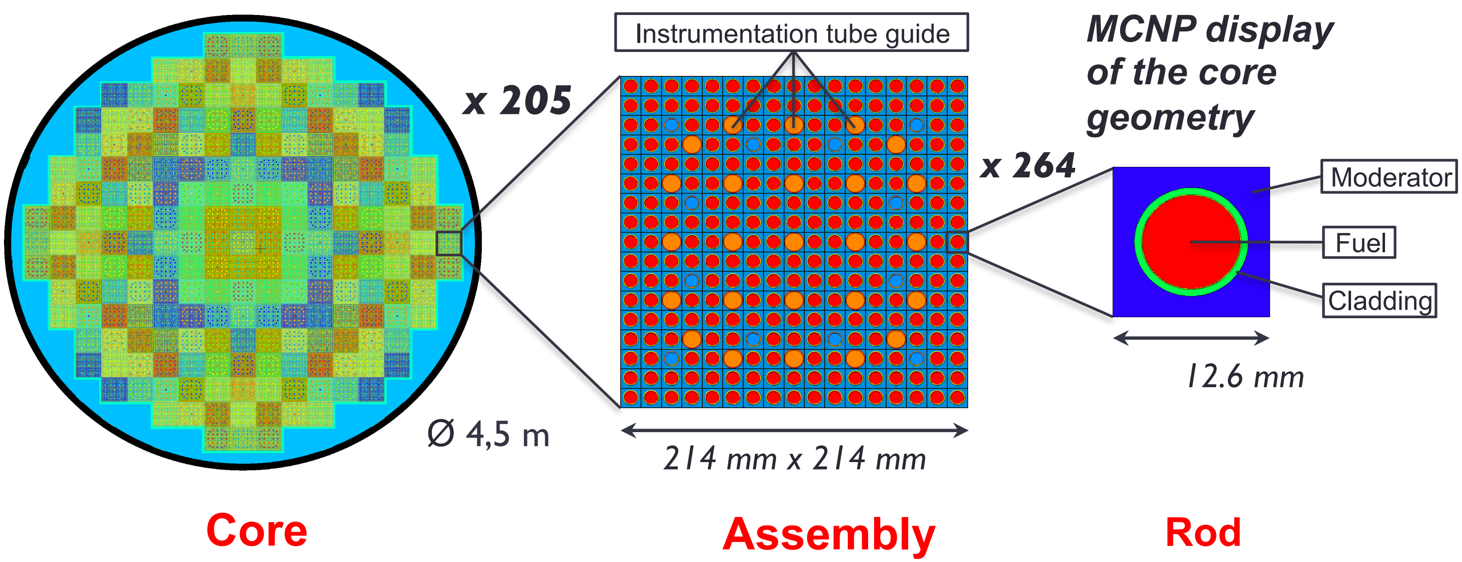
Schematic view of MURE usage



Validation of MURE code and PWR simulation

- Modelling a detailed PWR (N4, 4.25GWth) core with follow-up of operating parameters
  - Agreements with EDF : design data, operating parameters, fuel loading maps…
  - 3 fuel cycles simulated

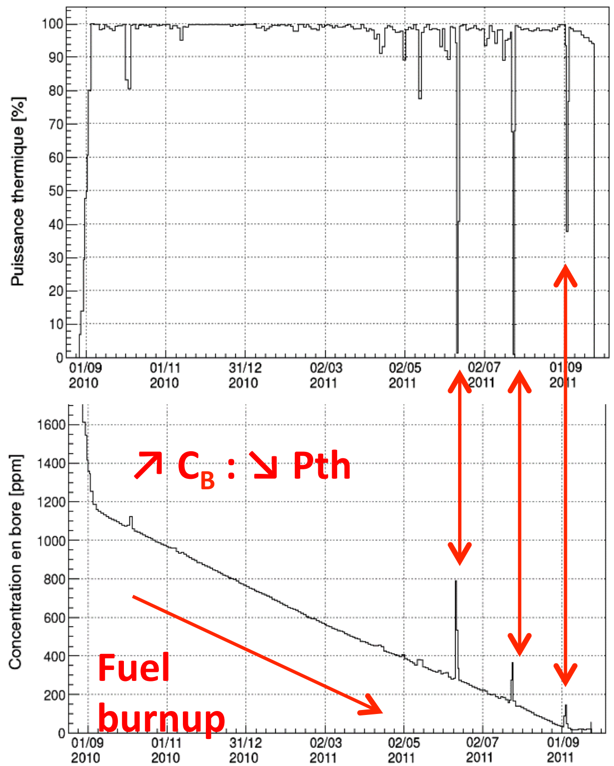
- Validation:
  - Benchmark MURE vs DRAGON @ assembly level: C. Jones et al. PRD 86 (2012) 012001
  - Benchmark MURE, APOLLO (EDF results), DRAGON

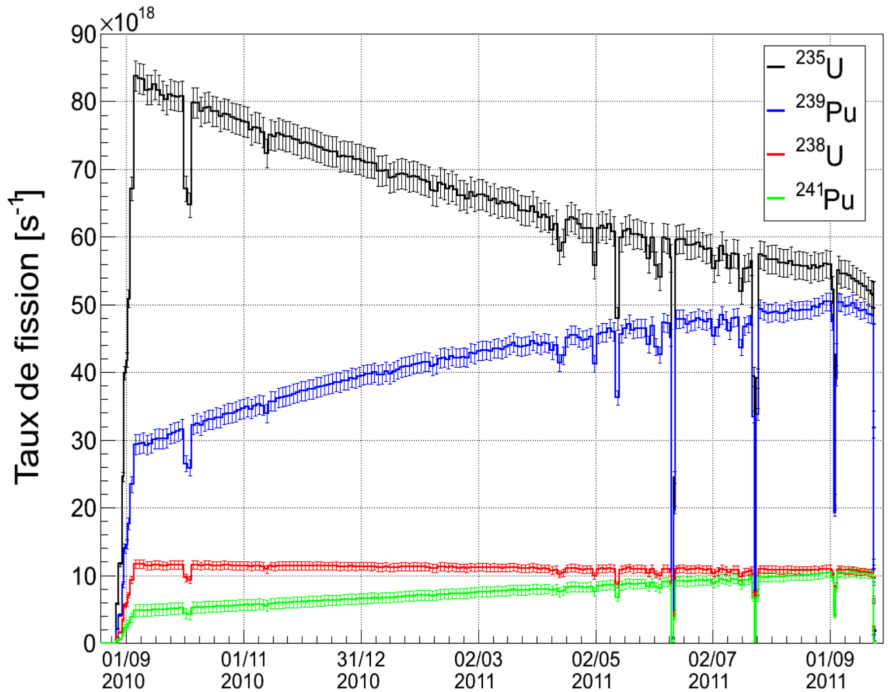


PWR simulation

- Simulation of the 4 assembly types with MURE: to extract assembly fuel composition at their loading burnup => Input of core simulations.

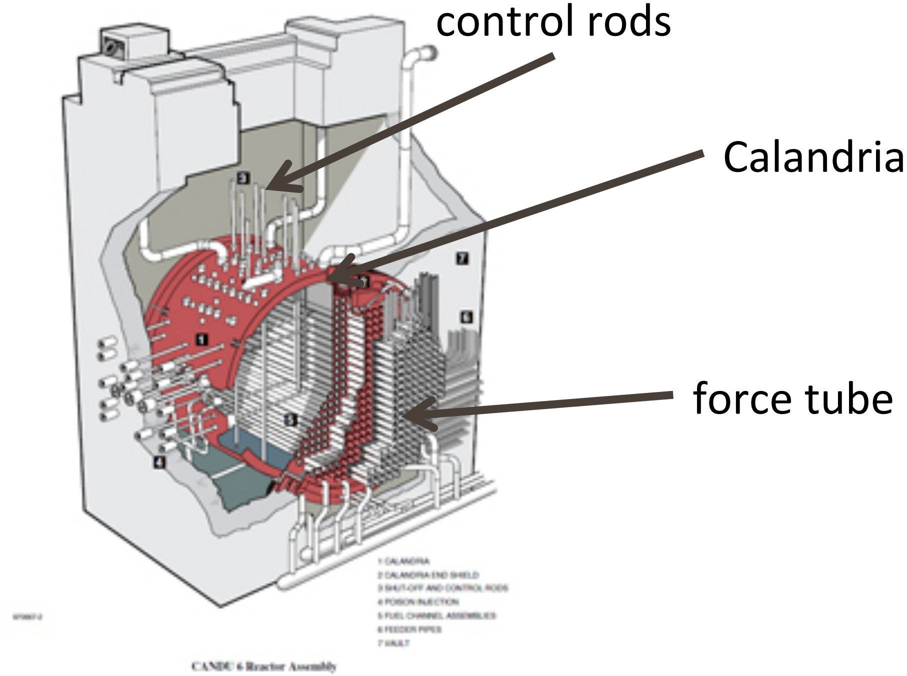
3 reactor cycles simulated with the full core model, following operating parameters:



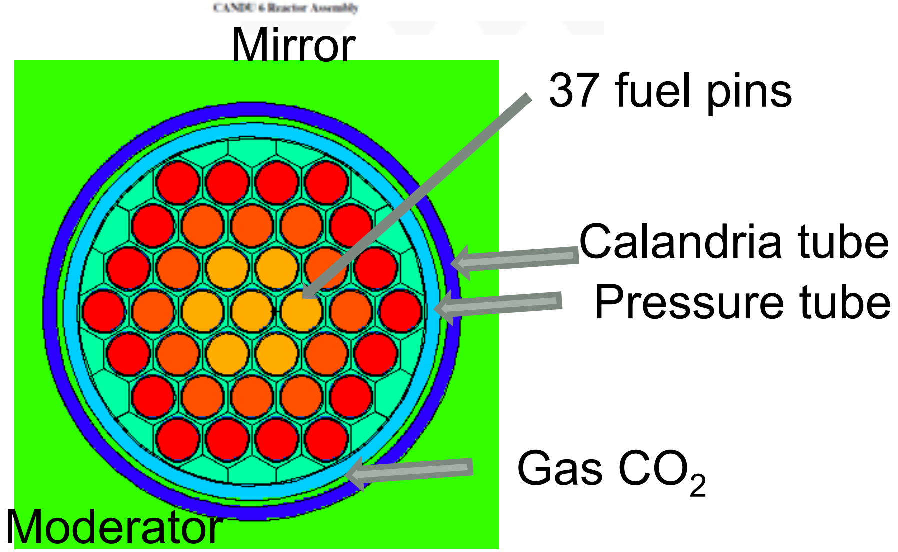


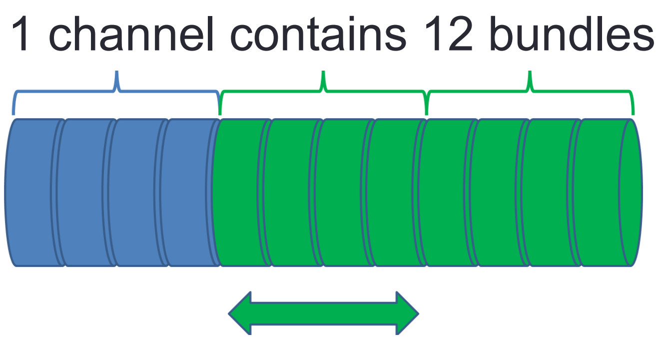
Performing a detailed simulation following operating parameters during the reactor cycles is possible

Onload refueling reactor - CANDU Reactor



CANDU 6 reactor: Power = 700 Mwe
Fuel = natural uranium
Moderator = heavy water
Coolant = heavy water



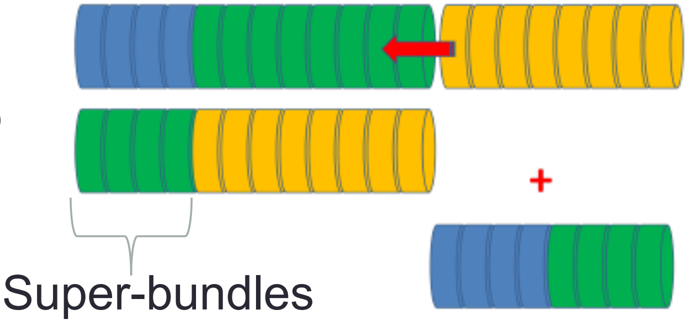


Channels are refueled by 1/3rd or 2/3rds

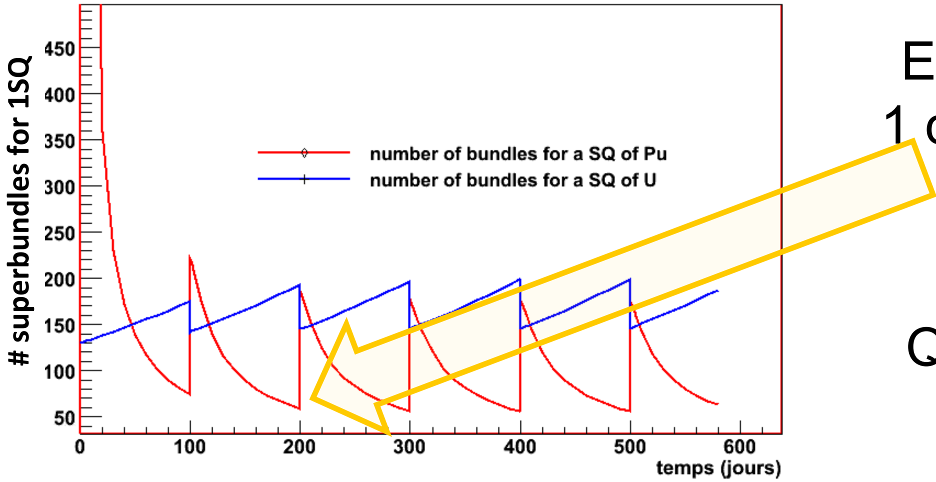
Studied scenario preserving # refuelling per day

Examples of Calculations

- **Reactor physics: V.M. Bui's PhD & S. Cormon's PhD**
  - Normal operation: **Refuelling every 200 days.**
  - Required reactivity reserve : **6$**.



- **Diversion scenario:** 100 channels refueled faster: @ 100 days (1/4) & 300 channels refueled slower @ 300 days (3/4) ➡ K_{inf} @equilibrium : 1.05 = **+ 7.7$ = feasible**



Ex. After 2nd refueling, we assume 1 diversion of one-third of channels/ day:

time to divert 1 SQ = 56 days

Quality of plutonium = fuel-grade

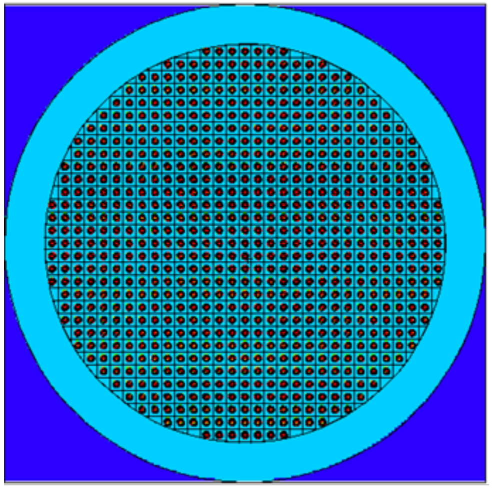
➡ **One can test a lot of scenarios (refuel even faster, transient scenarios, multi-reactor scenarios…): reactor physics brings the feasibility of such scenarios w.r.t. reactivity constraints.**

Onload refueling reactor - Pebble Bed Reactor

- An on-load refueling mode.
- Single pebble surrounded by a mirror, thus simulating an infinite reactor, with a packing fraction of 51%.
- Benchmark was done for the validation, filled with UOx, PuOx and ThUOx pebbles. Comparison shows that our results are within the predictions of the participants to the benchmark.

Results

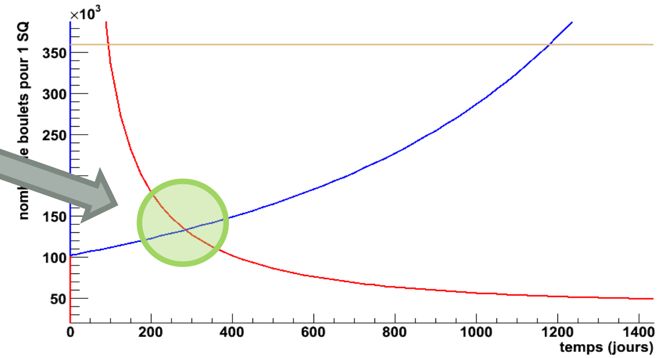
- Inventories from benchmark:
  - UOx fuel : 5% ^{235}U, 7% ^{239}Pu, 12% ^{241}Pu
  - ThUOx fuel: < 1% in ^{233}U
  - PuOx fuel: <1% in ^{239}Pu



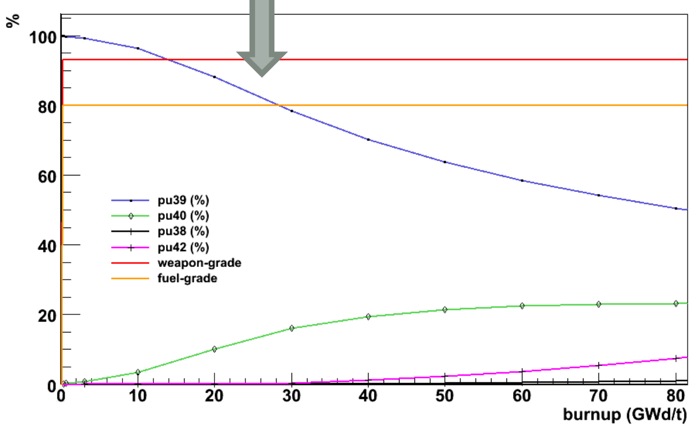
MCNP view geometry

Useful information from simulation results

Ex.1
First time when diverting 1 SQ of Pu is easier than U corresponds to a quality of Pu: fuel-grade



Number of pebbles for 1SQ



Pu isotopic vector

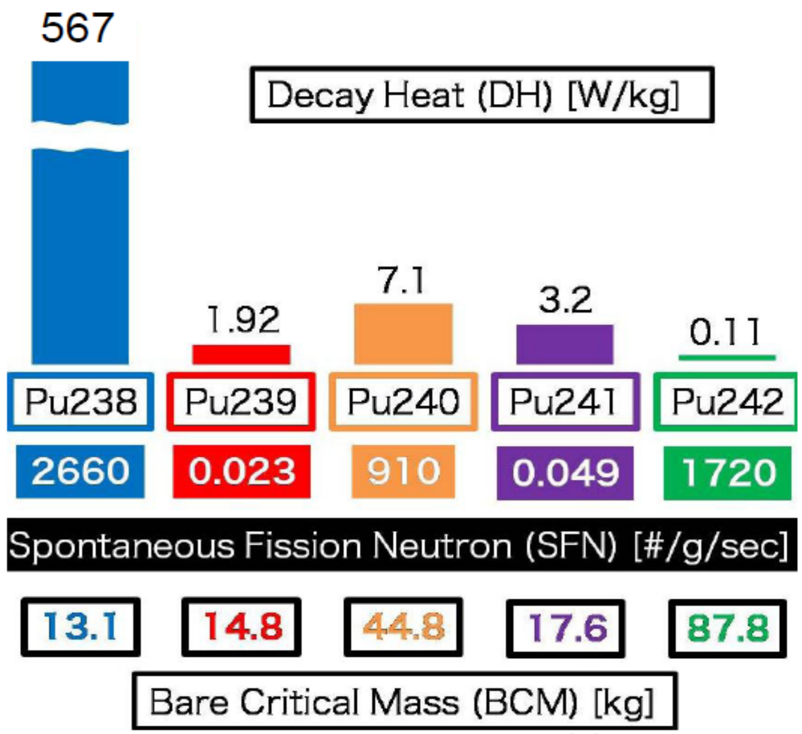
Ex.2
Simplified K-inf calculation shows that the diversion for 1SQ would take ~450 days

Such calculations could be used to determine with which accuracy margin the number of pebble movements should be controlled to prevent such diversion.

Protected Plutonium Production (P^3)*

- Proliferation resistance of Pu can be enhanced by: high decay heat, high spontaneous fission neutron rate and large mass.

- P^3 fuels have a high isotopic composition of ^{238}Pu. According to Kimura et al.**, if Pu has more than 15% of ^{238}Pu in isotopic composition, the fuel can be regarded as proliferation resistant enough.

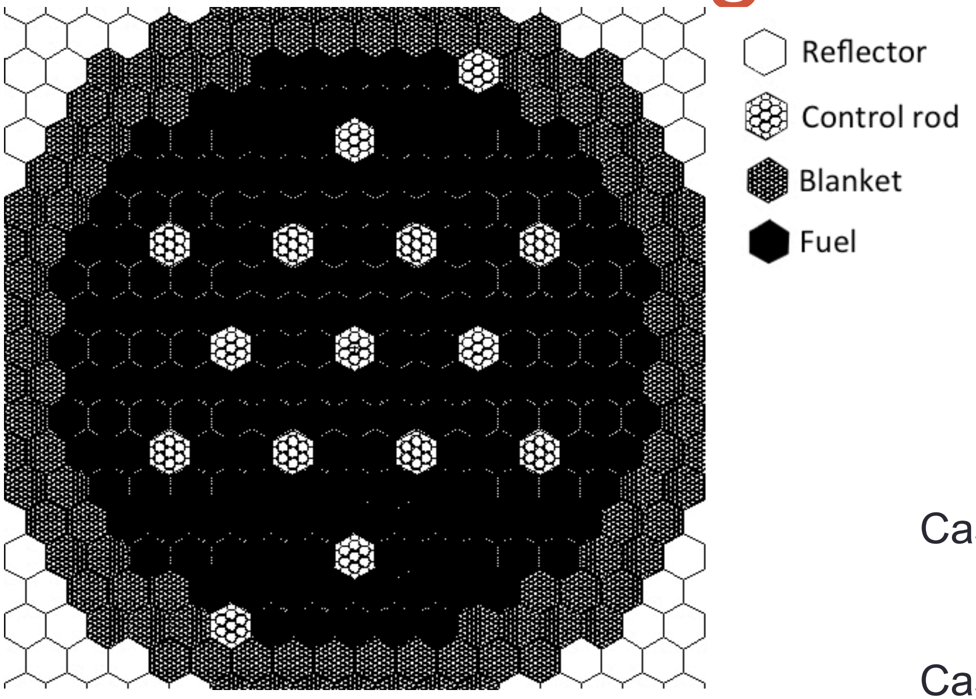


Physical characteristics of Pu isotopes***

* M. Saito, J. Nucl. Sci. Technol., 1(23), 127-138 (2005)
** Y. Kimura, et al., J. Nucl. Sci Technol., 48, 5 (2011)

*** Y. Kimura, "Study of Evaluation Methodology for Proliferation Resistance of Plutonium," PhD Thesis, Tokyo Institute of Technology (2011)

Reactor configuration*



Reactor configuration of the FBR core

- 1250 MWth (steady state)
- 3-D Full core analysis of prototype Fast Breeder Reactor
- Reloading is planned once every 180 EFPDs, when one third of the core and one eighth of the blanket are exchanged
- Pu content in inner core is 21 wt.% and outer core 28 wt.%

Case 1: Reference case (Normal MOX** : the spent fuel of 3.5% enrichment burned in PWR until 40 GWd/t and 5 years' cooling)
Case 2: P^3 case (P^3 core fuel**, Am blanket)
Case 3: P^3 case (P^3 core fuel**, Np blanket)

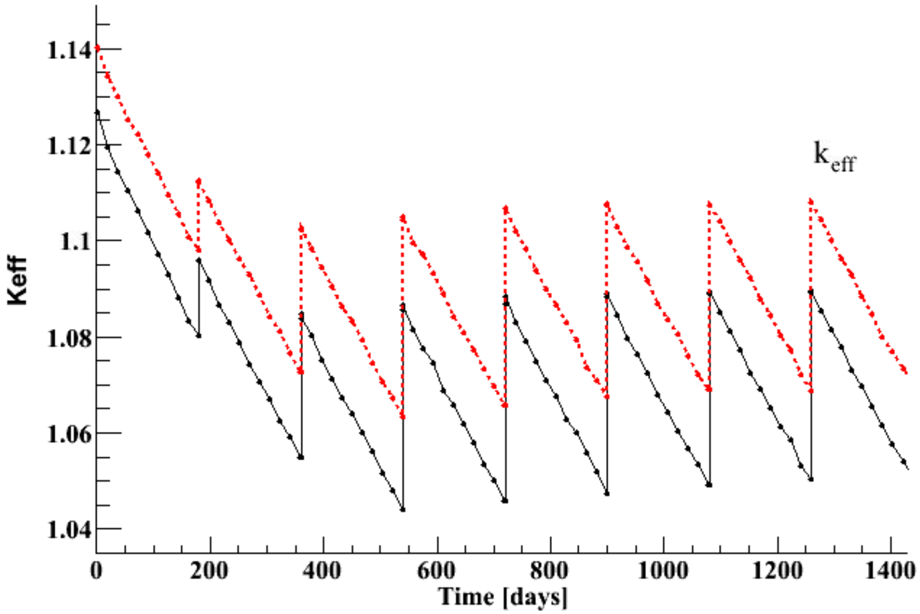
** Y. Kimura, PhD Thesis, Tokyo Institute of Technology (2011)

Isotopic composition of the analyzed cases

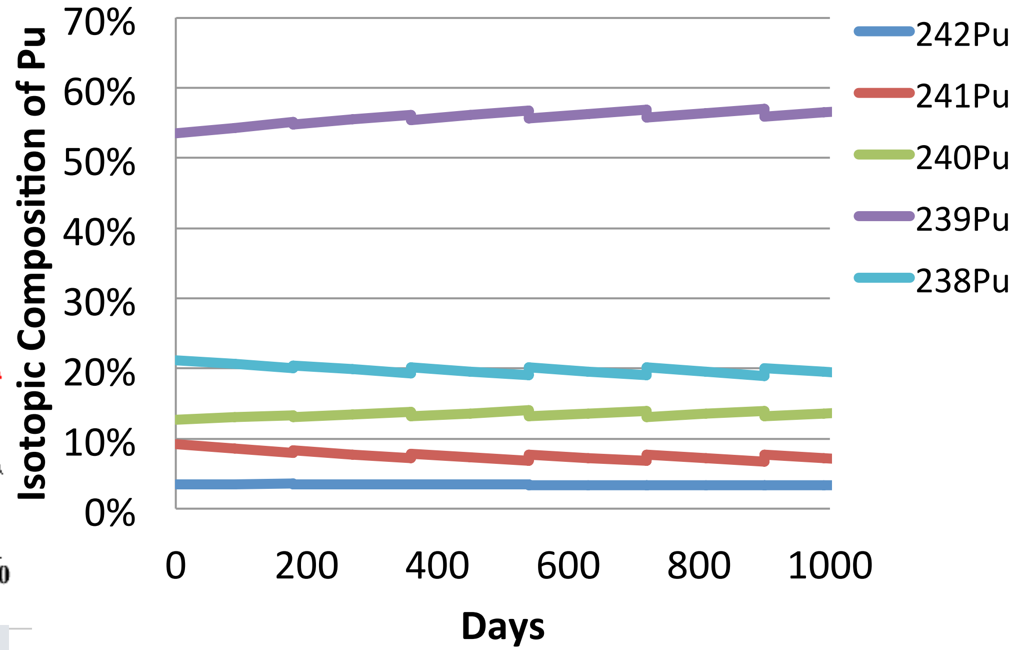
	Isotopic composition of Pu in driver fuel [%]					Isotopic composition in blanket fuel [%]		
	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	U-238	Am-241	Np-237
Case 1	1.9	56.8	22.9	12	6.4	100	0	0
Case 2	21.42	53.3	12.54	9.24	3.49	95	5	0
Case 3						95	0	5

* A. Glaser and M. V. Ramana, Sci. Glob. Sec. 15, 2, 85–105 (2007)

Results



Time evolution of K-eff: in red the FBR is loaded with the normal MOX fuel; in black with P^3 fuel (case 3)



Pu isotopic vector in the core

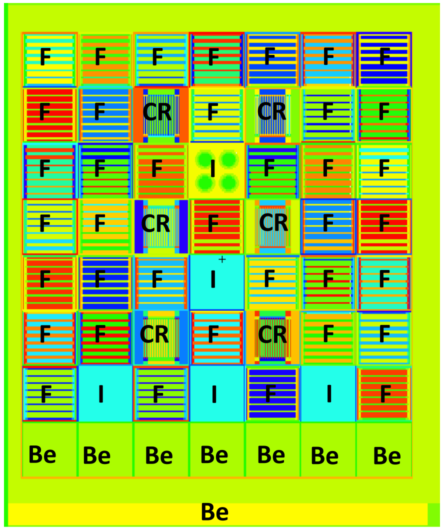
At all the time steps, isotopic composition of Pu-238 is over 15%, which meets the criterion of Kimura et al. It is enough proliferation resistant.

MURE is suitable for the analysis of innovative fuels with high proliferation resistance

Research reactors

3D MURE simulation of the OSIRIS reactor

- **for NUCIFER exp. (EPOSTER 34-10)**



F: Fuel
I: Irradiation cells
CR: Control rods

MURE Simulation of the OSIRIS reactor

- Light-water, open-core pool type, 70 MW, **U_3Si_2Al fuel enriched to 19.75%**

  - - > Fuel inventories as a function of Burnup

  - - > Simulation to propagate gamma from the core behind the concrete walls; detailed understanding of different processes involved, optimization of simulation

MURE sim. under development : BR2 reactor

- **for SOLID exp. (EPOSTER 34-08)**

- MTR-type reactor, 100 MW, **93% w enriched in ^{235}U**

Conclusions & Outlooks

- MURE is a versatile tool, suitable for various reactor designs
- MURE could be useful to study the feasibility of proliferation scenarios
- Application of MURE calculation (such as gamma-ray emission from spent fuel using CHARS module) could help finding indicators of a misuse or a diversion

⇒ Goal = help defining future safeguards approaches for new generation of reactors

Thank you!