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Development of a MOX equivalence Python code package for ANICCA

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Introduction

Decision for spent UOX fuel reprocessing strategy

- Situation = decision for spent UOX fuel reprocessing is taken after long period of once through operating mode:
  - Reprocessing strategy for spent UOX fuel will be defining parameter in evolution of spent fuel inventory: **FIFO (First In, First Out)** or **LIFO (Last In, First Out)**?
  - Identify possible need for interim storage buildings and associated capacity dimensioning
  - Analysis may become very complex as difference in origin (different PWRs) of spent fuel, irradiation history (burnup), and cooling time all introduce additional **dispersion to Pu vector**
- Scope = extend ANICCA (Advanced Nuclear Inventory Cycle Code), a fuel cycle analysis tool developed at SCK CEN (Belgium), with MOX equivalence Python code package:
  - **Determine reactivity evolution for any given Pu vector** by means of multidimensional interpolation on mesh of pre-calculated data tables generated by WIMS10, thereby covering physically accessible Pu vector space
  - **Perform online calculation of Pu content requirements** in MOX fuel fabrication for a given fuel cycle scenario to obtain energy equivalence

Introduction

Impact of reprocessing strategy on front-end of fuel cycle

- Neutronics:
  - During storage: ^{241}Pu decays into ^{241}Am
  - Reprocessing: ^{241}Am is eliminated
  - After reprocessing: new ^{241}Am accumulation

  ^{241}Am, ^{240}Pu and ^{242}Pu are neutron absorbers
- Storage and fabrication:
  - Residual heat: ^{238}Pu + ^{241}Am
- Radiation protection:
  - ^{240}Pu, ^{242}Pu = spontaneous fission
  - ^{238}Pu, ^{241}Am (α, n) on ^{17}O & ^{18}O
  - (weak γ by ^{241}Am)

Equivalence capabilities

Source term

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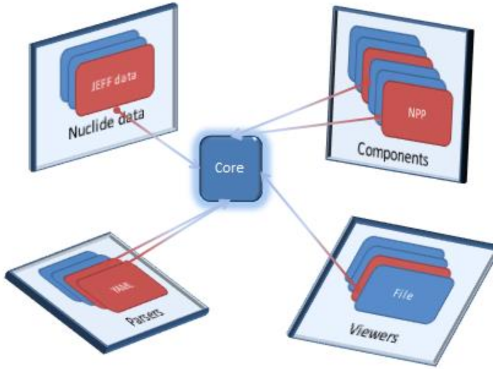
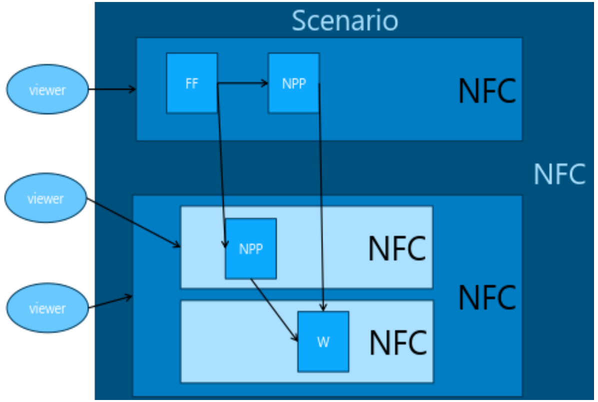
Tools and methods

ANICCA – Advanced Nuclear Inventory Cycle Code: ANICCA

- ANICCA = Advanced Nuclear Inventory Cycle Code: ANICCA
- Fuel cycle analysis tool to monitor flow of nuclear material between facilities
- Python code developed at SCK CEN (Belgium)
- Flexible/modular code allowing for easy modification of scenarios but also for further code development
- Mid- and long-term cycle calculations:
    - Nuclear power plant fleet management
    - Waste characterization
    - Reprocessing of spent fuel
    - …





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Tools and methods

Directive Pu vector mesh generation

- **Dispersion of average Pu isotopy** of MOX batch is mainly due to following (physical) processes:
  - Fuel assemblies with different burnups, enrichments and design (e.g., 8, 12 and 14 ft assemblies)
  - Radioactive decay due to cooling time of fuel assembly
  - Radioactive decay due to delay between reprocessing and loading of fuel in core
- Need to go beyond simplified equivalence model (with fixed weighting factors) depends on **in-core fuel management specificities** (cycle length, feed size, etc.):
  - Neutronic calculations required for every modification to re-determine weighting factors
  - Not very flexible for use in realistic (variable or perturbed) fuel cycle scenarios in ANICCA

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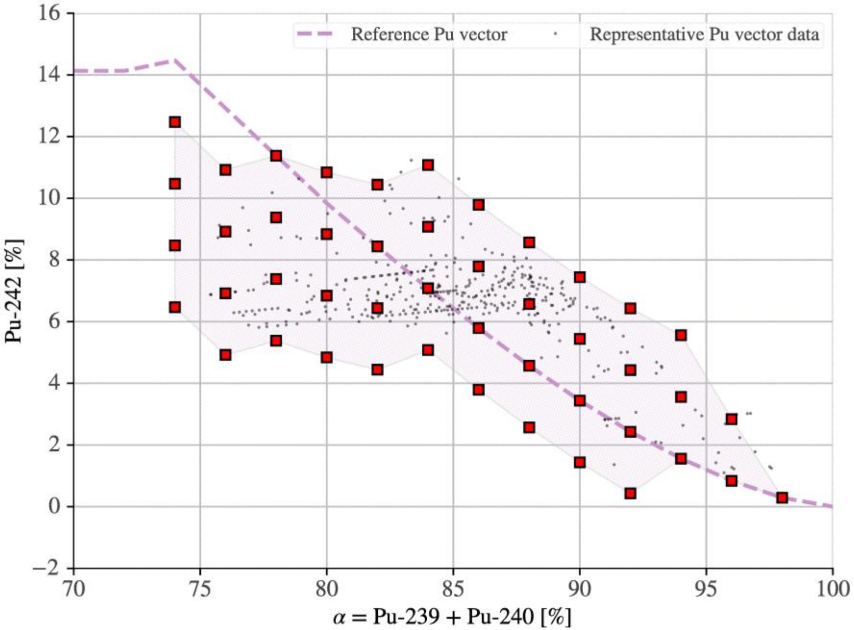
Tools and methods

Directive Pu vector mesh generation

- Build a multi-dimensional reactivity mesh for all realistically achievable:
  - Pu vectors (^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am)
  - Discharge burnups (0 – 64 GWd/tU)
  - Pu fractions (6% – 8% – 10% – 12%)
- Based on empirical correlations:
  - Typical reference Pu vector as starting point: 21 yrs cooling time + 1 yr between reprocessing and core loading + α between [70%-100%]
  - perturbations based on realistic Pu vector data
- ~3000 WIMS10 calculations (■) to cover physically accessible Pu vector space and Pu fractions per assembly



α is inversely proportional to assembly burnup

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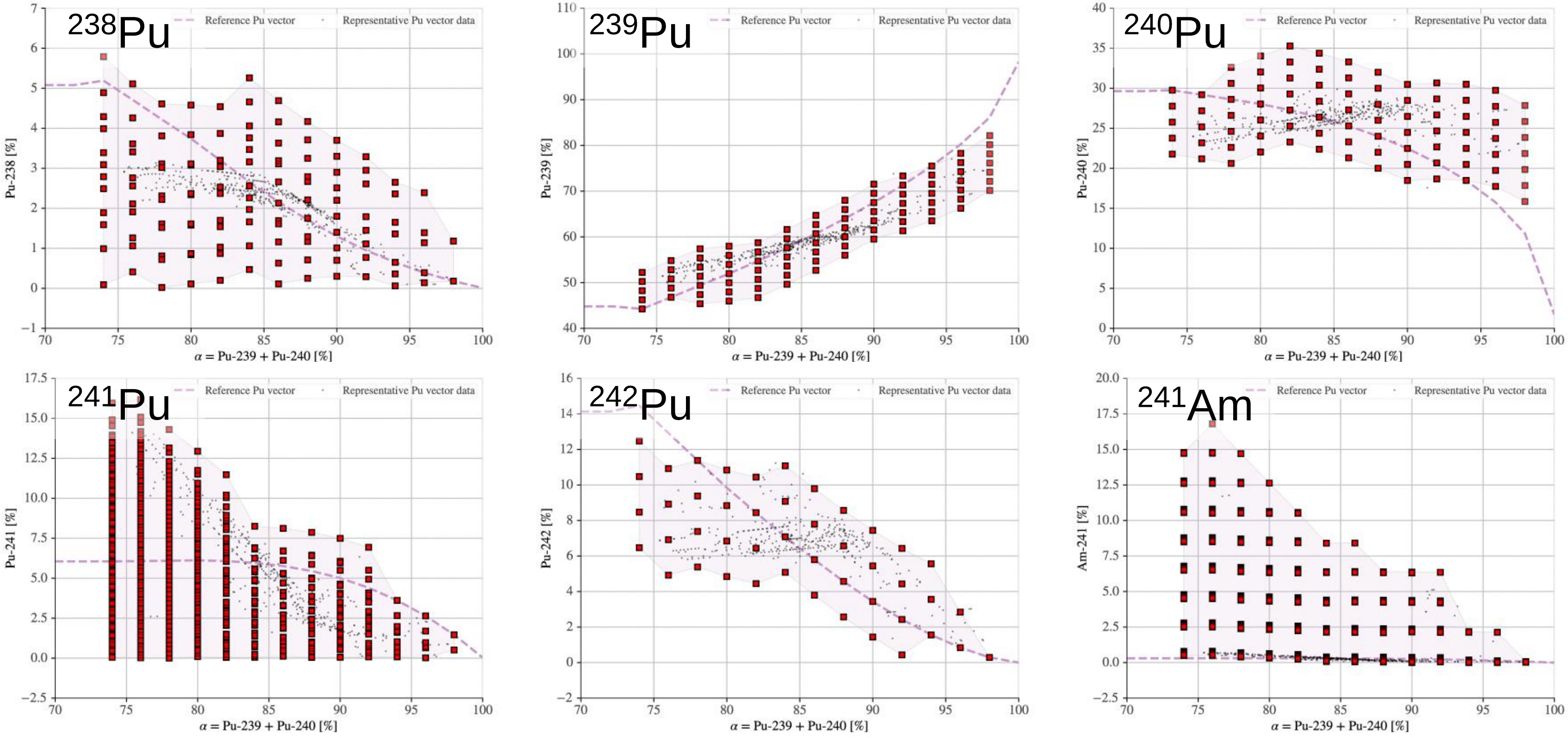
Tools and methods

Directive Pu vector mesh generation



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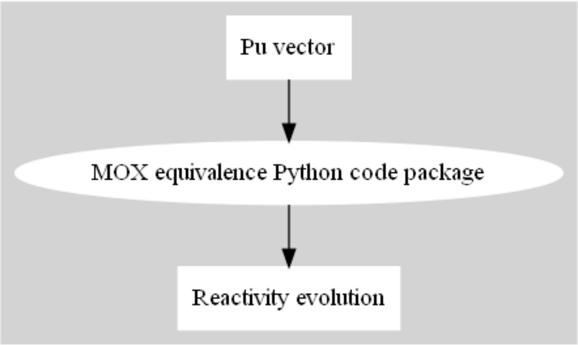
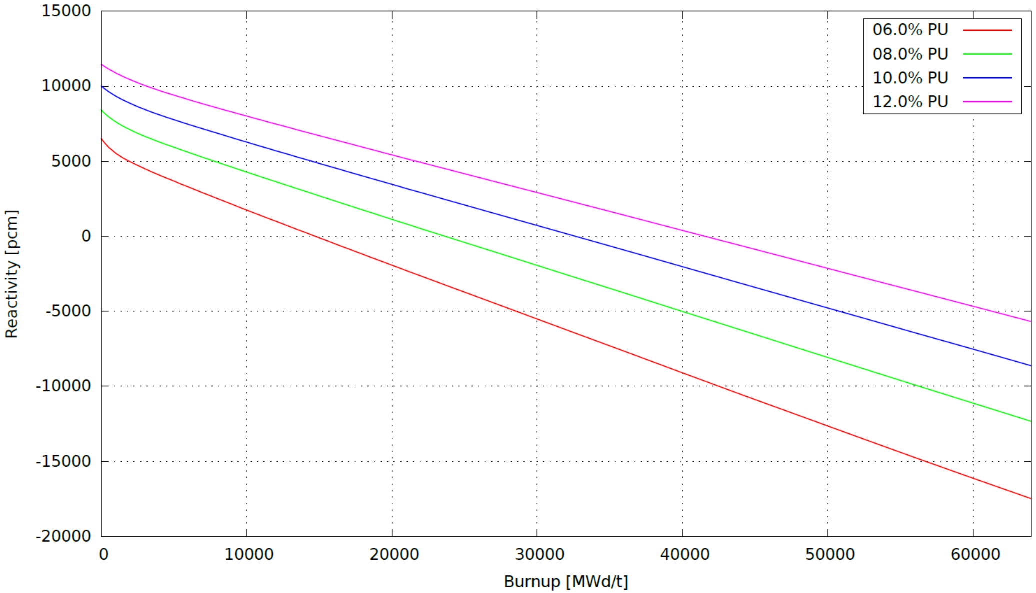
Tools and methods

Directive Pu vector mesh generation

- **MOX equivalence Python code package for ANICCA:** returns reactivity evolution for any given Pu vector covering Pu fractions (6% – 8% – 10% – 12%) and discharge burnups (0 – 64 GWd/tU) by means of interpolation on this directive Pu vector mesh





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Tools and methods

Linear Reactivity Model & MOX energy equivalence principle

- Linear Reactivity Model (LRM) = bi-linear equation providing reactivity (ρ) as function of burnup (BU) and U5 enrichment / Pu content (ε) with 4 calibrated parameters:

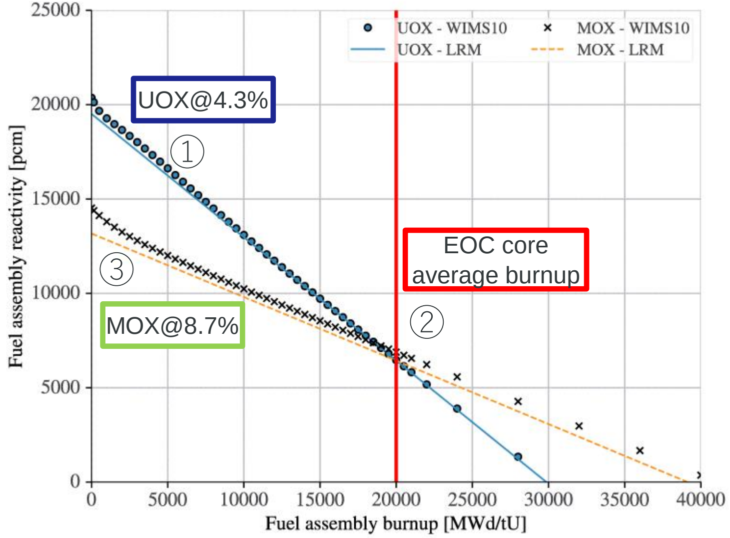
$$\rho = \rho_0 + BB * BU + BE * \varepsilon + BEB * \varepsilon * BU$$

- Determine required Pu content for given Pu vector and in-core fuel management requirements:

① Reactivity evolution of UOX given by Linear Reactivity Model (LRM):
reactivity UOX@EOC = f(EOC burnup, initial U235 enrichment)

② Request equivalence of MOX with UOX fuel at EOC core average burnup:
reactivity curves need to cross over at average EOC core burnup

③ Inverse operation on directive Pu vector reactivity mesh:
Pu content = f(reactivity UOX@EOC, EOC burnup, Pu vector)



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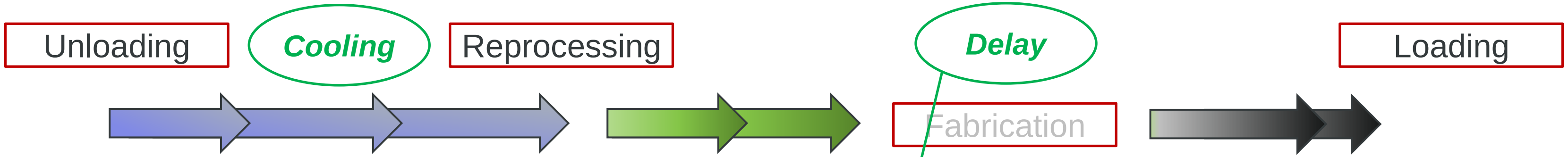
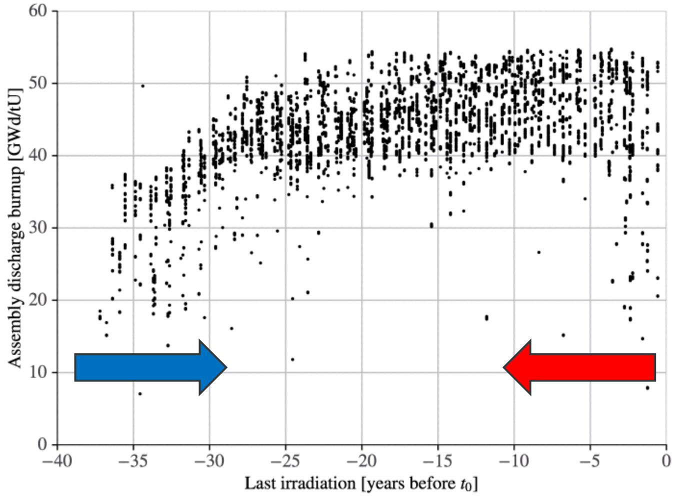
Case study

Fuel reprocessing of representative irradiated fuel stock



- Illustrative application based on representative and realistic spent fuel stock:
  - Huge dispersion in burnups, enrichments and cooling times
  - Trend to increase burnup in more recently unloaded assemblies
- Comparison of 4 scenarios (with 1.5 or 12 yrs delay):
  - **FIFO = First In, First Out, or "Cold first": oldest assemblies are reprocessed first**
  - **LIFO = Last In, First Out, or "Hot first": newest assemblies are reprocessed first**



Cooling time from unloading to t_0 = assumed first reprocessing

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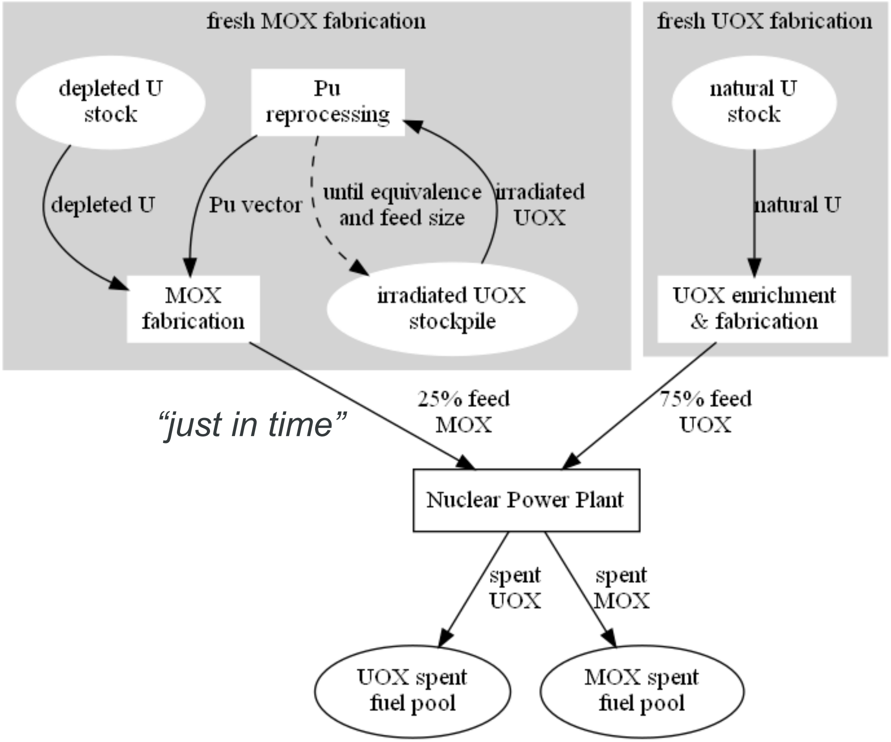
Case study

Fuel reprocessing of representative irradiated fuel stock



* accounting for reduced ^{235}U support enrichment in burnable poison rods

Equivalence target in following ICFM:

Reactor power	3 GWth
Cycle length	18 months
Capacity factor	93%
Core heavy metal mass	84.7 tHM
Fresh feed size	64 FAs
Number of fuel batches	3
Average assembly discharge burnup	44.1 GWd/tHM
UOX enrichment*	4.3 $\%^{235}U$
MOX support enrichment	0.25 $\%^{235}U$
MOX/UOX ratio	1/4

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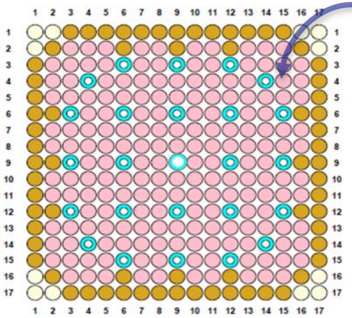
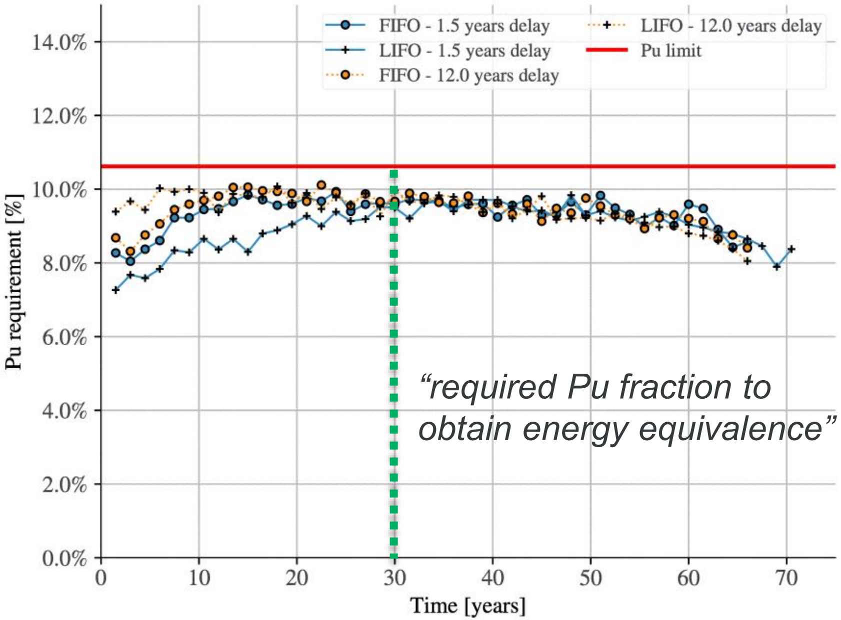
Case study

Fuel reprocessing of representative irradiated fuel stock

- Industrial MELOX process limited to <12% Pu max, or <10.6% average when accounting for radial zoning



- FIFO: almost not sensitive to delay
- LIFO: reduced Pu requirements if MOX fuel is loaded shortly after Pu reprocessing



t_0 = assumed first reprocessing, then every 1.5 yrs 16 MOX assemblies are fabricated from irradiated fuel stock (=1/4 of feed size)

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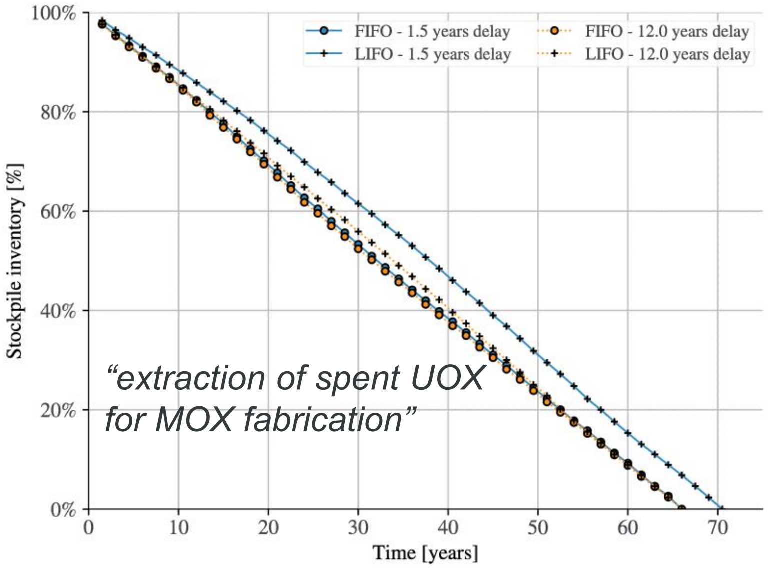
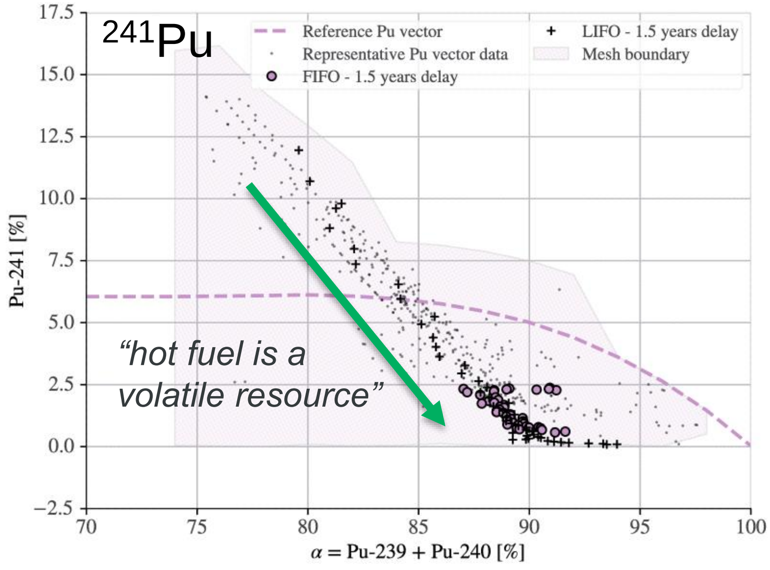
Case study

Fuel reprocessing of representative irradiated fuel stock

- LIFO (1.5 yrs delay): less demands on reprocessing effort because less spent UOX fuel needed for MOX fabrication, but slows down emptying of existing spent fuel stockpile
- FIFO (1.5 yrs delay) + FIFO/LIFO (12 yrs delay) are rather similar





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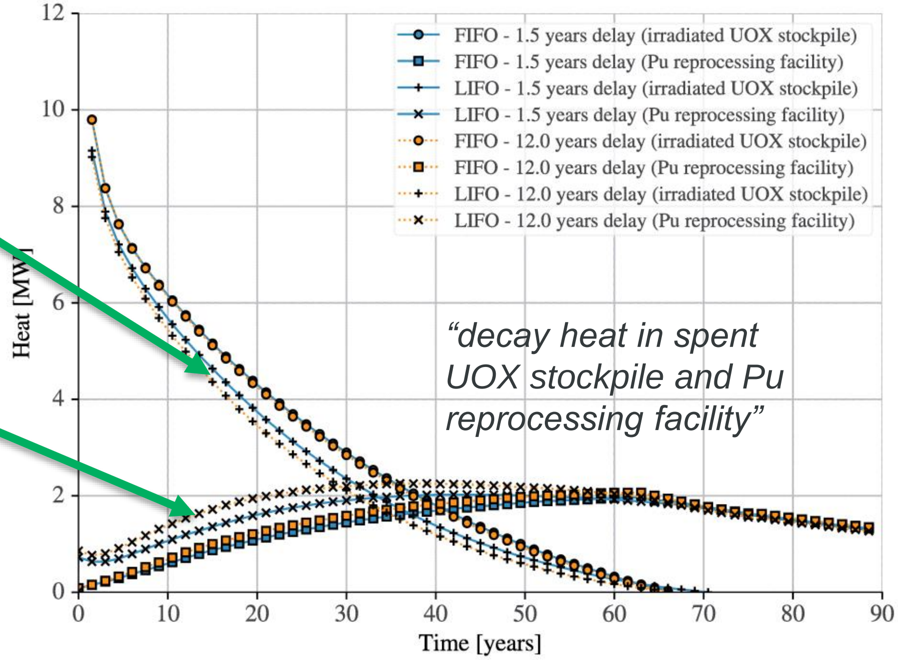
Case study

Fuel reprocessing of representative irradiated fuel stock

- LIFO strategies are more beneficial in terms of heat load removal even though stockpile inventory remains higher than FIFO at all times

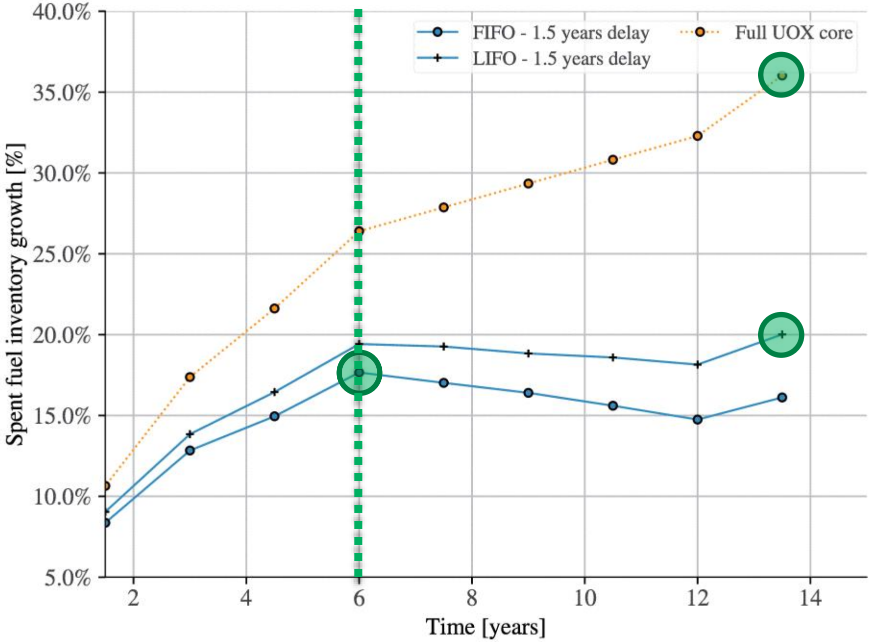
- Possible impact on radiation protection in Pu reprocessing facility: LIFO strategies result in higher heat load and radiotoxicity of vitrified waste



Case study

Fuel reprocessing of representative irradiated fuel stock

- Scenario analysis for capacity dimensioning of interim spent fuel storage buildings:
  - Gradual phase-out of all but two PWRs between t_0 and t_0 + 6 years
  - One remaining PWR continues UOX operation until t_0 + 13.5 years
  - Other remaining PWR switches at t_0 to:
    - ¼ MOX – FIFO – 1.5 yrs delay (reprocessing → loading)
    - ¼ MOX – LIFO – 1.5 yrs delay (reprocessing → loading)
    - Full UOX core (as before)
- On-site spent fuel inventory growth can be reduced to +18 à 20% instead of +36%!



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Conclusion

- Fuel cycle analysis tool ANICCA (SCK CEN) has been extended with a MOX equivalence Python code package (Tractebel Engie): online calculation of Pu content requirements in MOX fuel fabrication to obtain energy equivalence for different types of in-core fuel management

- Best choice of scenario depends on specific needs:

  - **LIFO = Last In, First Out, or "Hot first":** much less spent UOX to reprocess for same energetic content in MOX fuel = reduced reprocessing effort

  - **FIFO = First In, First Out, or "Cold first":** accelerated emptying of spent fuel pools = reduced storage facility capacity requirements

  - Exercise needs to done for each specific case as results depend on storage constraints, in-core fuel management, equivalence objectives, acceptable MOX fraction, … very attractive to think about and optimise it!

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