FUEL CYCLE STUDIES ON MINOR ACTINIDE BURNING IN GAS COOLED FAST REACTORS

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Introduction

- 2400 MW thermal power design developed by CEA and investigated in the framework of the GoFastR project (funded by EU FP7)
  - C. Poette et al.: Gas Cooled Fast Reactors: Recent Advances and Prospects, FR13 Fast Reactors and Related Fuel Cycles, 4-7 March 2013, Paris, France, Technical Session 1.5, Paper IAEA-CN-199-132
- BME NTI task in the GoFastR project:
  - Assessment of the transmutational capabilities and fuel utilization of the GFR integrated in a symbiotic nuclear energy system of thermal and fast reactors
- Challenges in fuel cycle simulation with MA management
  - Charged isotope vector can vary in a wide range
  - Precise results required on MA composition for the estimation of long-term risks of final disposal
- Description of the one-group cross-sections as functions of the composition is needed
  - Regression on the results of full-core calculations

Mathematical model

- Bateman-equations for 50 isotopes

$$\frac{dN_i}{dt} = \sum_{j \neq i} \left(\sigma_{j \to i} \Phi + \lambda_{j \to i} \right) N_j - \left(\sigma_i \Phi - \lambda_i \right) N_i \longrightarrow \frac{d\overline{\mathbf{N}}}{dt} = \overline{\overline{\mathbf{A}}}_k \overline{\mathbf{N}}$$

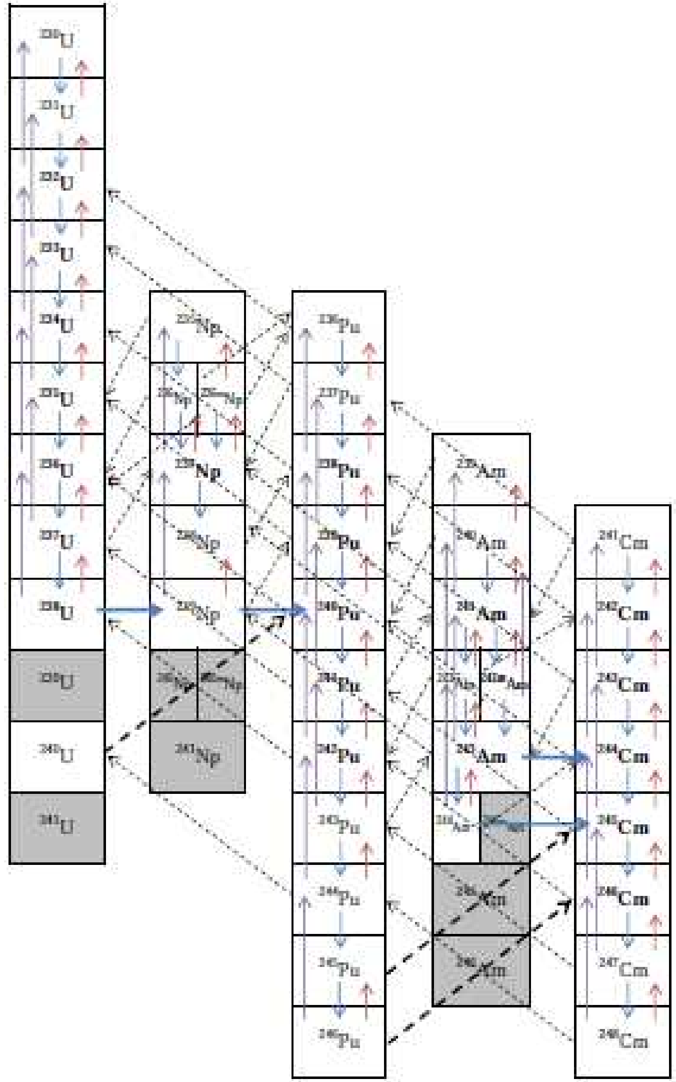
- Fission, (n,γ), (n,2n), (n,3n) reactions considered
- Flux determined from the power:

$$\Phi = \frac{P}{E_f \sum_{i=1}^{n} \sigma_{f,i} N_i}$$

- Recalculation of reaction rates at burnup steps is replaced by the insertion of composition dependent cross-sections:

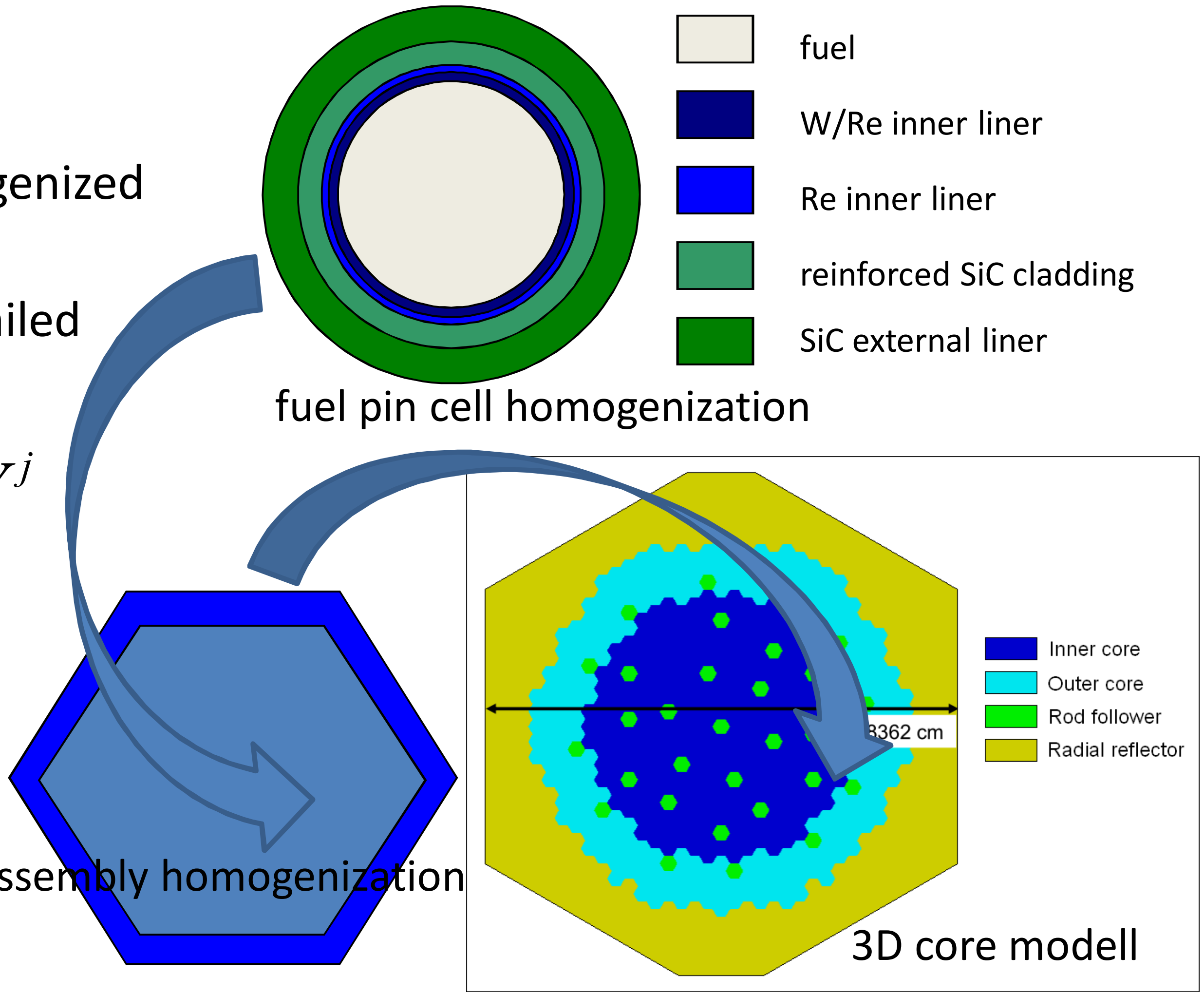
$$\overline{\overline{\mathbf{A}}}_k \rightarrow \overline{\overline{\mathbf{A}}}(\overline{\mathbf{N}})$$

- Modified Bateman-equations solved with the matrix exponential method

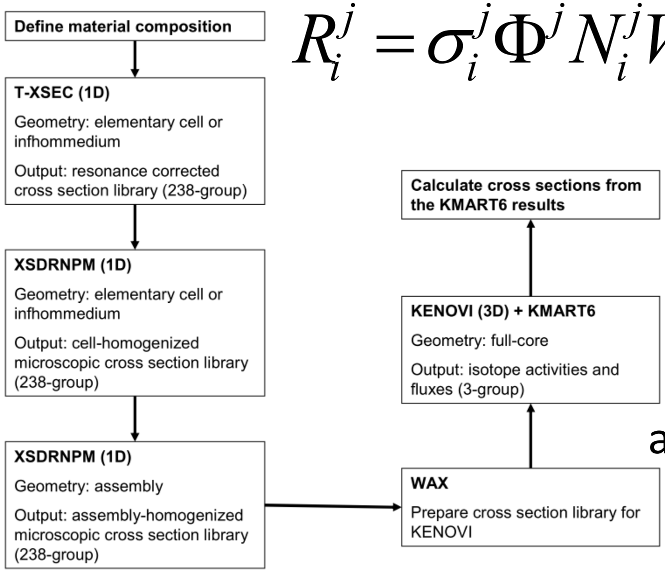


Cross-section calculation in homogenized modell

- SCALE code system
- 2 step homogenization
- 3D core model with homogenized materials
- Good agreement with detailed burnup calculations



$$R_i^j = \sigma_i^j \Phi^j N_i^j V^j$$



Cross-section calculations

- Almost 8000 cross sections sets were prepared with different (random) core compositions
- Material compositions:
  - 14-22 % Pu
  - 0-10 % MA (homogenous loading)
- Reaction rates, fluxes were calculated for inner and outer region of the core
- k_{eff} for each composition
- Flux ratio of the inner and the outer core (F) is needed for the calculation of the full-core homogenized cross-sections

$$\sum_j R_i^j = \overline{\sigma}_i \, \overline{\Phi} \overline{N}_i V_{core}$$

$$\overline{\sigma}_i = \frac{\sum_j R_i^j}{\sum_j \Phi^j N_i^j V^j} \quad \overline{N}_i = \frac{\sum_j \Phi^j N_i^j V^j}{\sum_j \Phi^j V^j} \quad \overline{\Phi} = \frac{\sum_j \Phi^j V^j}{\sum_j V^j}$$

$$F = \frac{\Phi^{in}}{\Phi^{out}} \qquad C_i = \frac{N_i^{in}}{N_i^{in} + N_i^{out}}$$

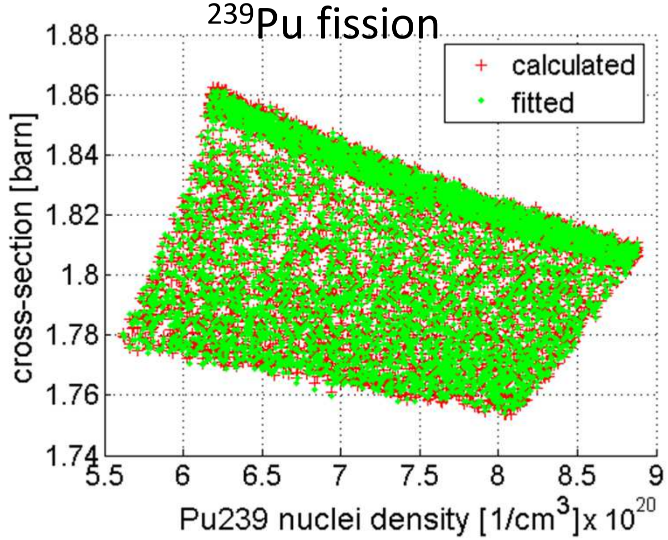
$$\overline{N}_i = \left(N_i^{in} + N_i^{out}\right) \frac{CFV^{in} + CV^{in} - V^{in}}{FV_{in} + V_{out}}$$

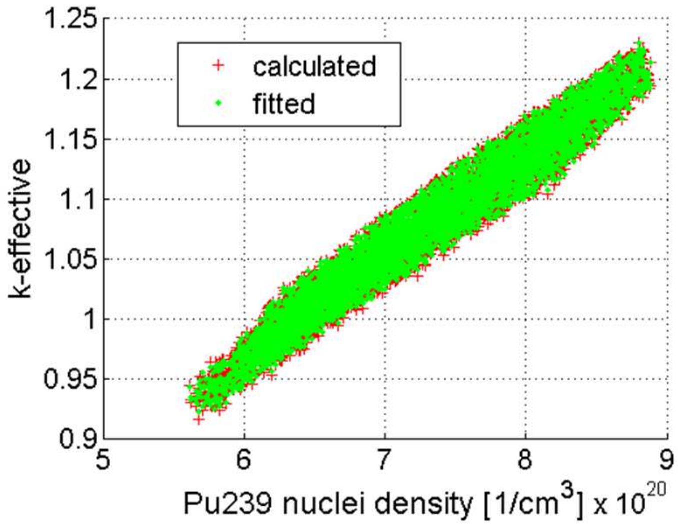
Regression method

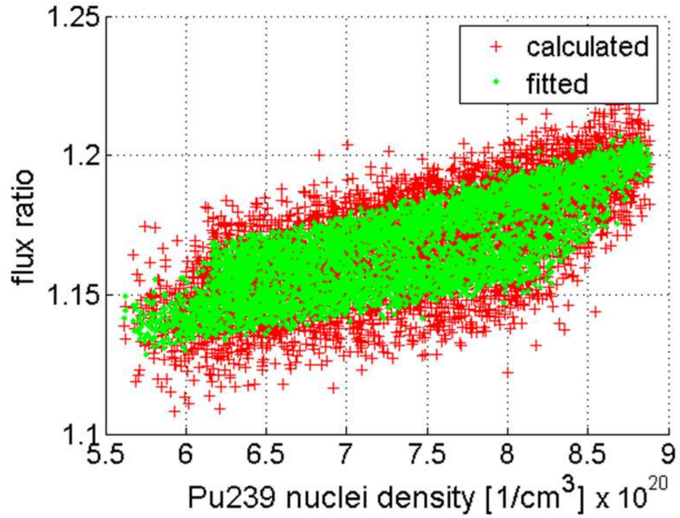
- Second order polinomial fits with the Moore-Penrose pseudo-inverse method:

$$\sigma_i(\overline{N}) = a_0 + \sum_{j=1}^{n} a_j N_j + \sum_{j=1}^{n}\sum_{k=j}^{n} a_{j,k} N_j N_k$$

- Separate fit for cross-sections, flux ratio (F) and k_{eff}

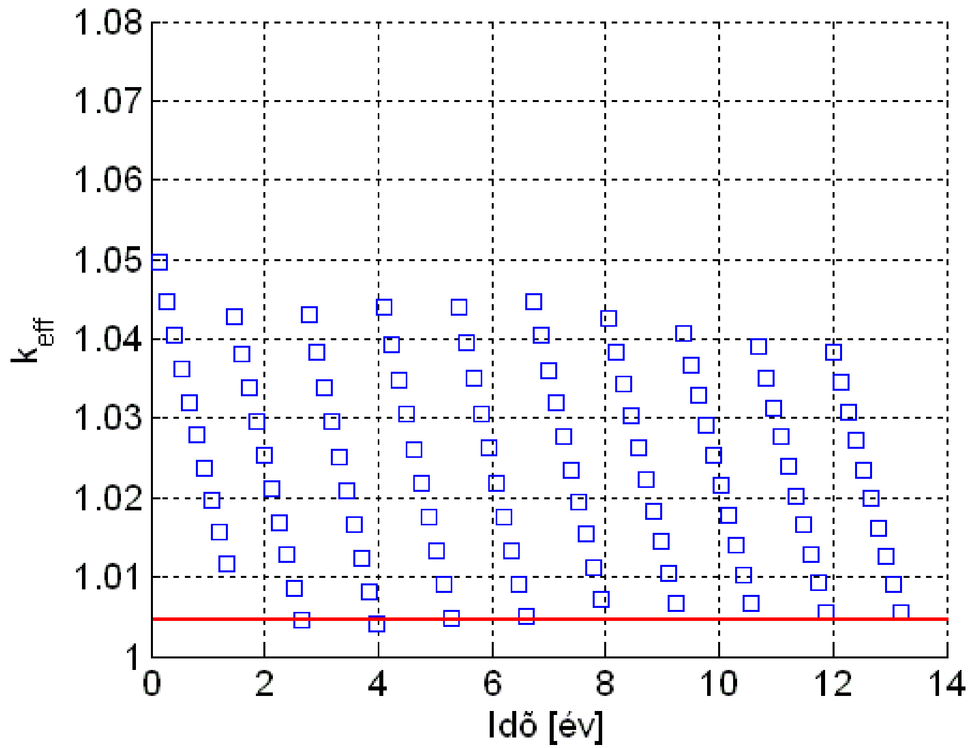






Burnup model

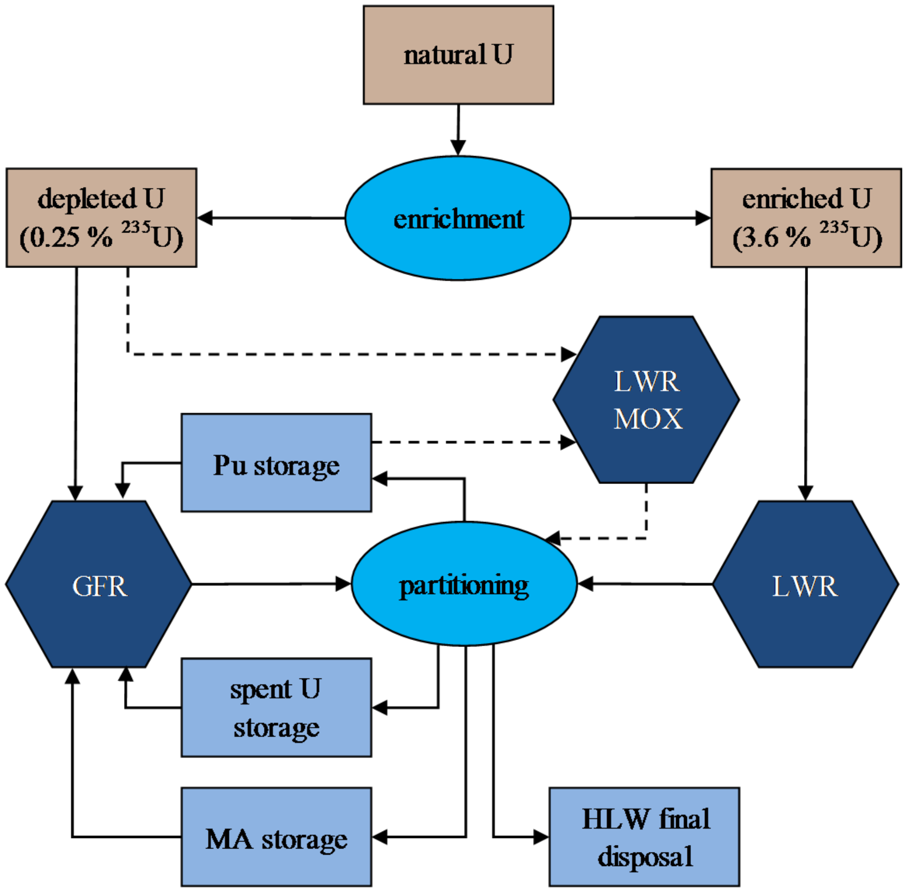
- Fitting of the k_{eff} makes possible to set the BOC k_{eff} with the Pu content



$$k_{eff}^{BOC'} = k_{eff}^{BOC} - k_{eff}^{EOC} + 1.005$$

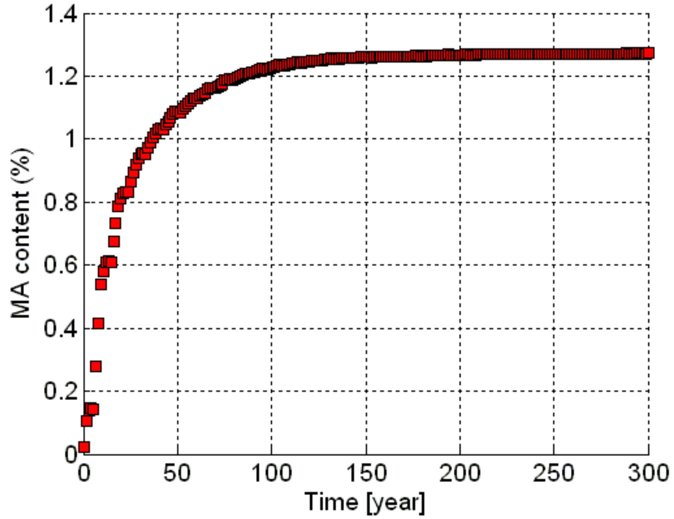
Fuel cycle model

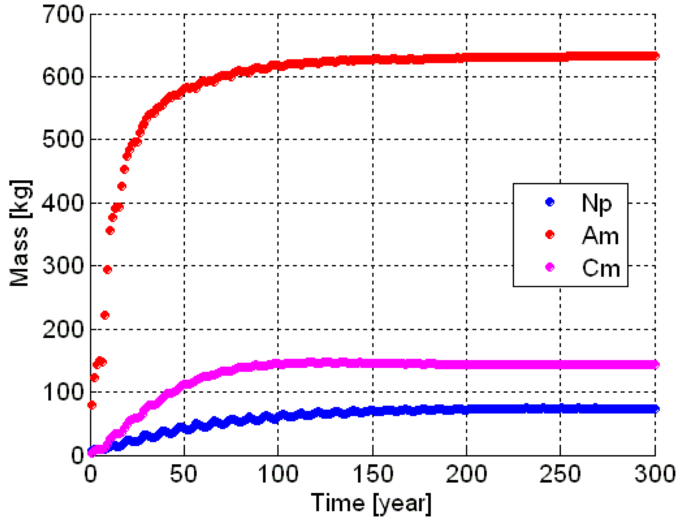
- Simple fuel cycle containing conventional LWRs and GFRs
- Optional Pu recycling from spent LWR fuel to LWR MOX
- Different Pu and MA recycling options investigated:
  - no MA recycling
  - GFR self-recycing
  - constant MA feed into GFR
- Reprocessing losses are not considered
- Simulation focuses on GFR core inventory

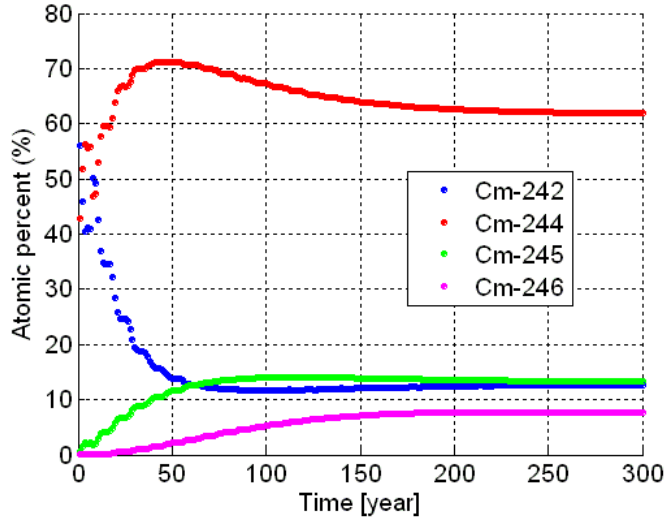


MA GFR self-recycling equilibrium conditions

- MA content in the core stabilizes at ~1.24%
- Am becomes the major component
- Cm isotopic composition stabilizes – no Cm buildup!

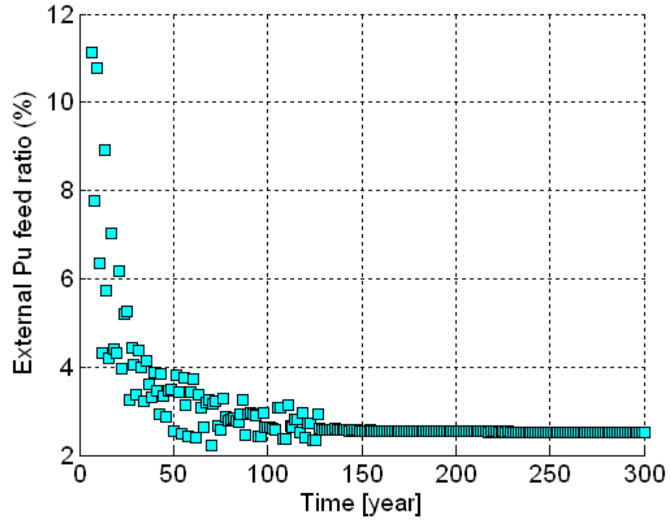


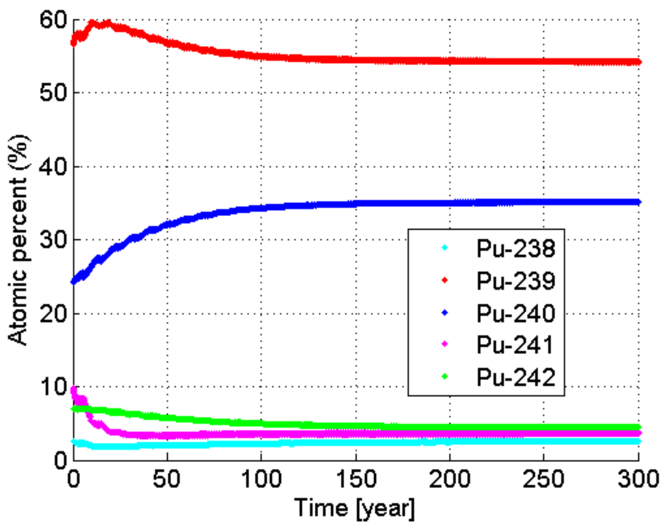


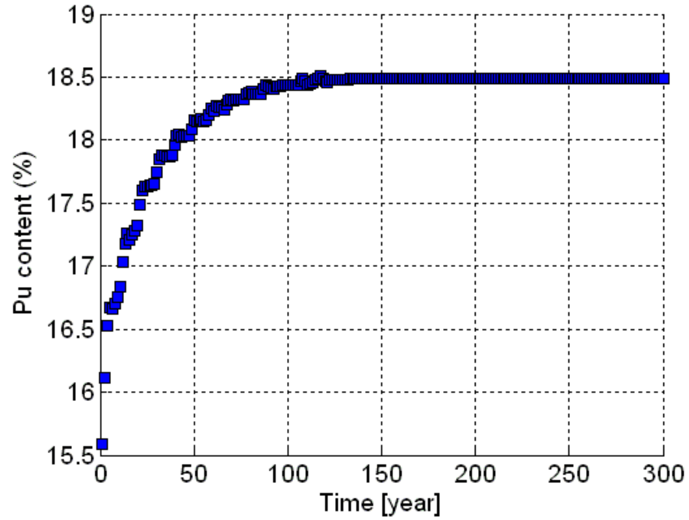


Pu management

- Pu vector deteriorates
  - ^{240}Pu accumulates
- Pu content increases
- External Pu feed decreases to ~2% - close to self-breeding

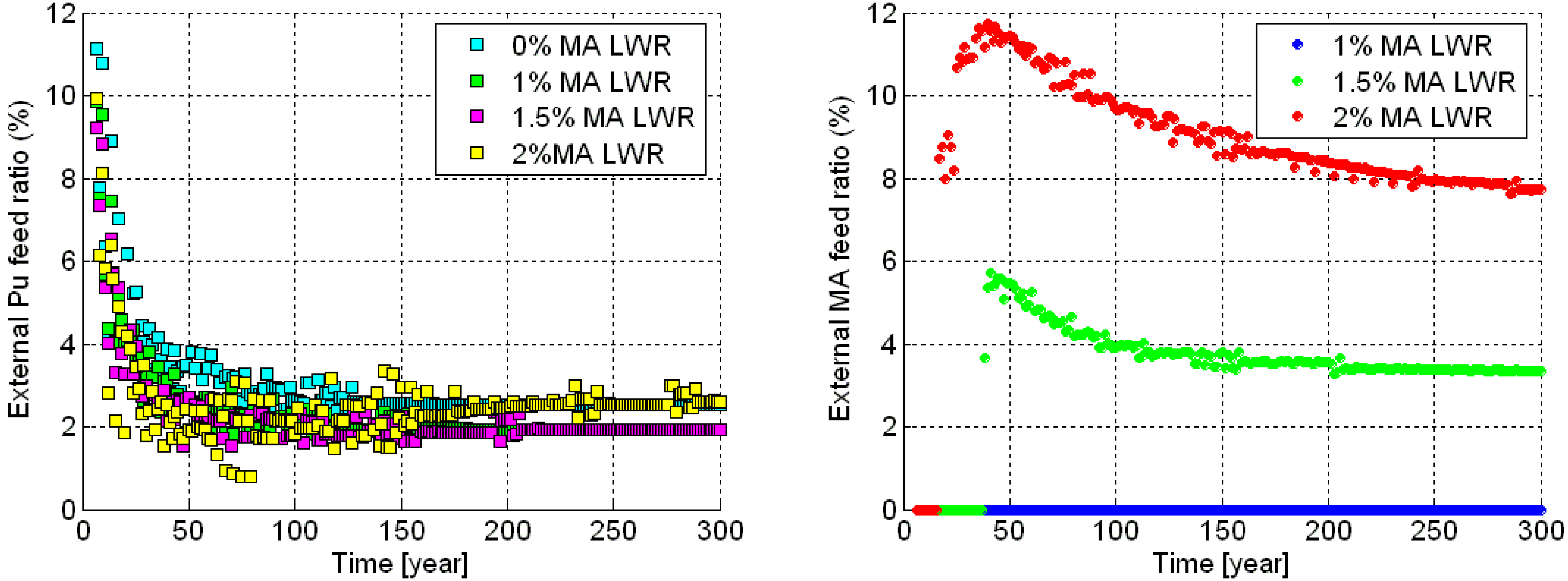






Different MA loading options

- MA load above 1.24 % (1.5 % and 2 %) results in MA consumption
- In the transient period Pu need decreases with increasing MA content



Equilibrium parameters for different MA recycling cases

Case	Fuel utilization (%)	External Pu feed ratio (%)	External MA feed ratio (%)
Pu recycling	1.64	2.53	-
MA self-recycle	2.04	1.88	-
1% MA feed	1.90	1.99	0.00
1.5% MA feed	1.96	1.96	3.26
2% MA feed	1.57	2.58	7.62

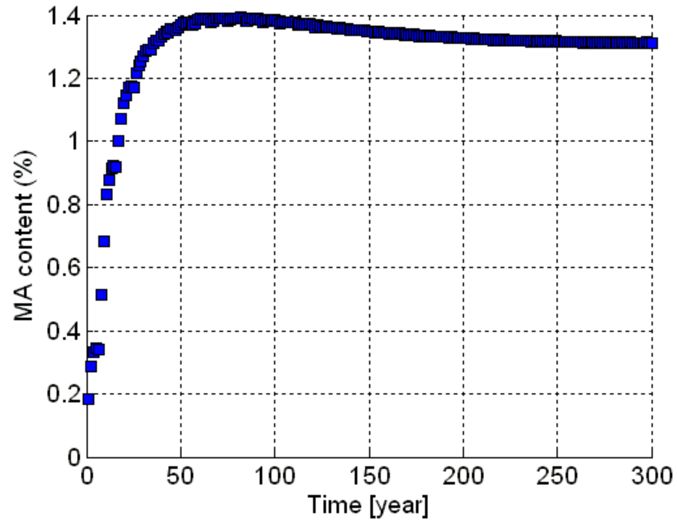
Power plant fleet composition

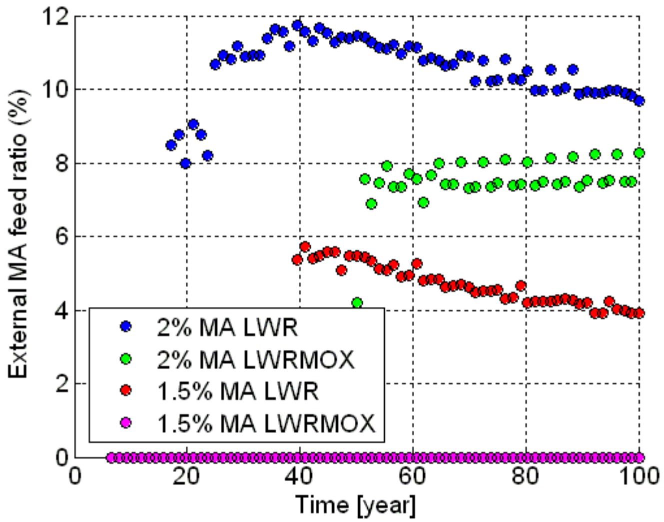
- GFR may burn MA from more LWR then those producing its Pu need (symbiotic cycle)

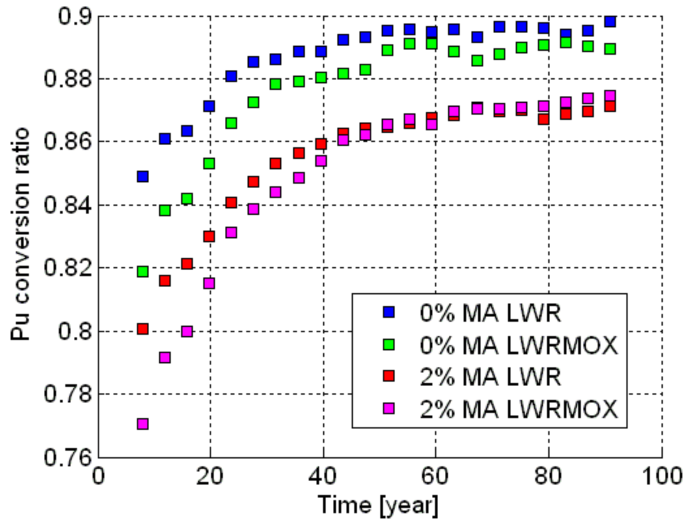
Case	LWR power ratio (%) producing	
	Pu feed	MA feed
Pu recycling	27.10	-
MA self-recycle	21.74	-
1% MA feed	23.37	0.00
1.5% MA feed	22.61	32.25
2% MA feed	28.30	59.73

Effect of LWR MOX loading

- Equilibrium MA content with GFR self-recycling increases
- Amount of consumed MA decreases
- Conversion ratio decreases with increasing MA feed







Conclusions

- Quick and flexible burnup modelling tool was developed based on regression of cross-section as a function of composition
- Further development and validation of the model is needed to improve accuracy
  - Departure from the regression domain needs to be avoided
- The model was used for simulation of fuel cycles including GFR
- GFR is close to self-breeding and can be a net MA burner
- GFR is capable to burn both Pu and MA from an LWR park (symbiotic cycle)
- Pu recycling into LWR MOX slightly deteriorates the performance of the system, since GFR has better potential in Pu utilization