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Towards Analysis of the Bowing Effect on Burnt Nuclear Fuel Compositions Using SERPENT

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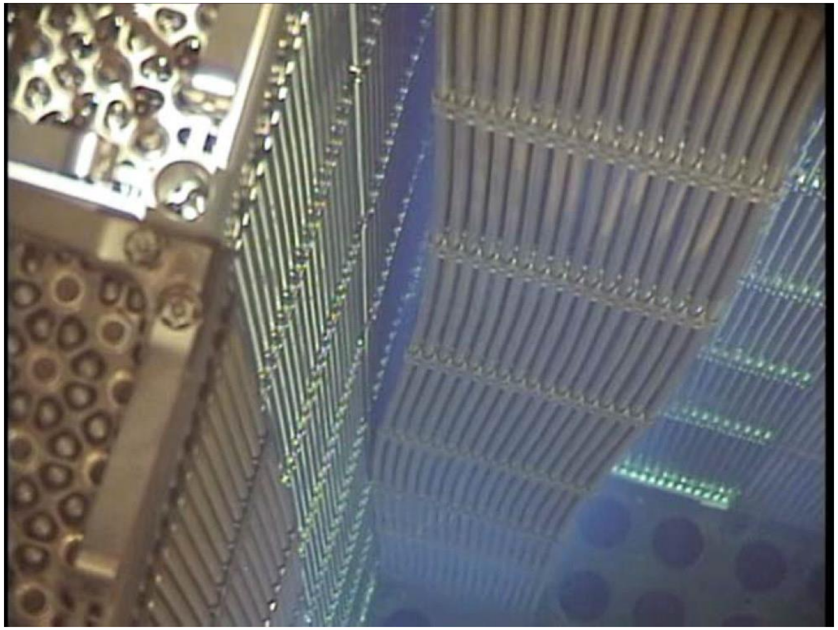
Introduction

- Assembly bow (PWR) and Channel bow (BWR) are widely observed
  - Handling Difficulties
    - Incomplete control rod insertion
    - Axial offset anomaly
  - Fuel / Reactor Simulations
    - Variation on moderation
      - Neutron spectrum
      - Isotopic concentrations
      - Fuel burn-up
  - Computational Biases
    - Not take into account bowing effect
    - Biases between Post Irradiation Examination (PIE) simulations and measurements



Objectives

- Develop a methodology to investigate bowing effects
  - Use SERPENT Monte Carlo Continuous-Energy Depletion Code
  - Subdivide depletion zones for details
  - Compare the difference of isotopic concentrations

- Assess the capability of 3D modelling and SERPENT depletion calculation
  - 3D advanced and complicated modelling
  - Computational resource and time demanding
    - Neutron histories / Model size / Depletion zones
  - Study neutron source convergence

- Approach a preliminary simulation of bowing effects
  - On moderation
  - On isotopic concentrations
  - Against burn-up

- Quantify Numerical Bias for possible safety analyses
  - Optimize computational simulation models

Bow Mechanism

- Axial Compressive forces + Irradiation growth & Creep

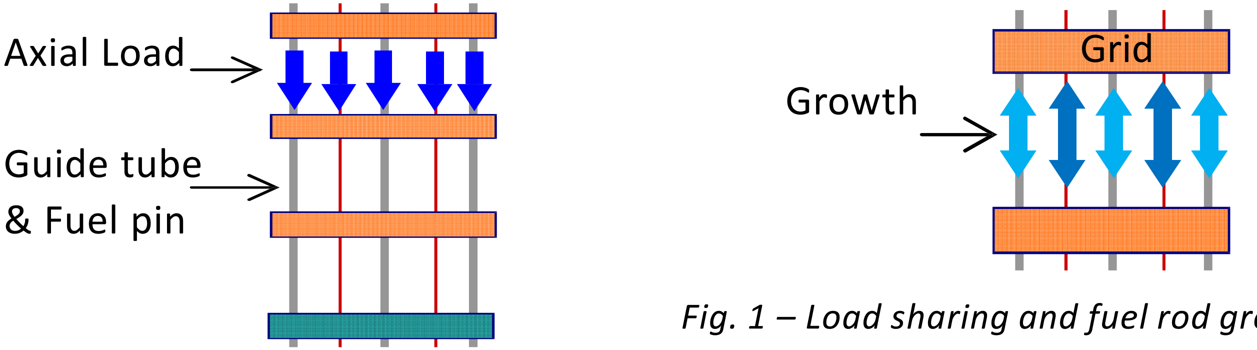


Fig. 1 – Load sharing and fuel rod growth - Ref. [1]

- S – shape and C – shape Assembly bow

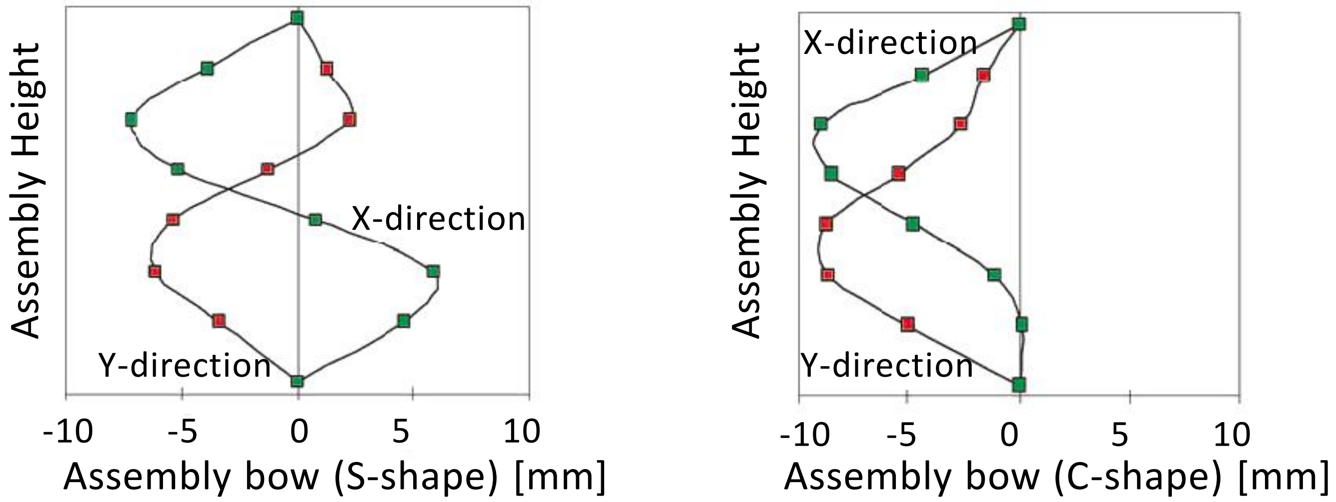


Fig. 2 – S-shape and C-shape assembly bow examples - Ref. [2]

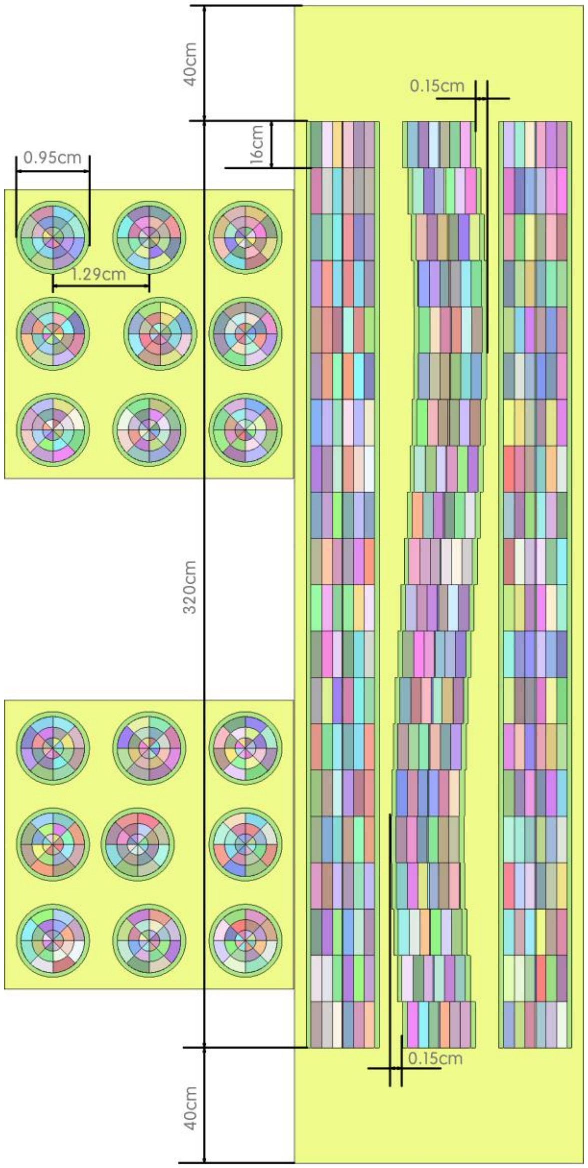
[1]. S. Y. JEON, The Effects of Fuel Design on the Fuel Assembly Bow Characteristics in PWR
[2]. V. INOZEMTSEV, Review of Fuel Failures in Water Cooled Reactors

Methodology and Modelling

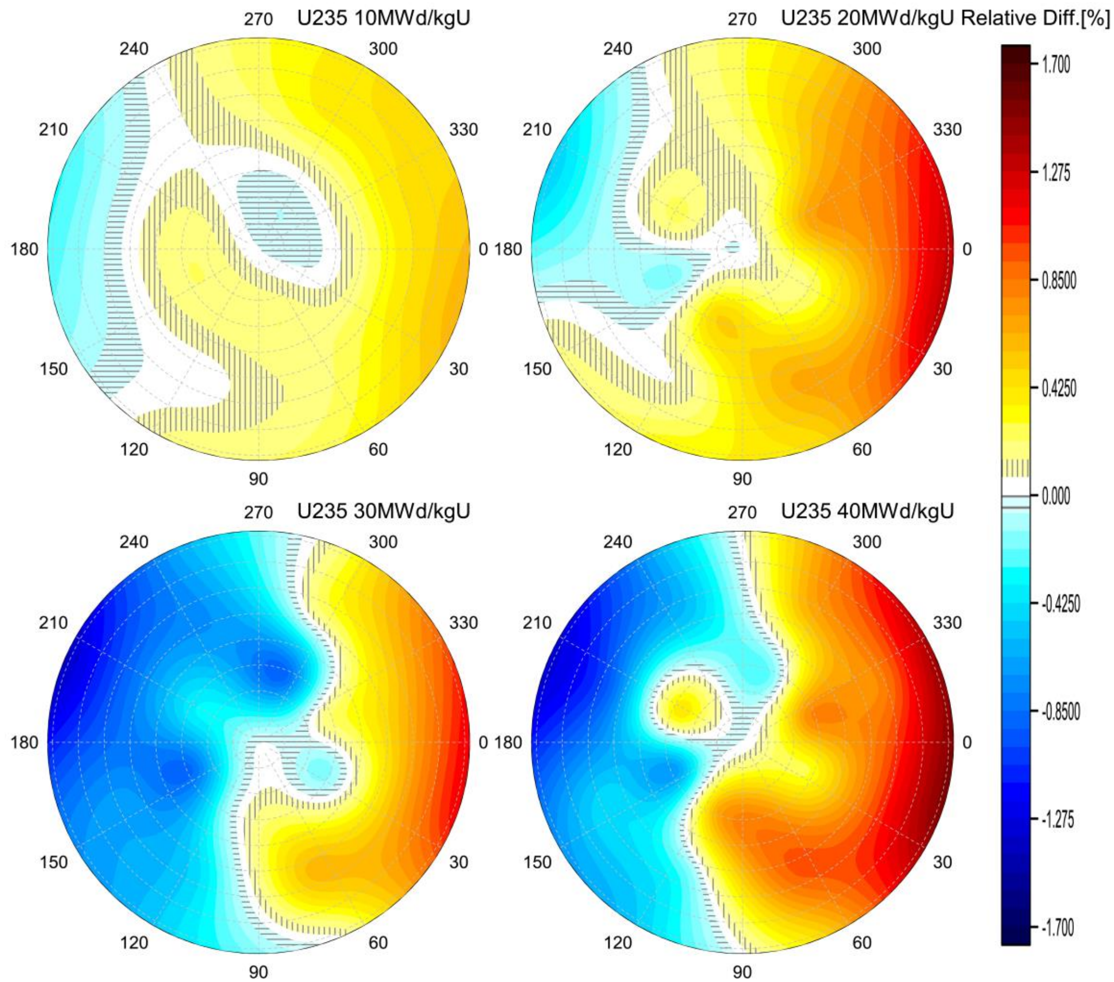
- Modelling 3D Fuel bow
  - Simplified into 3x3 pin lattice
  - Subdivide into 4320 depletion zones [20x3x8x9]
  - Max displacement is 1.5 mm [5th, 16th layers]
  - **Two simulations (Nominal & Deformed)**
  - **Rel. Diff** = $\frac{C_D(i) - CN(i)]}{C_N(i)}$, i = U^{235}, Pu^{239} …

- Operational conditions

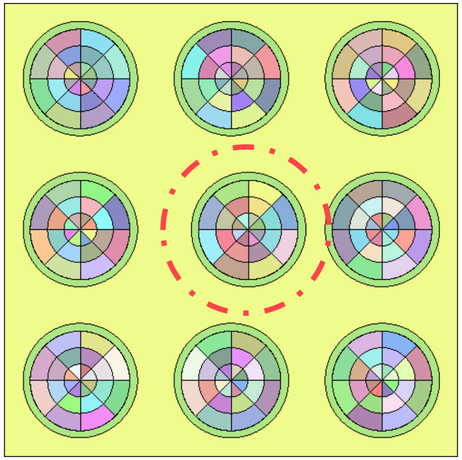
Enrichment	Temperature	Power	Neutrons
5 w/o	900 K (Fuel) 600 K (Water)	0.025 KW/g	**10,000** (per cycle)
Act. Cycles	**Inact. Cycles**	**Burn-up step**	
250	**25**	0.5 MWd/kgU	



Relative Diff. of Azimuthal U^{235} Concentration



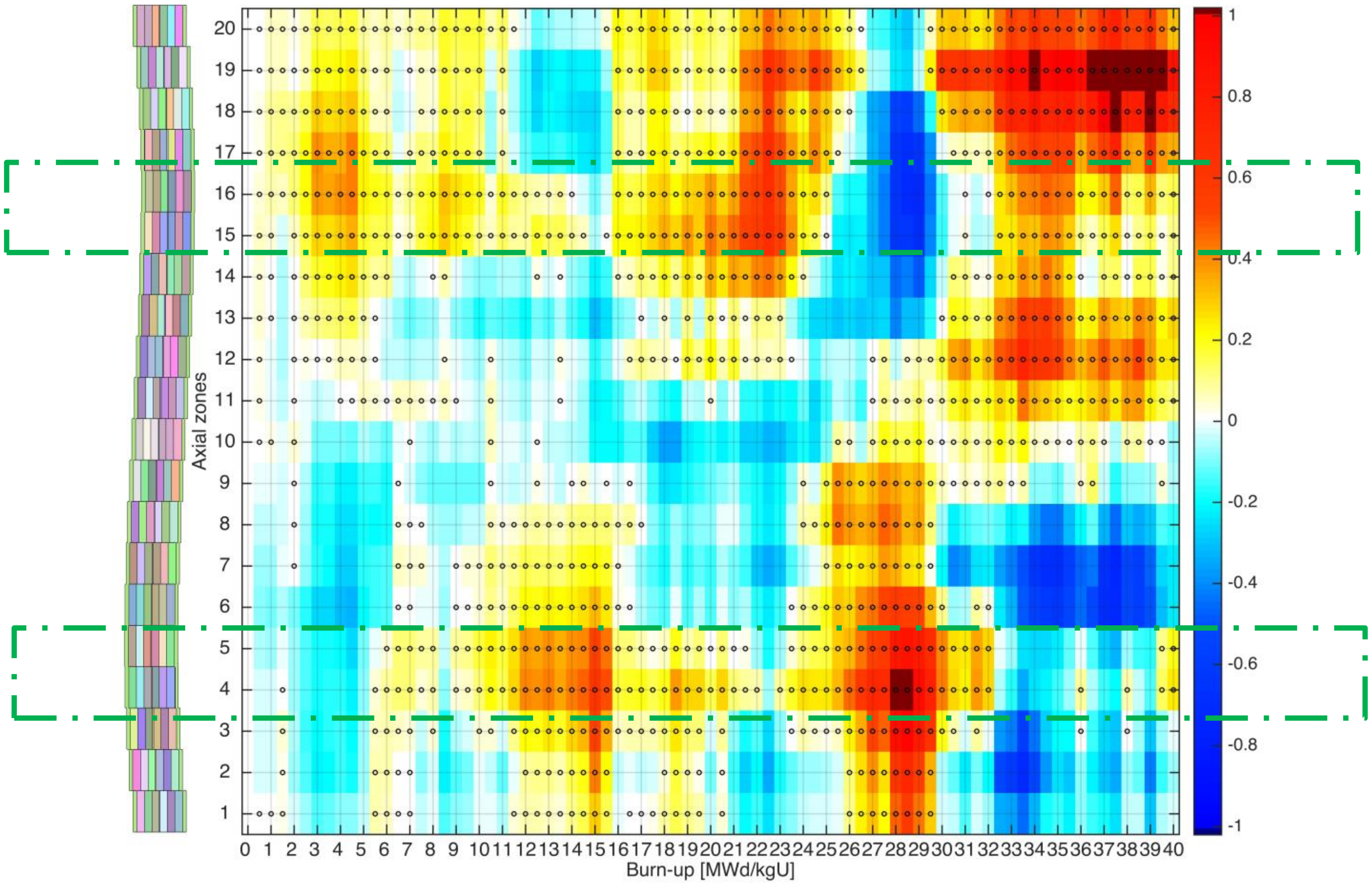
Azimuthal U^{235} Concentration Relative Difference



U^{235} – 16^{th} layer

- **Left side:**
  - Enhance moderation
  - Less U^{235} remains
- **Right Side:**
  - Reduce moderation
  - More U^{235} remains
- **Total Effect:**
  - Cancel out?

Relative Diff. of Axial U235 Concentration



U^{235} Relative Difference vs Burn-up

U^{235} – Full Life (0 – 40 MWd/kgU)

- Positive: 4th, **5th**, 15th, **16th**
- Indication: More U235 remains in bow

Convergence and Asymmetry problems

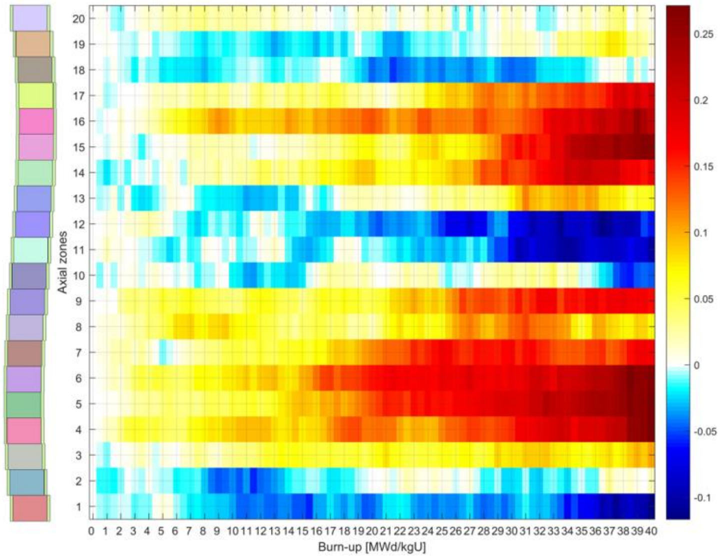
- Asymmetry
  - Symmetric conditions leading to asymmetry results
  - Asymmetry oscillates with burn-up
  - Asymmetry variation amplitude larger than relative differences

- Reasons
  - **Neutron source not converged in the full-size scale model**
  - Axial power perturbation accumulates -> depends on burn-up increment
  - Power uncertainty is larger towards two ends (**1.5%**) than the center (**0.3%**)

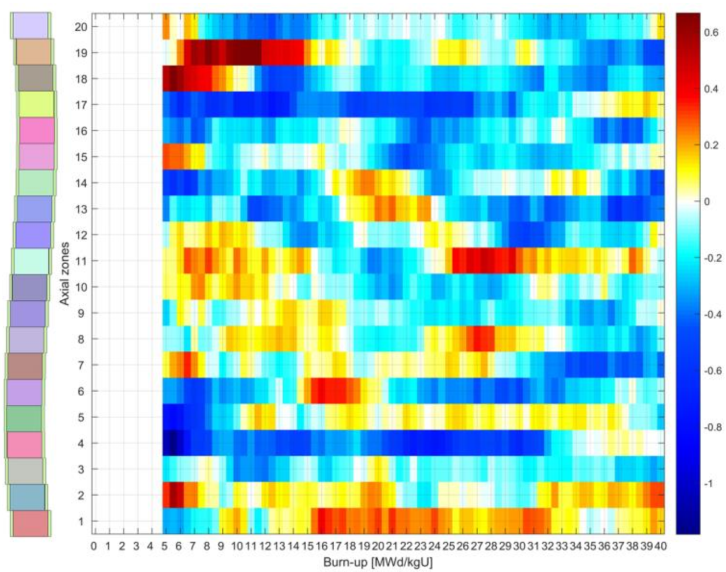
- Solutions
  - Short length fuel model
  - More neutron histories -> limited by computational power
  - Alter S-shape to C-shape (change point symmetry to plane symmetry)

[3]. M. D. DEHART, Three-dimensional depletion analysis of the axial end of a Takahama fuel rod

Solution I: Short Fuel Model

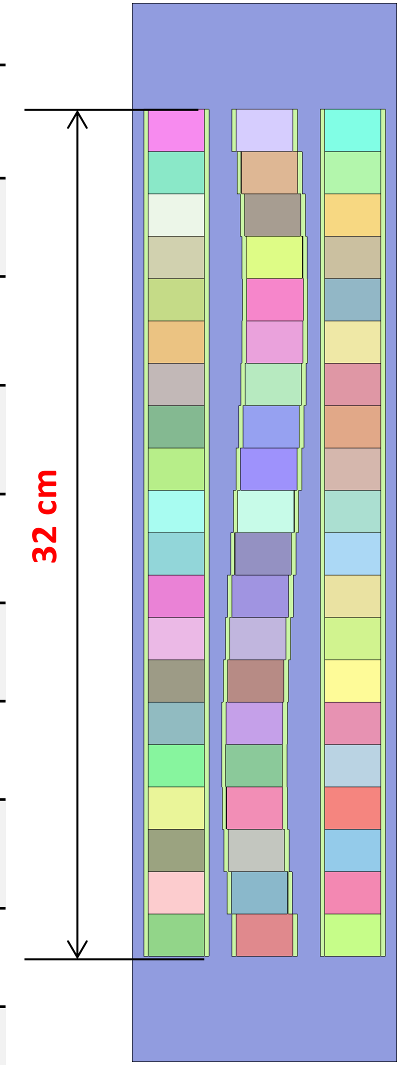


U^{235} Relative Difference vs Burn-up

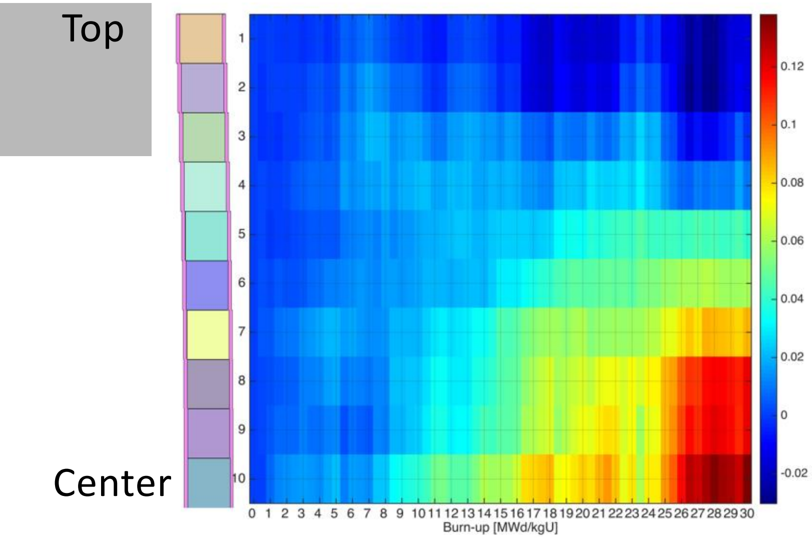


Pu^{239} Relative Difference vs Burn-up

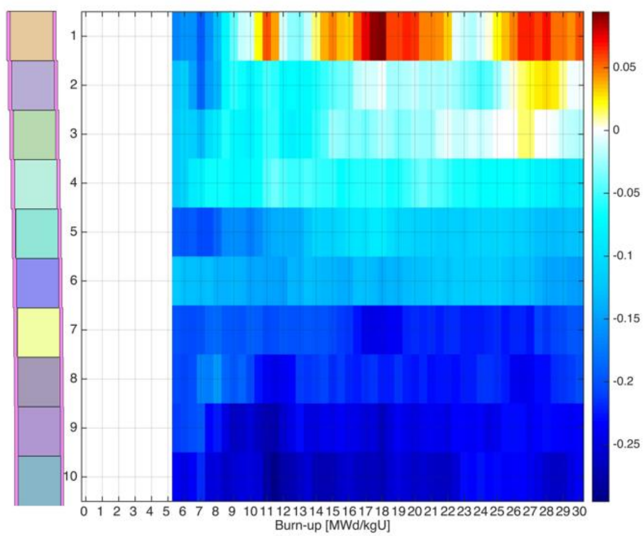
Length	**32cm** (0.1 x real)
Max disp.	0.15mm
Neutron	**10,000** (1x)
Active cycle	**300** (1.2x)
Inact. cycle	**300** (12x)
U^{235} Rel. Diff.	< 0.25%
Pu^{239} Rel. Diff.	> -1%
Burn-up length	40 MWd/kgU 82 steps
Depletion zones	**180** (1/24x)
Calculation Time	**9 hours** (1/5x) **96 cores** (8x)



Solution II: C-shape and Symmetric Model

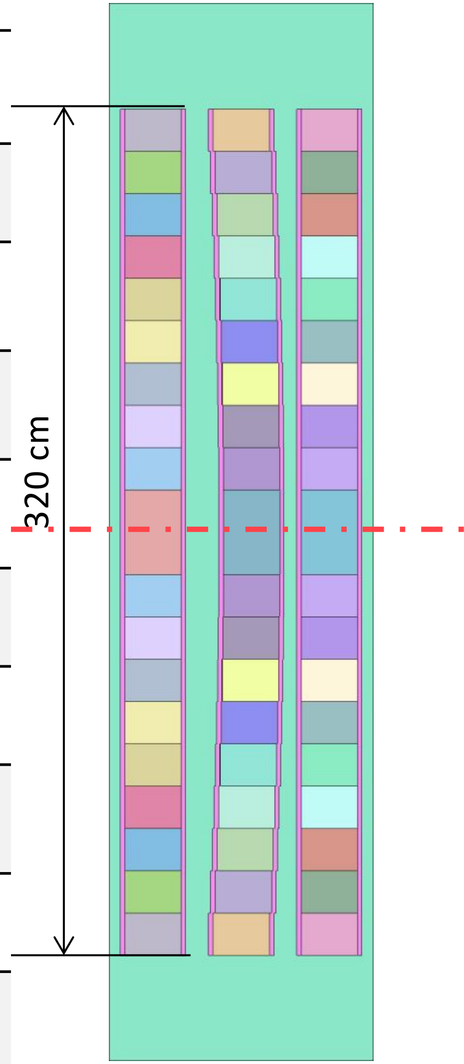


U^{235} Relative Difference vs Burn-up



Pu^{239} Relative Difference vs Burn-up

Length	**320cm** (real)
Max disp.	0.15mm
Neutron	**100,000** (10x)
Active cycle	**1000** (4x)
Inact. cycle	**1000** (40x)
U^{235} Rel. Diff.	< 0.14%
Pu^{239} Rel. Diff.	> -0.27%
Burn-up length	30 MWd/kgU **62 steps**
Depletion zones	**60** (1/72x)
Calculation Time	**50 hours** (1x) **384 cores** (32x)



Uncertainty of Results

- Statistical Uncertainties
  - Each calculated tally is provided with a statistical uncertainty
  - Statistical uncertainty of each transport step is not propagated to burn-up step
  - Thus, no statistical uncertainty of isotopic inventories
  - Possible Solution: **Perform independent simulations with different random seeds**

- Systematic Error
  - Fluxes and reaction rates are considered stationary in each step
  - Uniform isotopic concentration in each depletion zone
  - Non-linear Bateman Equation
    - $N_R = g(\phi_R) \neq E(g(\bar{\phi}))$
    - N_R : Real isotopic concentration
    - $g(\phi_R)$: Bateman Eq. solving with real flux
    - $E(g(\bar{\phi}))$: Expectation of Bateman Eq. solving with Estimated flux

Conclusion

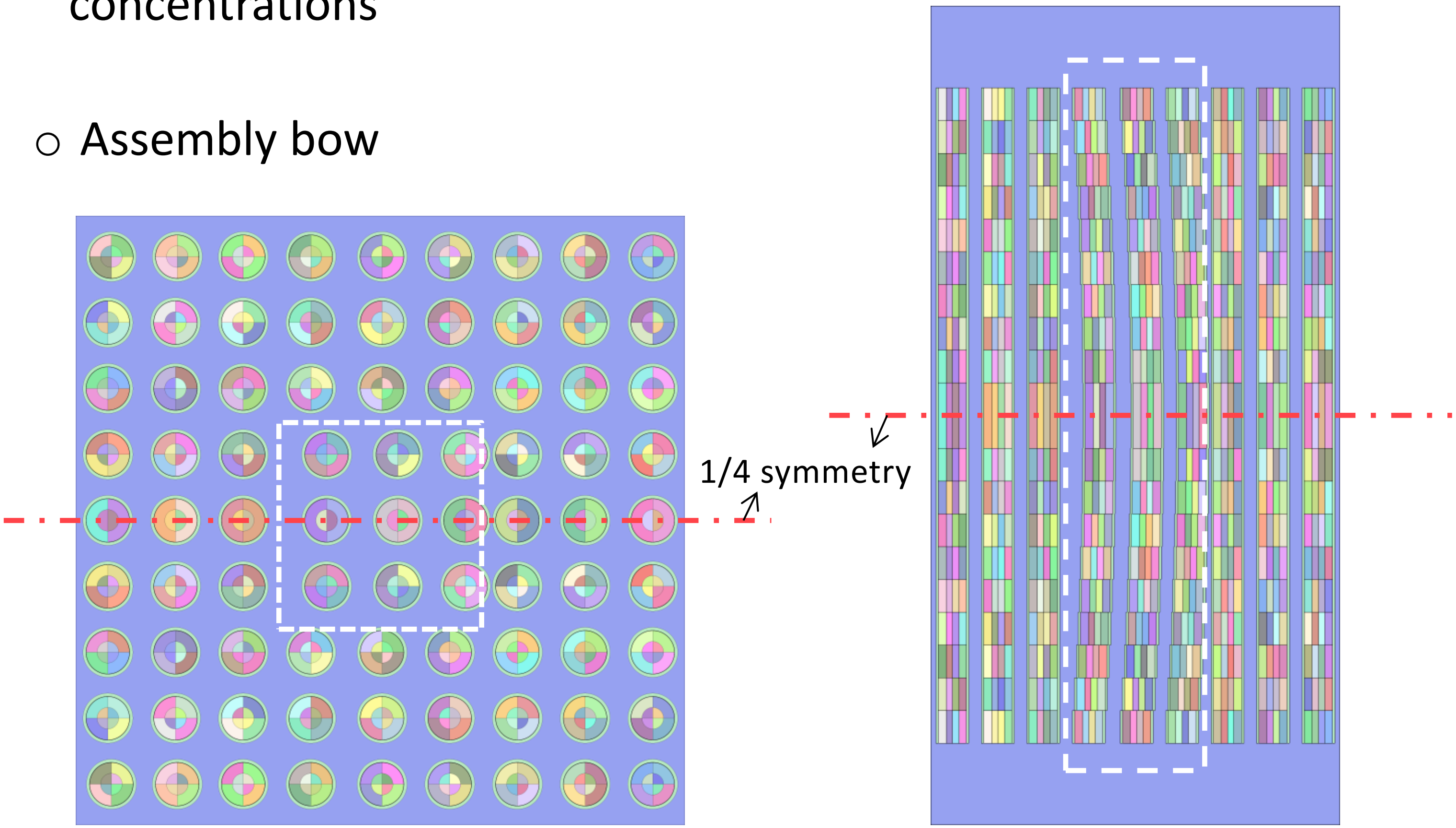
- A methodology to investigate bowing effects has been achieved
- A few preliminary simulations has been performed to illustrate
  - quantifying numerical bias
  - bowing effects on isotopic concentrations
- Convergence problems have been thoroughly investigated and solved
  - A few methods are suggested to converge
  - More Neutron, Smaller Size, Less depletion zones, C-shape, Symmetry
- Statistical uncertainty of the results are not available but analyses are present
- Future work …

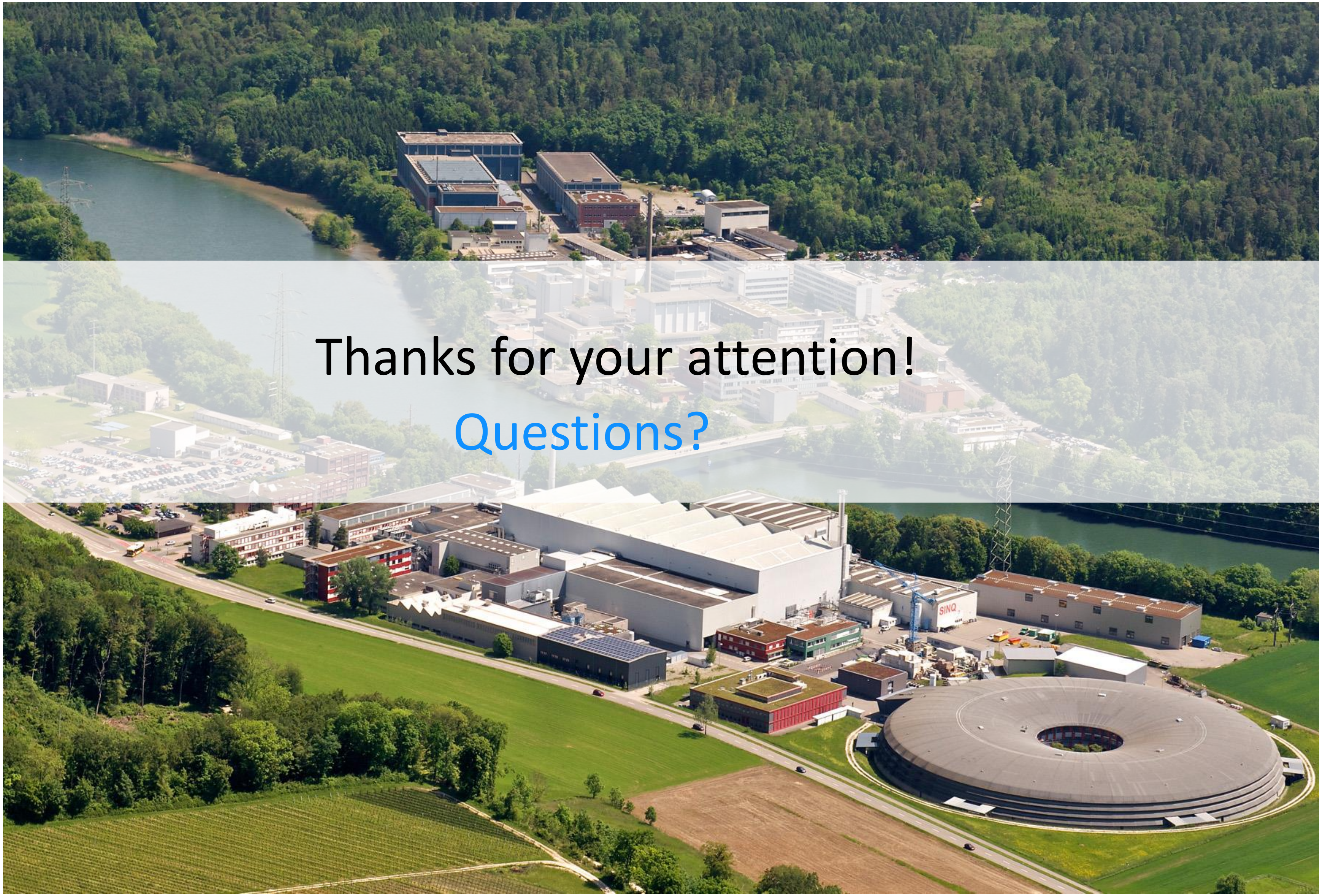
Future Work

- Progressive C-shape deformation with burn-up + more neutron histories

- Subdivisions on the C-shape model to investigate azimuthal isotopic concentrations

- Assembly bow





Thanks for your attention!

Questions?