OAK RIDGE National Laboratory

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Impact of cross section and fission yield uncertainties on the fuel inventory in a high temperature fluoride salt-cooled reactor

Nuclear Data Week 2025, CSEWG

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U.S. DEPARTMENT of ENERGY

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Motivation

Advanced reactors

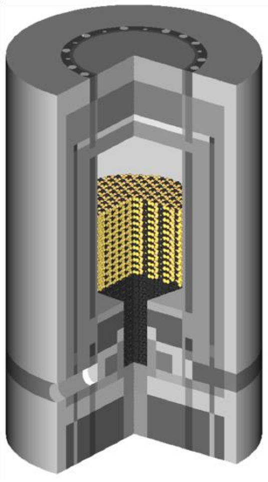
- Gained interest to meet global energy demands
- Increase in deployment expected in the near to mid future
- Significantly different from well-studied LWRs: different fuel forms, coolants, enrichments (e.g., HALEU), elevated burnups and temperatures

Nuclear data

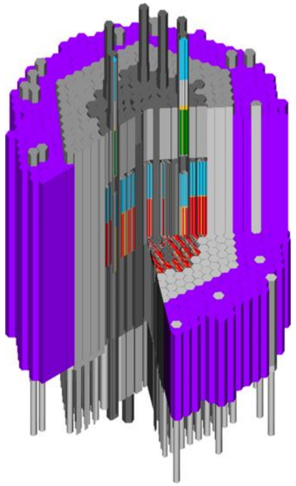
- Limited experimental data increases reliance on mod&sim
- Impact of uncertainties in nuclear data on mod&sim must be assessed
    - Reactivity: Several assessments were conducted
    - Fuel inventory: Very few studies available

This work

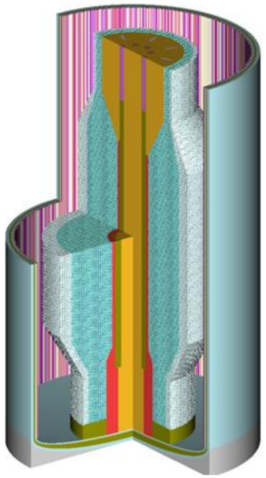
- Propagate cross section and fission yield uncertainties to the fuel inventory during operation and spent fuel inventory of a fluoride salt-cooled high-temperature pebble-bed reactor (pebble-bed FHR)
- Identify key contributors to resulting uncertainties



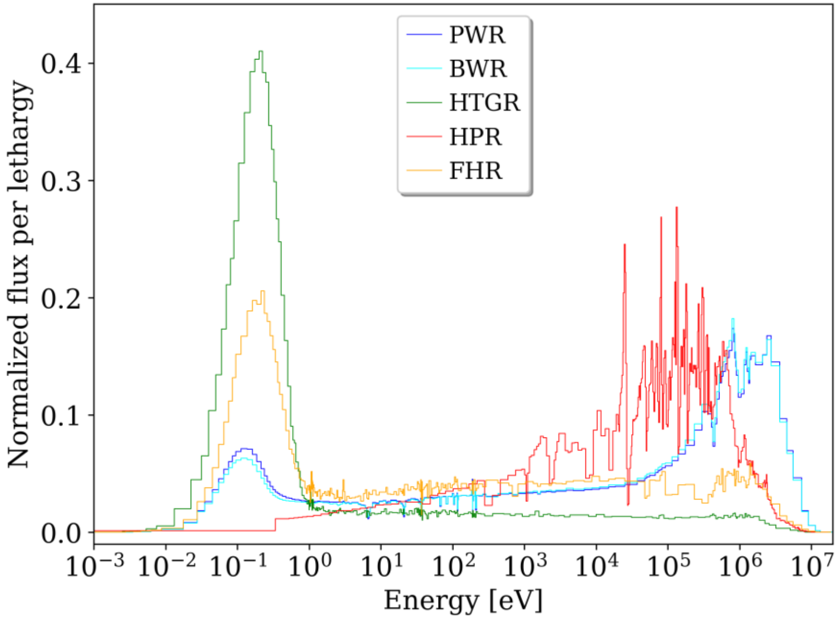
Pebble-bed HTGR



SFR



Pebble-bed FHR



Neutron spectrum: advanced reactors vs. LWRs

Application: UC Berkeley FHR Mark I

General characteristics:

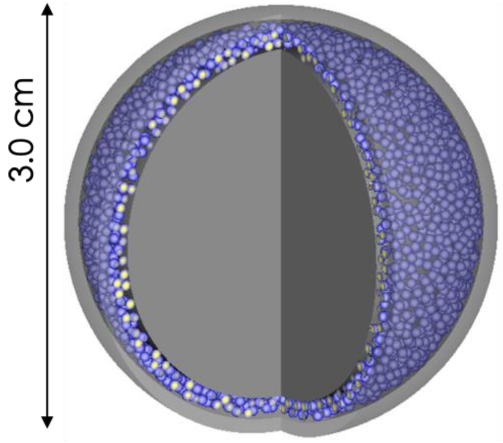
- 236 MWth
- 470,000 fuel pebbles + 218,000 graphite pebbles
- **FLiBe** molten salt coolant, T ≃ 873–973 K
- **Graphite** reflector, T ≃ 873–973 K

Fuel pebbles:

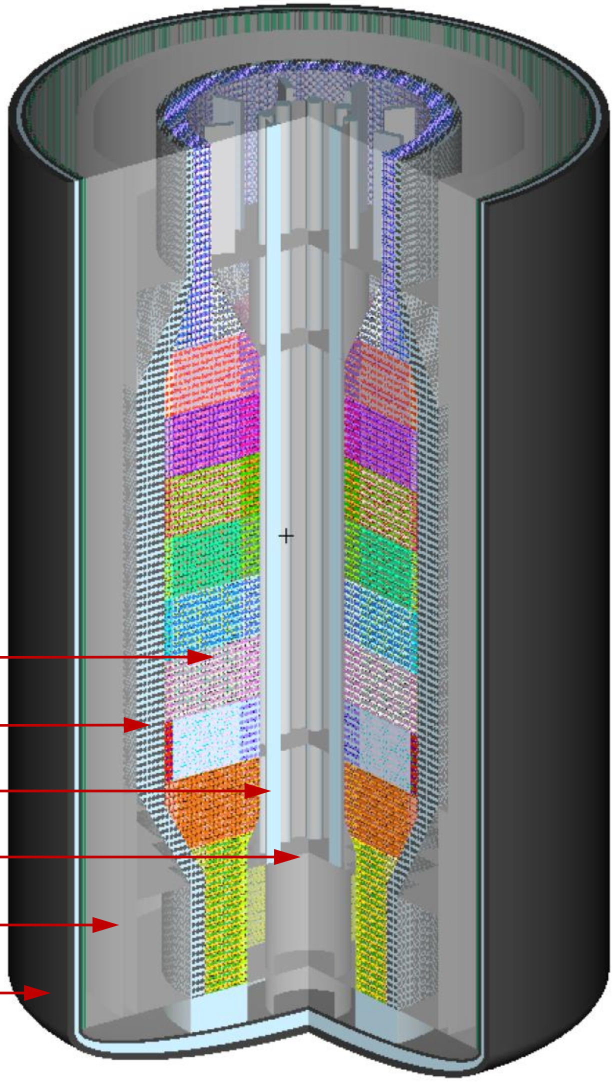
- TRISO fuel particles at 40% packing fraction
- **UCO fuel with 19.9 wt% ^{235}U enrichment**, T ≃ 1,003 K
- Average discharge burnup: **180 GWd/tU**

Equilibrium core:

- Fuel pebbles at target burnup continuously replaced by fresh fuel pebbles
- Core contains fuel pebbles at different levels of burnup
- Average conditions in each zone approximately constant: average inventory / burnup, flux and power profiles, temperatures, etc.



FHR fuel pebble
(4,730 TRISOs)

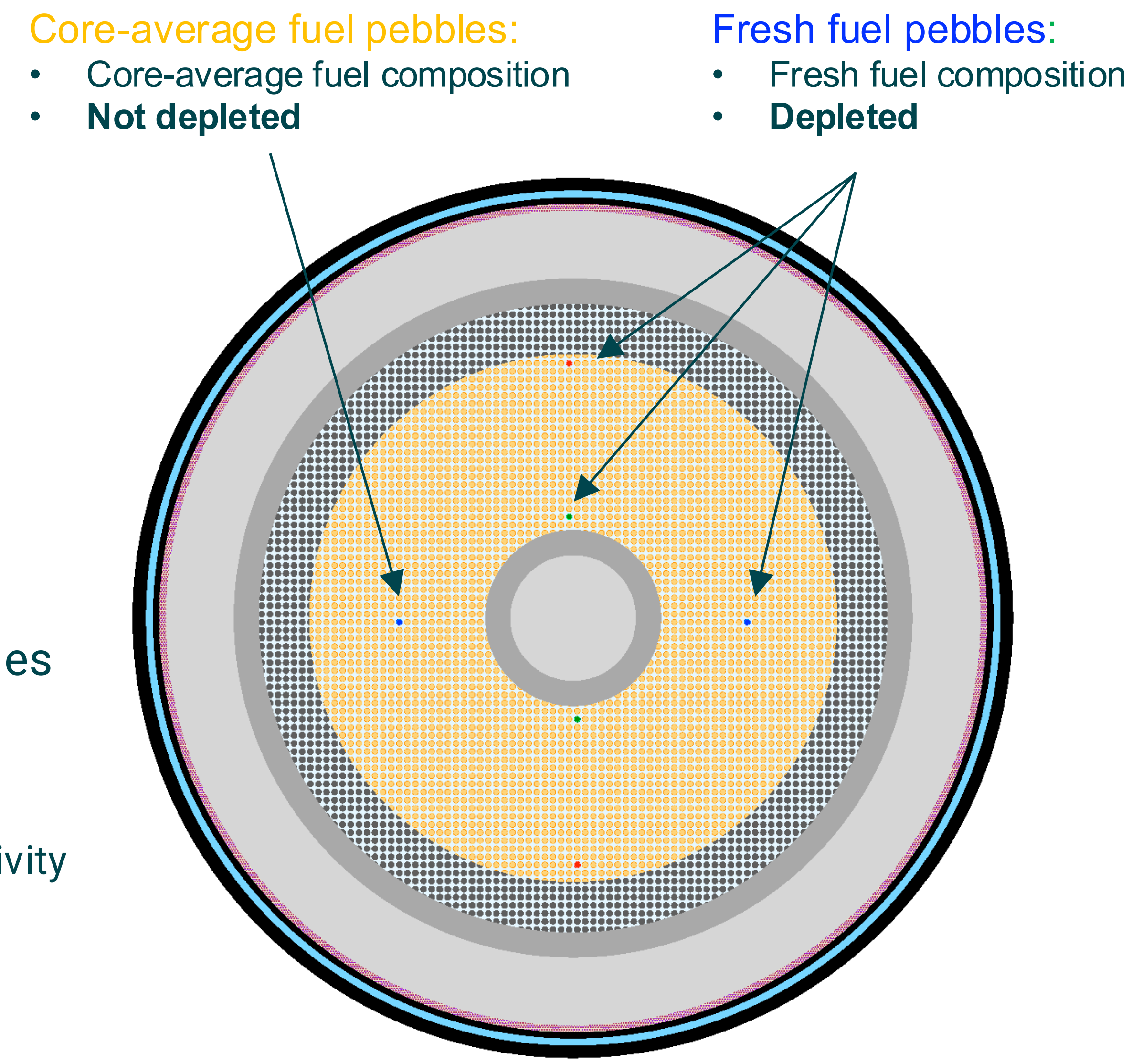


FHR core

Approach

1. **Spent and equilibrium core fuel inventory:**
   - Application of "**S**CALE **L**eap-**I**n method for **C**ores at **E**quilibrium" (SLICE)
   - Depletion of fuel pebbles in representative spectral environment
   - Tool: SCALE/TRITON with KENO-VI and ORIGEN
2. **Uncertainty and sensitivity analysis:**
   - Generate random samples of XS and FPY using covariance data
   - Perform 1,000 calculations using these random samples
   - Perform statistical analysis of results
   - Tool: SCALE/Sampler
     - Importance ranking of cross sections in terms of sensitivity index $R^2 \in [0,1]$

Covariance library: ENDF/B-VII.1 or ENDF/B-VIII.1, plus BNL-LANL-ORNL (BLO) uncertainty data



Axial slice through the FHR core

Approach

Calculations performed with the SCALE code system and ENDF/B-VII.1 or ENDF/B-VIII.1 data, plus BNL-LANL-ORNL (BLO) uncertainty data

1. Spent and equilibrium core fuel inventory:

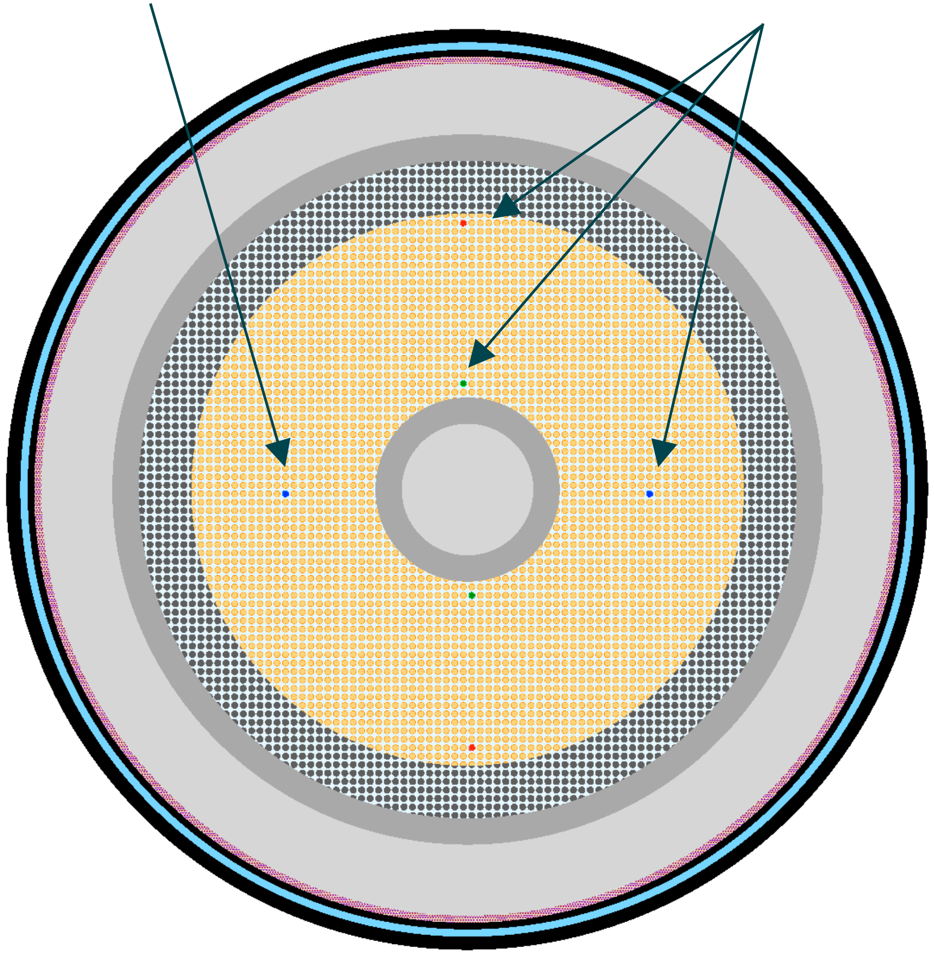
- TRITON reactor physics sequence
  - KENO-VI Monte Carlo neutron transport
  - ORIGEN depletion and decay solver

2. Uncertainty and sensitivity analysis:

- Sampler uncertainty and sensitivity analysis sequence
- Importance ranking of cross sections in terms of sensitivity index $R^2 \in [0,1]$

Core-average fuel pebbles:
- Core-average fuel composition
- **Not depleted**

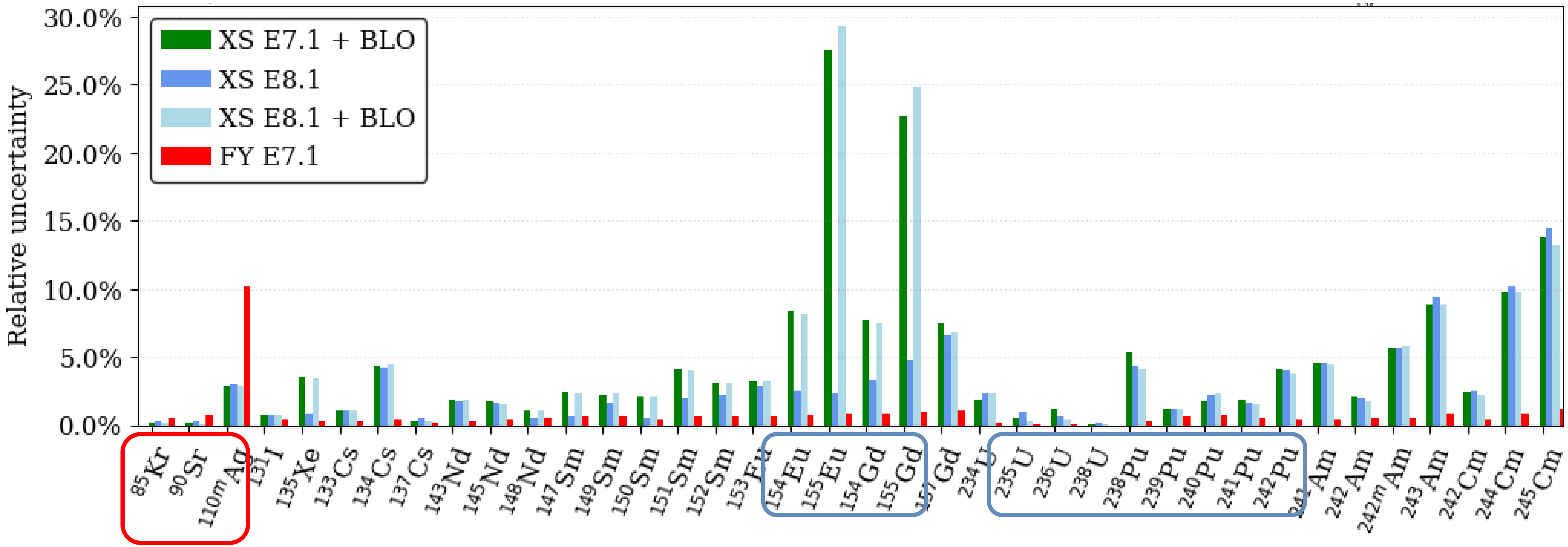
Fresh fuel pebbles:
- Fresh fuel composition
- **Depleted**



Axial slice through the FHR core

Relative uncertainty of spent FHR fuel inventory at discharge

Burnup: 180 GWd/tU



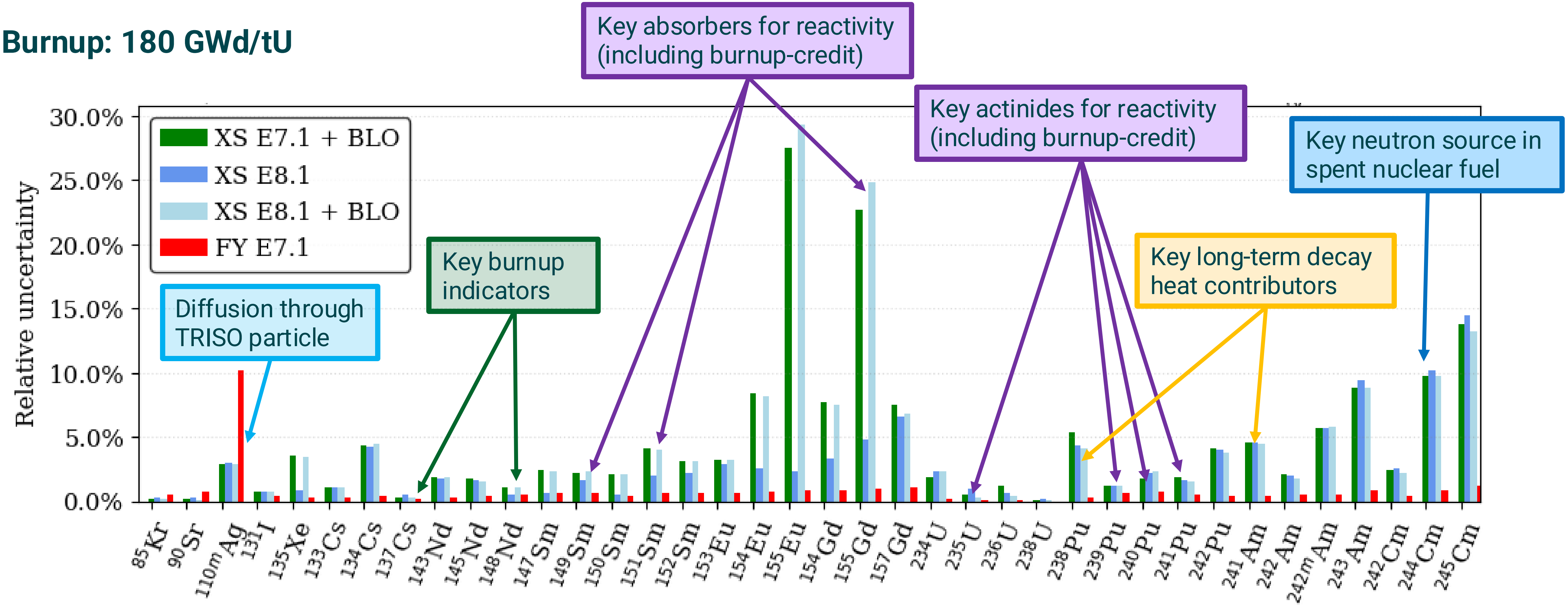
Cross section uncertainties are major drivers for uncertainties, with few exceptions for Ag^{110m}, Kr^{85}, Sr^{90}

Differences between E8.1+BLO and E7.1+BLO are small, mostly below <1% relative difference

Impact of BLO uncertainties for key fission products Sm, Eu, Gd point to important missing covariance data

FHR fuel inventory uncertainties are relevant for different applications

Burnup: 180 GWd/tU



Cross section uncertainties are major drivers for uncertainties, with few exceptions for Ag^{110m}, Kr^{85}, Sr^{90}

Differences between E8.1+BLO and E7.1+BLO are small, mostly below <1% relative difference

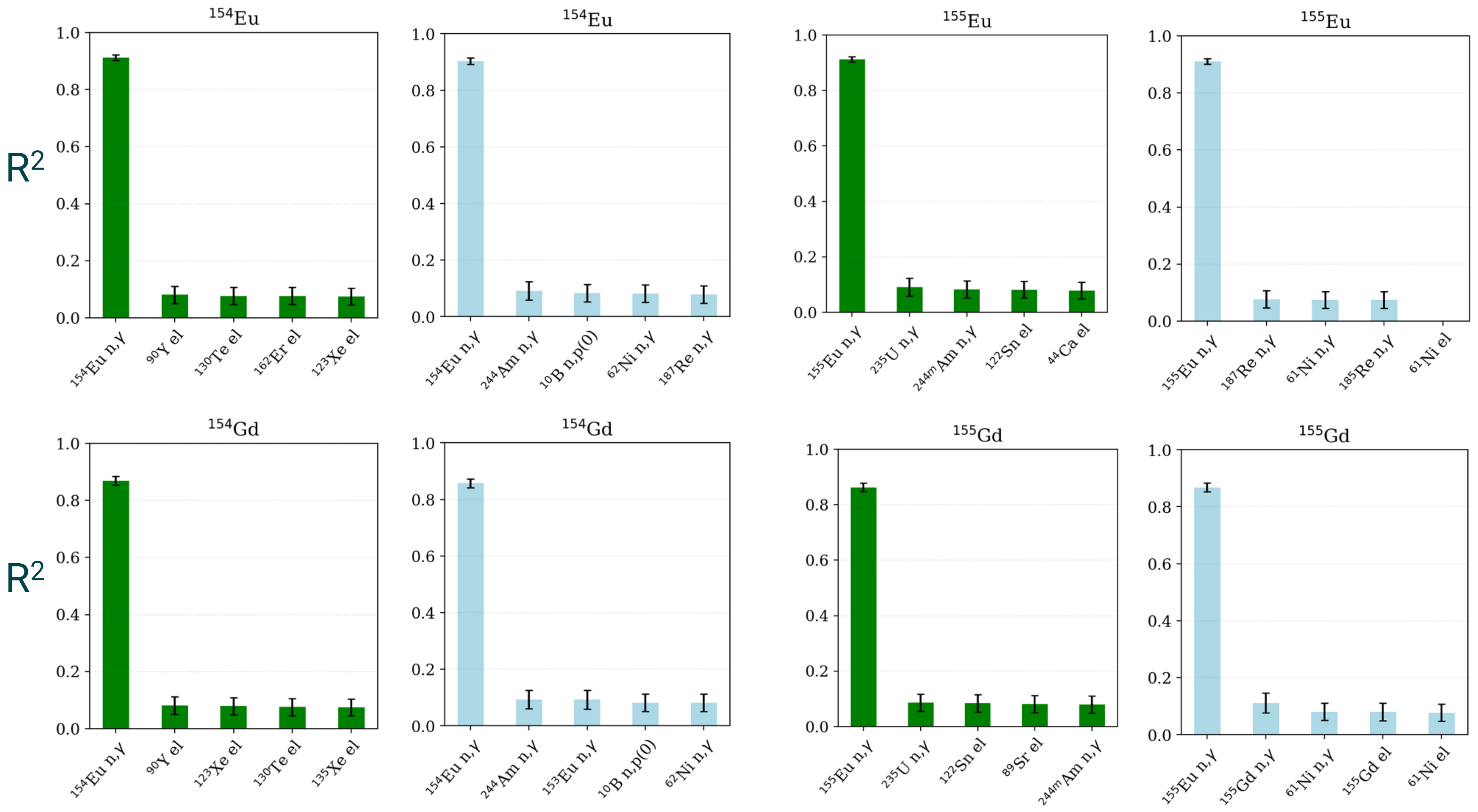
Impact of BLO uncertainties for key fission products Sm, Eu, Gd point to important missing covariance data

Sensitivity analysis reveals missing covariance data influencing important neutron absorber

E7.1+BLO

E8.1+BLO

- Uncertainty in Eu-154 (n,γ) is the main contributor to Eu-154 and Gd-154 concentration uncertainty
- Uncertainty in Eu-155 (n,γ) is the main contributor to Eu-155 and Gd-155 concentration uncertainty
- **BUT: Eu-154 (n,γ) and Eu-155 (n,γ) covariance data is not included in E8.1, only in BLO**



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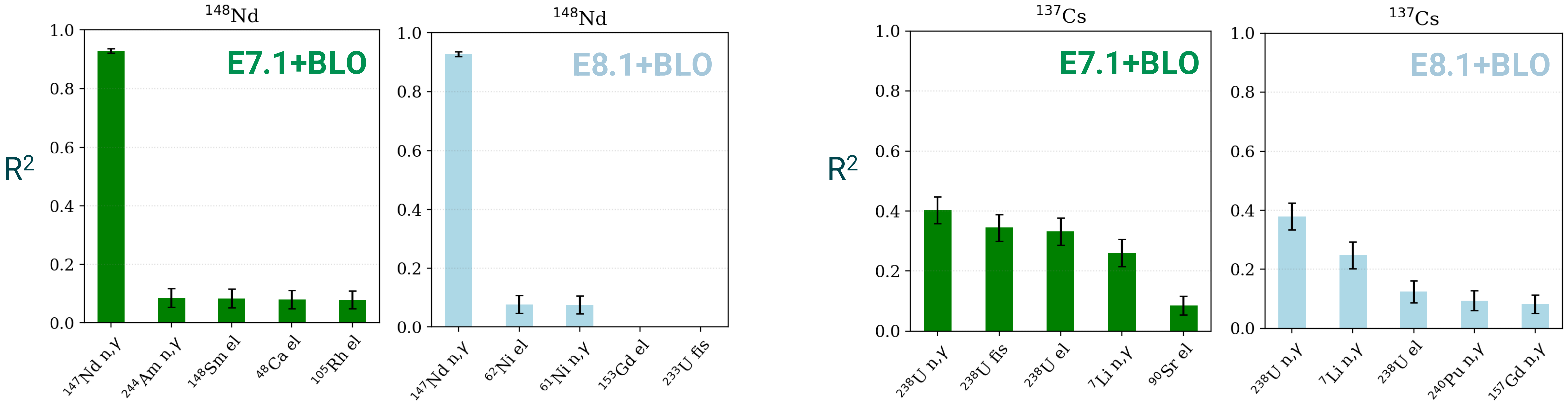
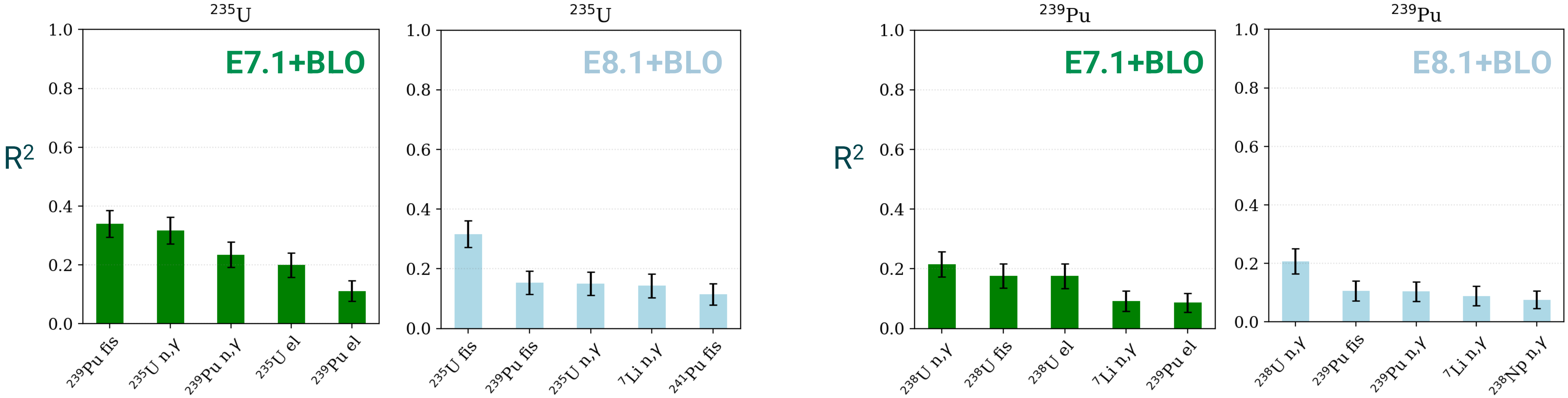
Sensitivity analysis reveals missing and updated covariance data impacting burnup indicators



- Uncertainty in Nd-148 concentration is mainly impacted by Nd-147 (n,γ)
  BUT: Nd-147 (n,γ) covariance data is not included in E8.1, only in BLO
- Uncertainty in Cs-137 concentration (0.3%-0.5%) showed small changes between libraries, mainly due to updates in U-238 (n,γ) and fission

Sensitivity analysis reveals covariance data updates impacting major actinides U-235 and Pu-239



- Uncertainty in U-235 concentration (0.4%-0.5%) shows only small change between libraries, likely due to compensating effects from updates of (n,γ) and fission in U-235 and Pu-239
- Uncertainty in Pu-239 concentration (1.2%) did not change between libraries; but individual uncertainty contributions changed, mainly due to updates in U-238 (n,γ) and fission

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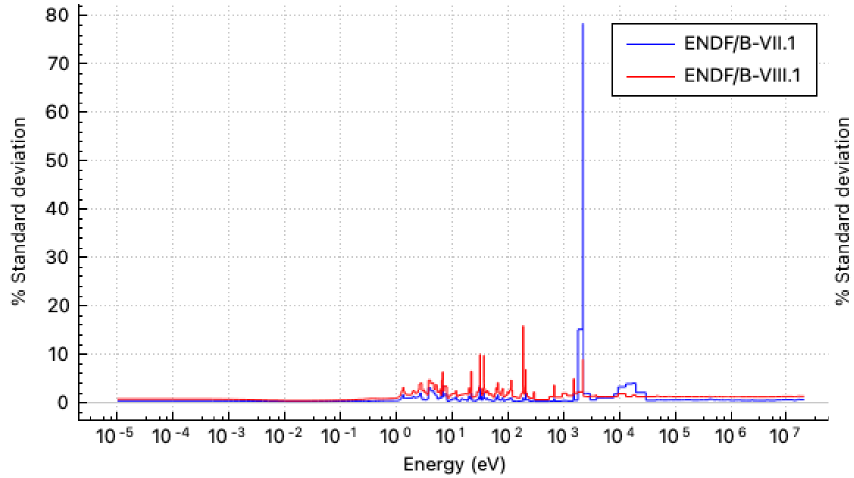
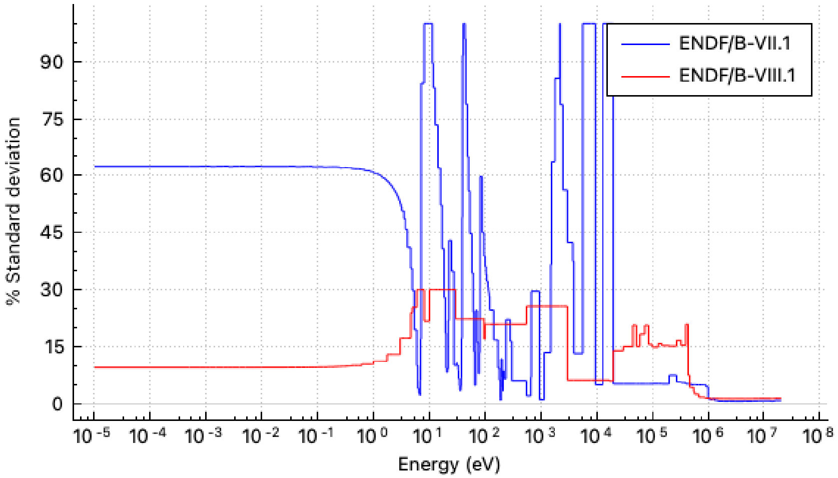
Relevant cross section uncertainty updates between E7.1 and E8.1

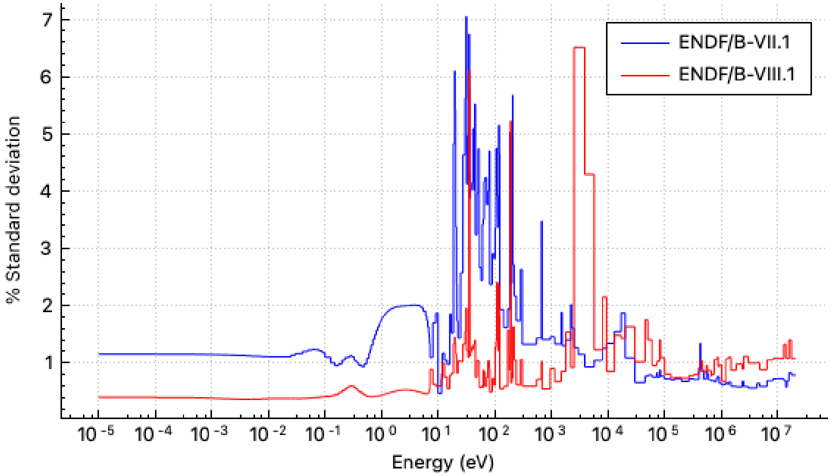
U-235 mt=18 fission



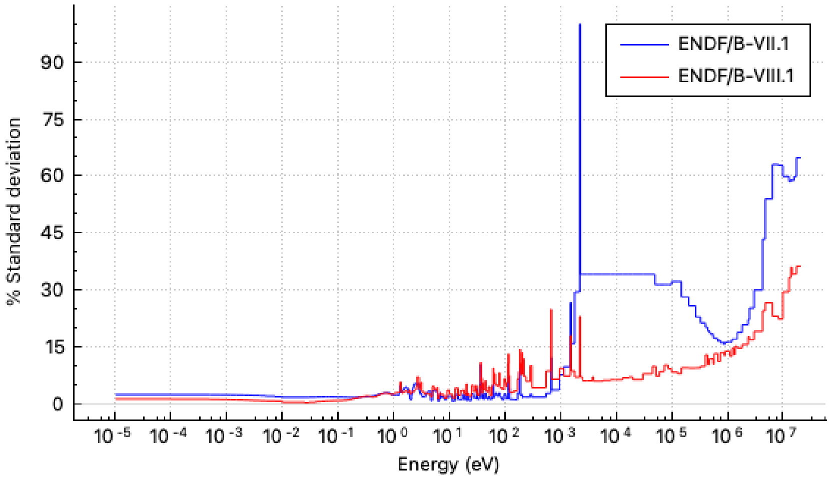
U-238 mt=18 fission



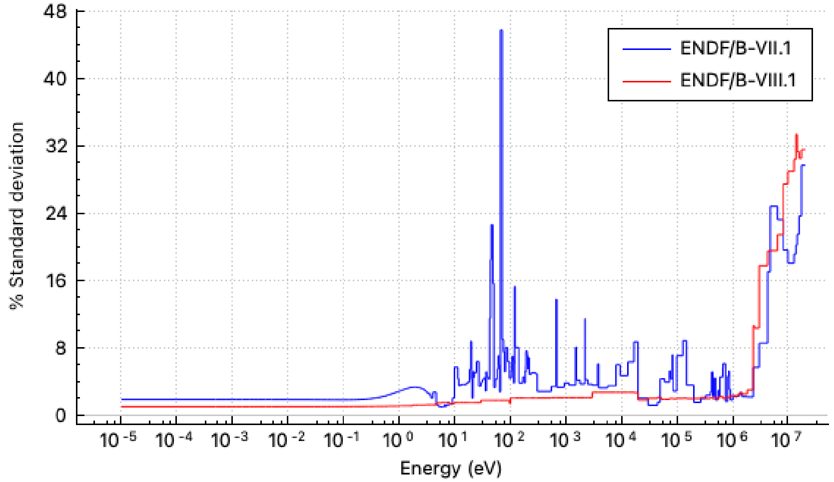
Pu-239 mt=18 fission



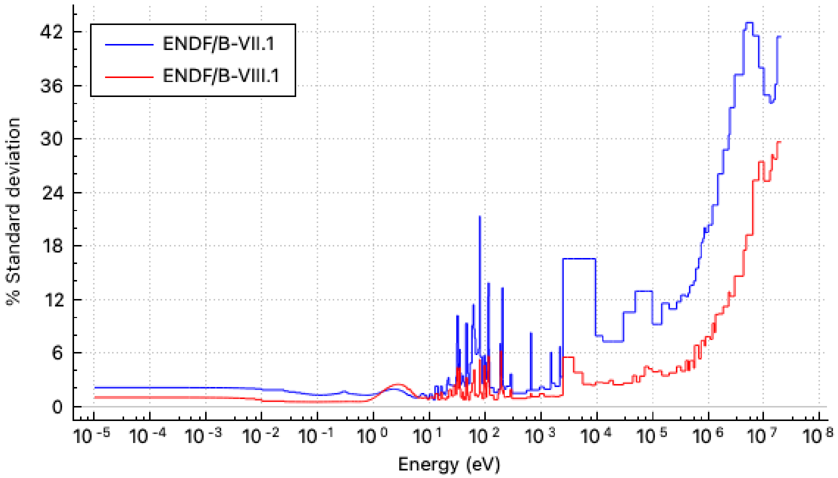
U-235 mt=102 n,gamma



U-238 mt=102 n,gamma



Pu-239 mt=102 n,gamma



Summary and Conclusions

Random sampling approach was applied to investigate the impact of uncertainties in cross sections and fission yields on uncertainties in FHR spent fuel pebble inventory

- Fission product yield uncertainties have minor impact, with few exceptions
- Cross section uncertainties cause inventory uncertainties of up to 25% (Sm, Eu,Gd)
- Comparison of cross section uncertainties between libraries highlight:
    - Impact of covariance data update in ENDF/B-VIII.1: U-235, U-238, and Pu-239 (n,γ) and fission
    - Missing important covariance data ENDF/B-VIII.1, as identified through use of BLO data: Nd-148 (n,γ) and Eu-155 (n,γ)
- *Preliminary results presented, with the more comprehensive analysis to follow soon*

Sensitivity analysis identified cross sections that are top contributors of uncertainties in fuel inventory predictions:

- Change in cross section importance points to relevant cross section uncertainty updates between ENDF/B libraries
- Use of BLO-data reveals impact of cross section covariance data missing in ENDF/B-VIII.1
- Identified top contributing cross sections can inform recommendations for new measurements and evaluations

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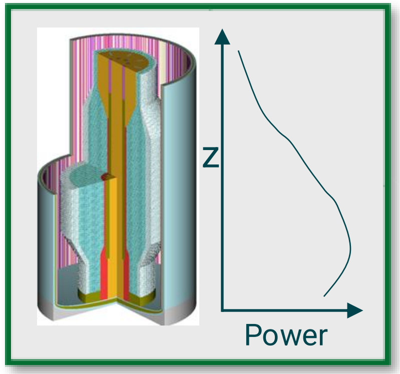
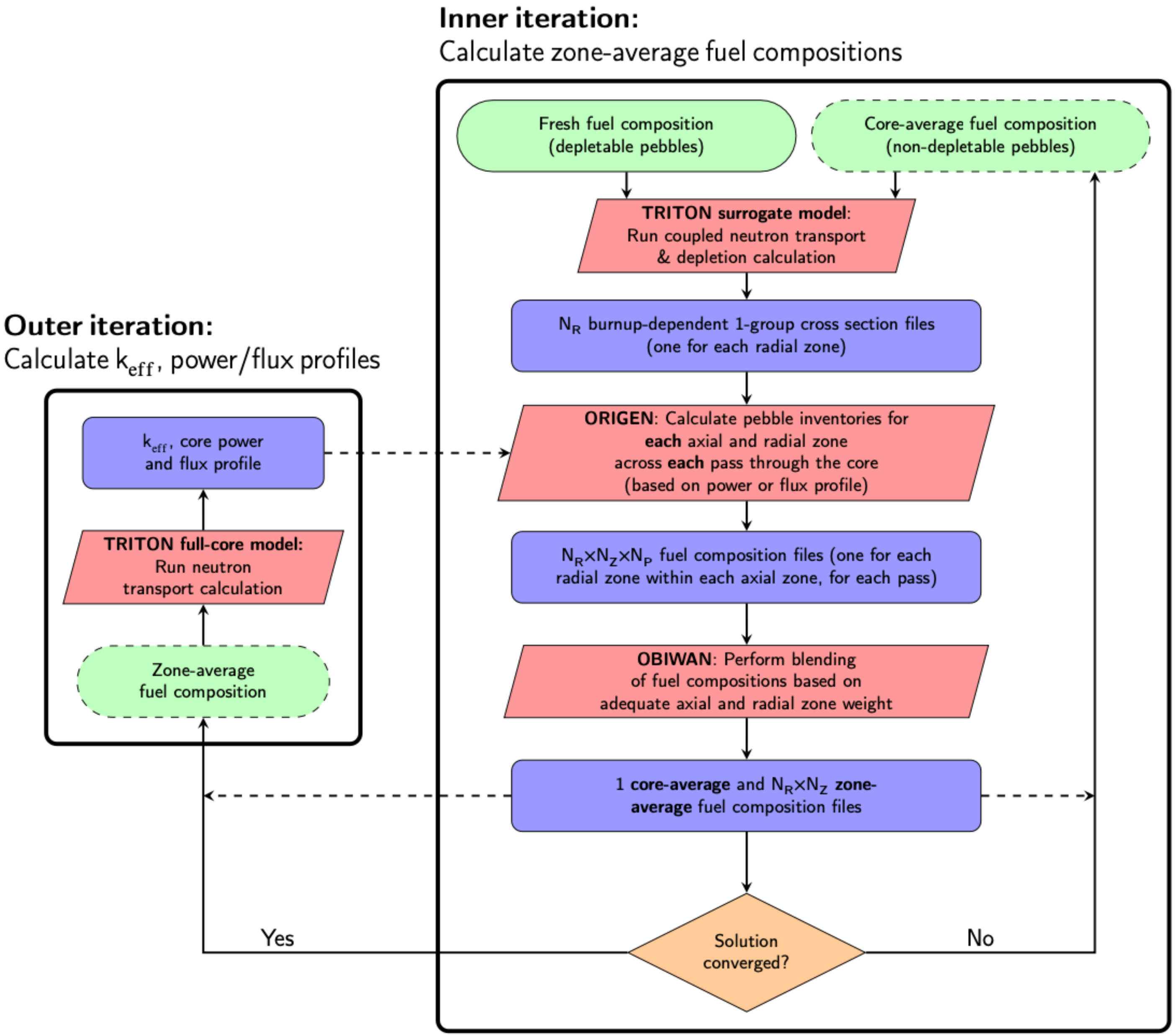
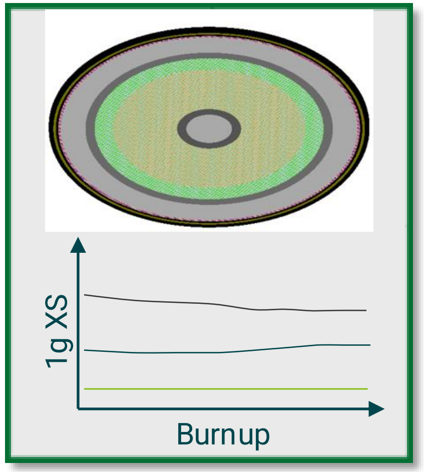
Backup

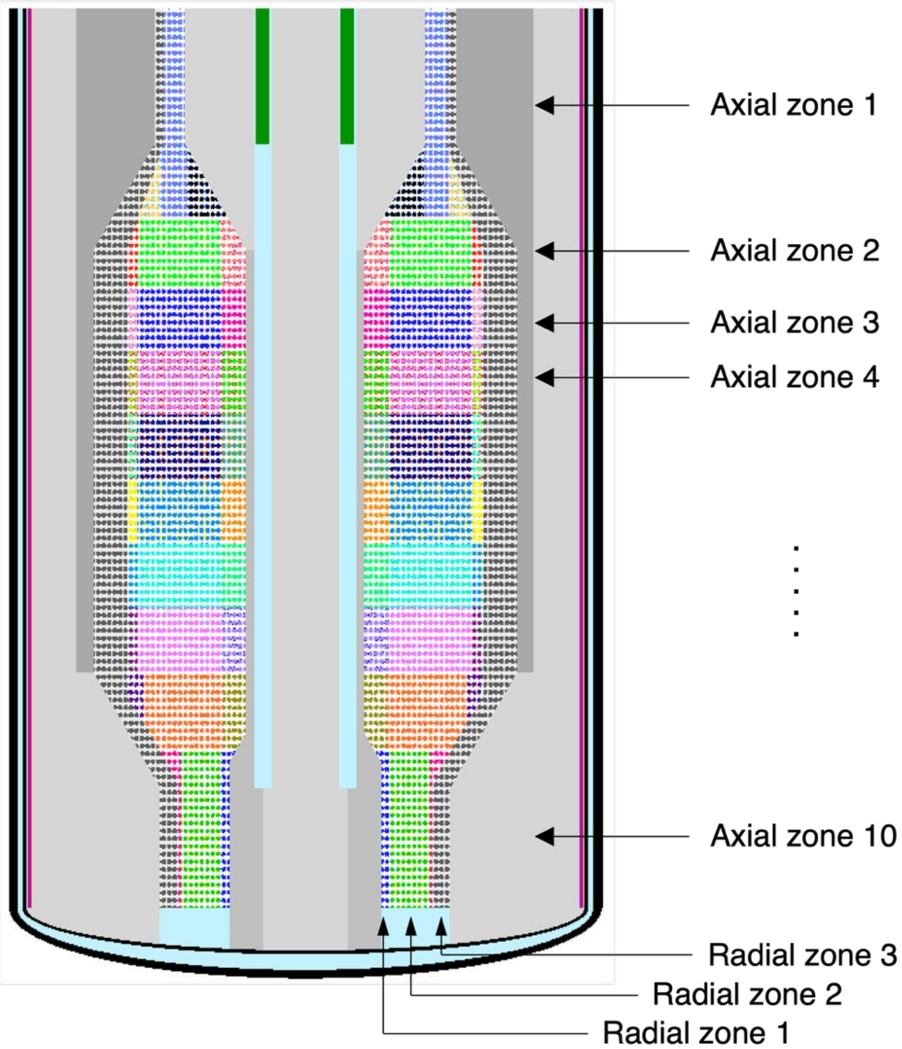
SLICE method for PBR equilibrium core generation







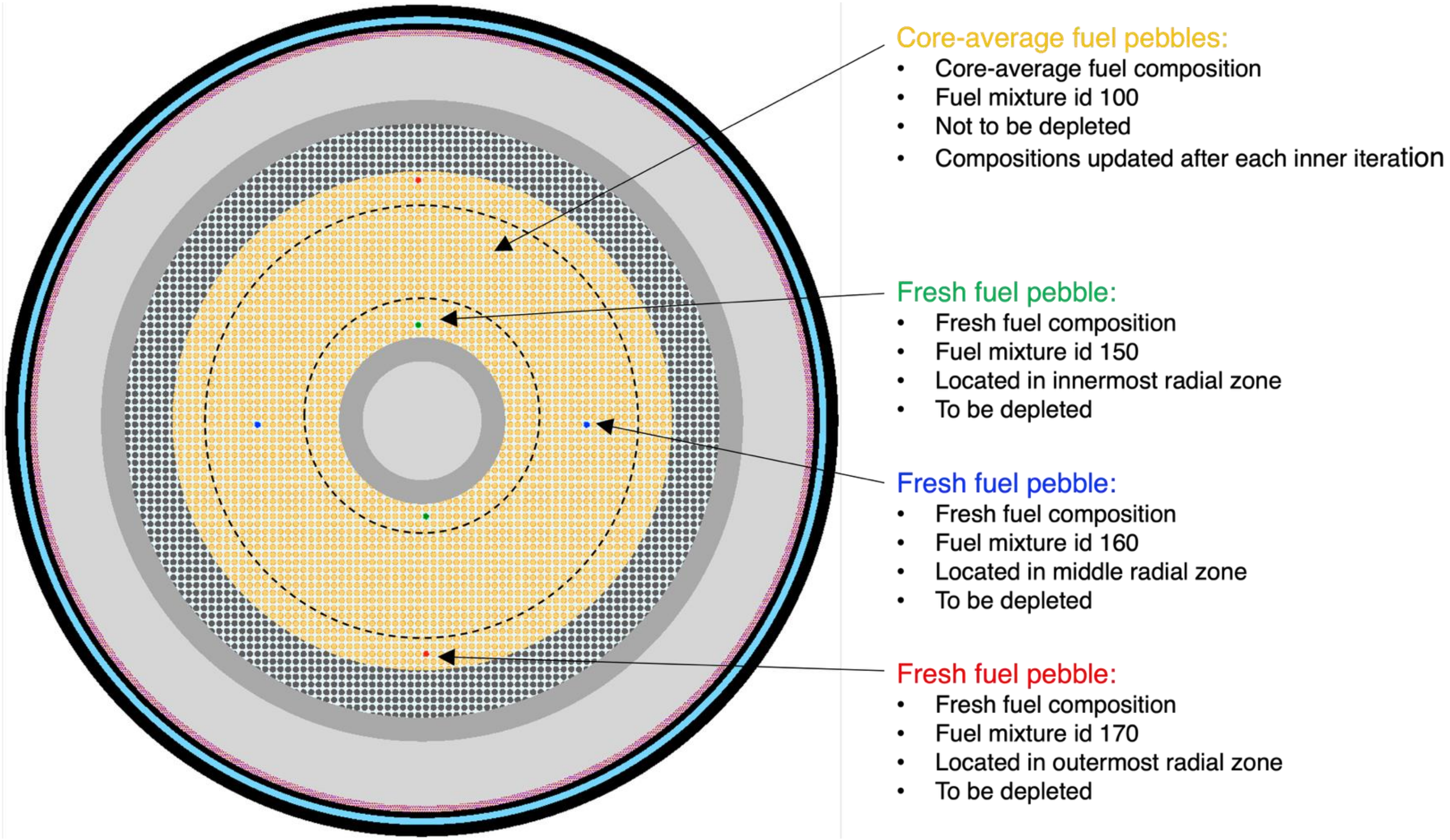
Discretized full core model



Example FHR full core with discretization of fuel region

- Model discretization based on radial and axial flux profile
- Each region (i.e. specific radial zone within specific radial zone) has unique region-average fuel inventory
- Region-average fuel inventory represents average of fuel pebbles at different passes, at different burnups in this region
- TRITON calculation of this model results in axial/radial flux/power profiles

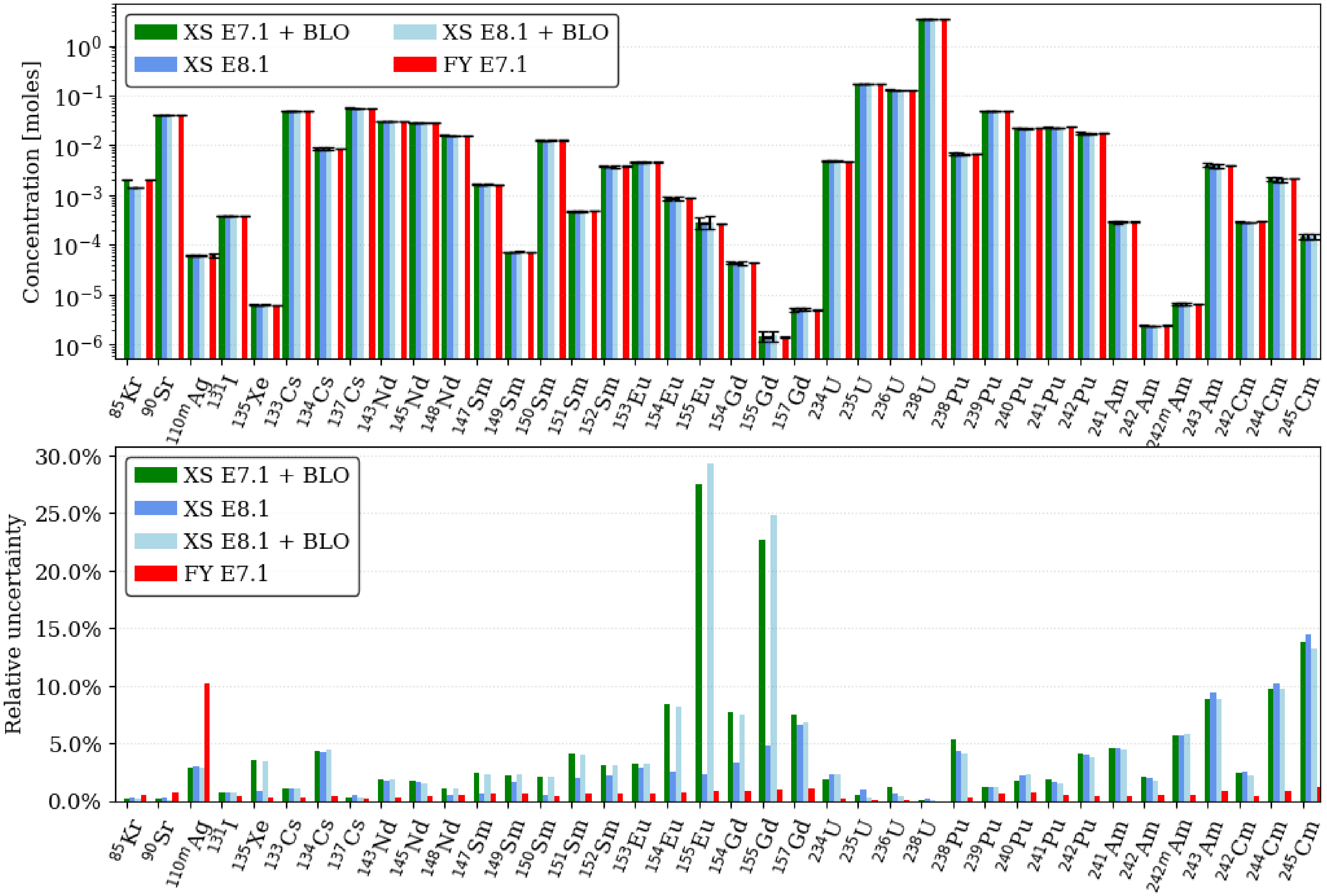
Axial slice surrogate model



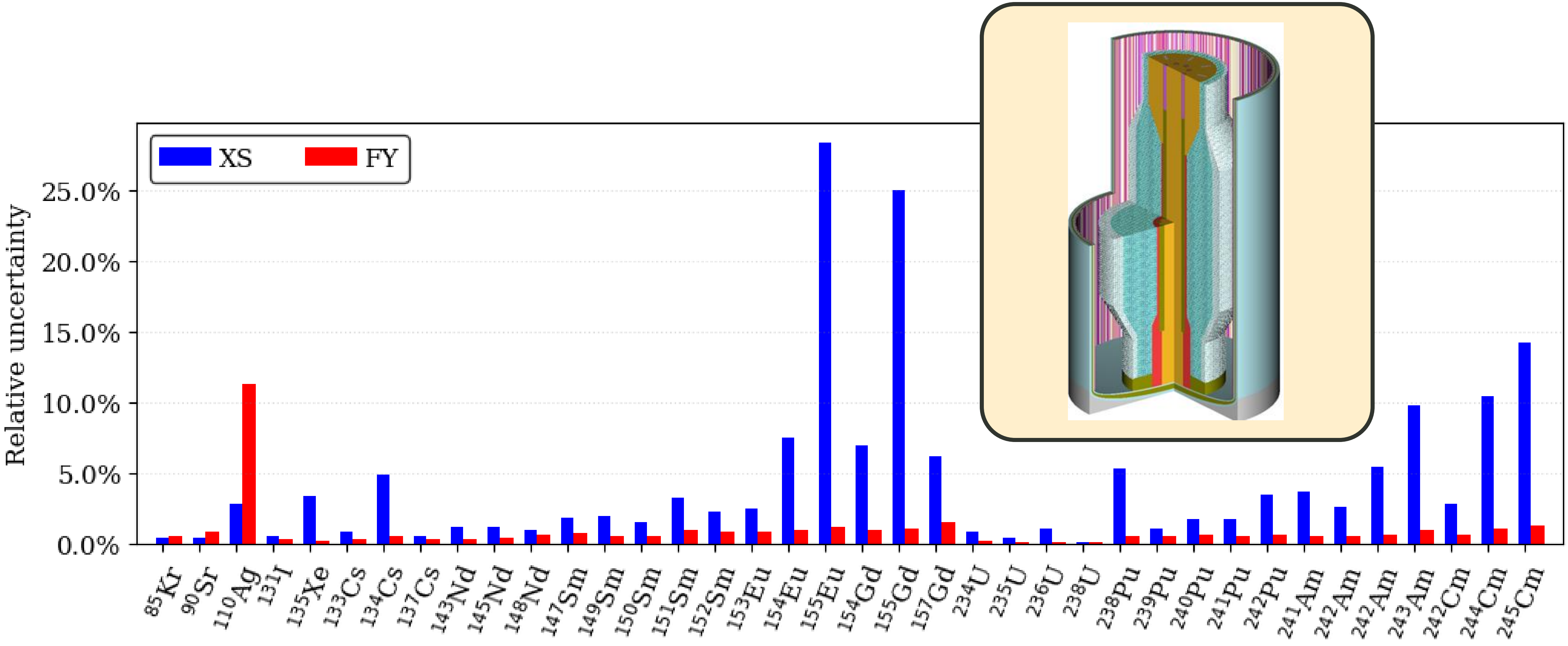
Example FHR axial slice model

- TRITON model of axial slice through center of the core
- Depletion of only "depletable" fuel pebbles to target discharge burnup
- "Core-average" fuel pebbles provide representative spectral conditions
- TRITON depletion calculation of this model results in ORIGEN cross section libraries (1-group cross sections)

Inventory of a discharged FHR fuel pebble



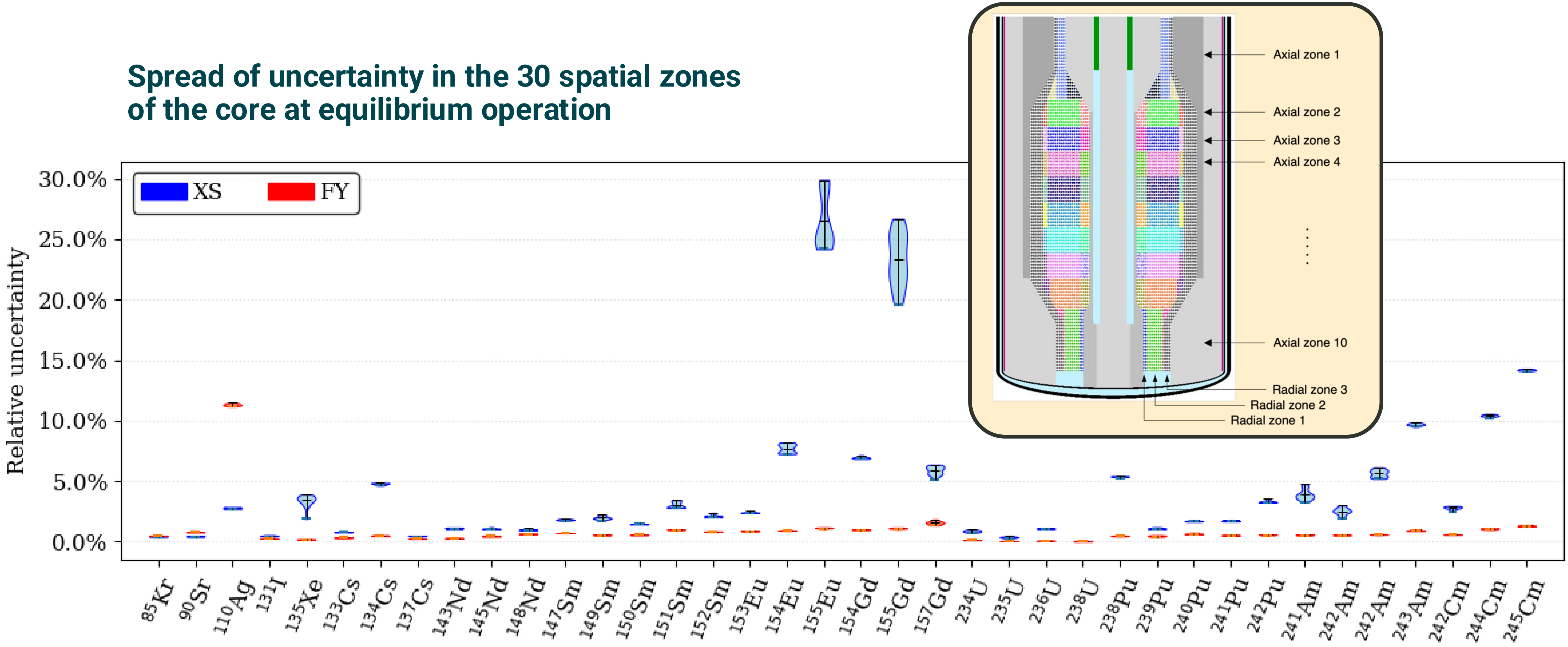
Core-average FHR inventory uncertainty at equilibrium operation using ENDF/B-VII.1



Uncertainties are approximately the same as for the spent fuel inventory

Zone inventory uncertainty at equilibrium operation using ENDF/B-VII.1

Spread of uncertainty in the 30 spatial zones of the core at equilibrium operation



Significant uncertainty spread for only few nuclides: Eu, Gd, Cm isotopes