OPTIMIZATION OF STREAM BURNUP CHAIN USING DEPLETION PERTURBATION THEORY

Khang Nguyen Hoang Nhat, Sooyoung Choi and Deokjung Lee

UNIST-CORE

CONTACT

Ulsan National Institute of Science and Technology
Address 50 UNIST-gil, Ulju-gun, Ulsan, 44919, Korea
Tel. +82 52 217 0114 Web. www.unist.ac.kr

Computational Reactor physics & Experiment lab
Tel. +82 52 217 2940 Web. reactorcore.unist.ac.kr

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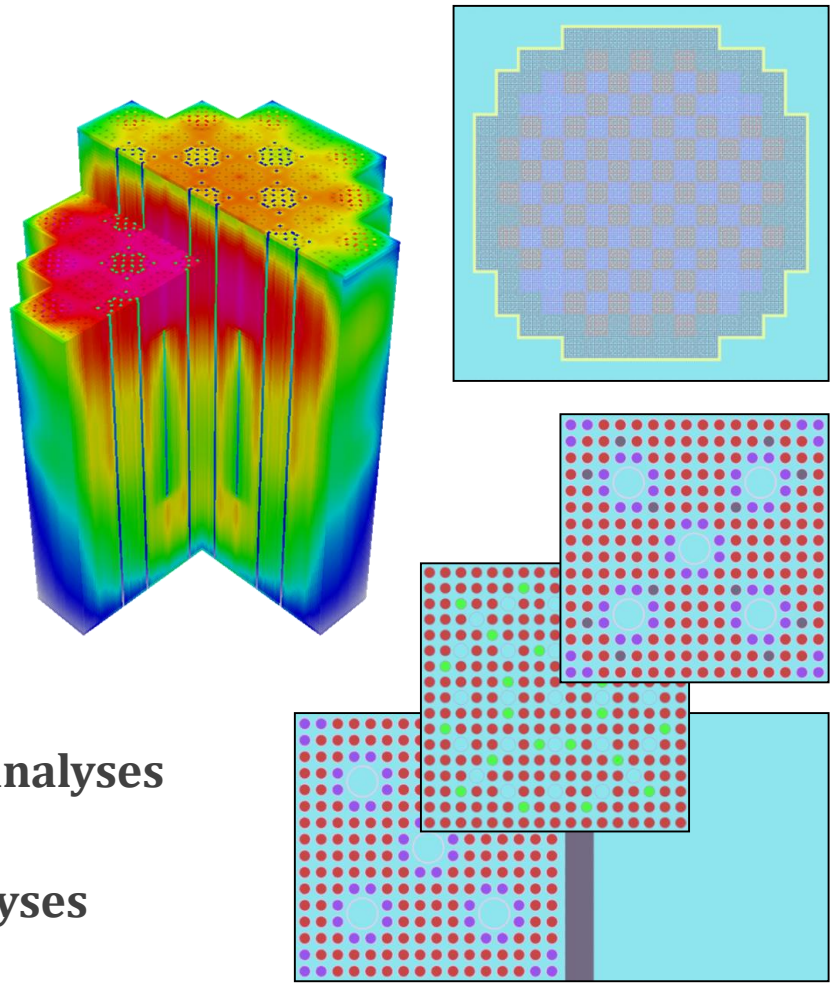
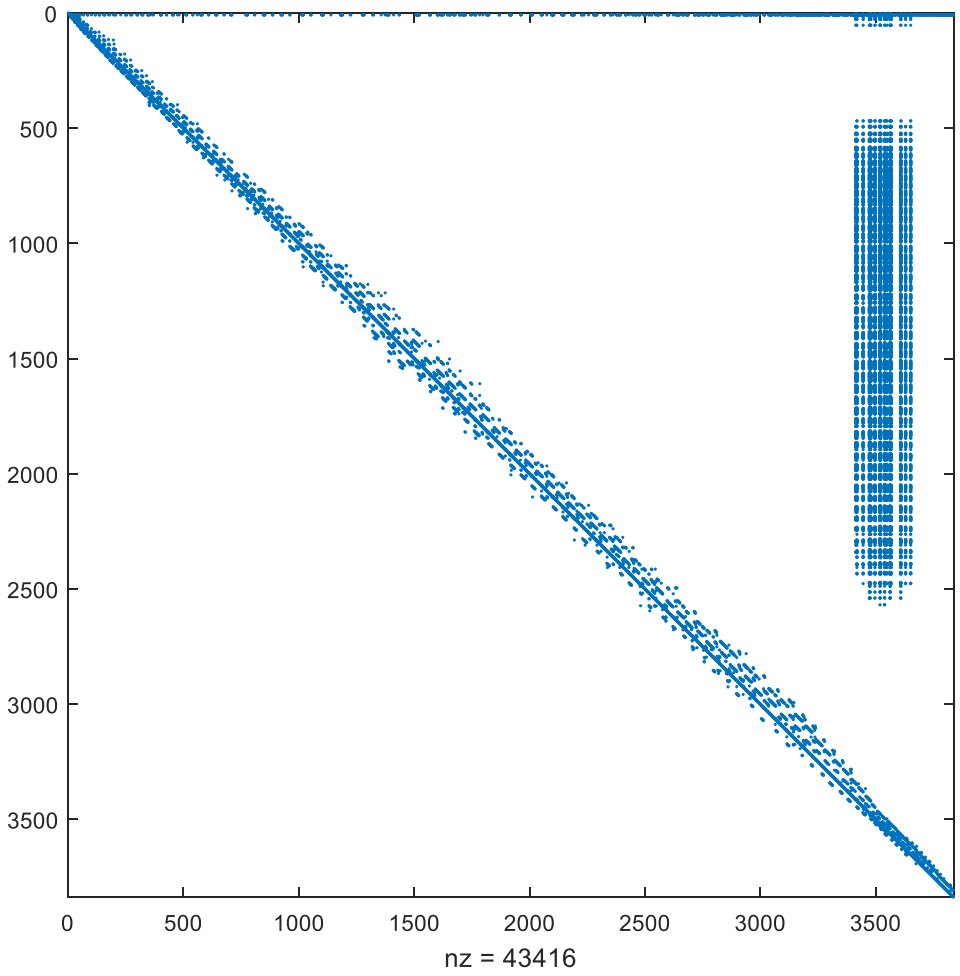


I. Introduction

Introduction (1/4)

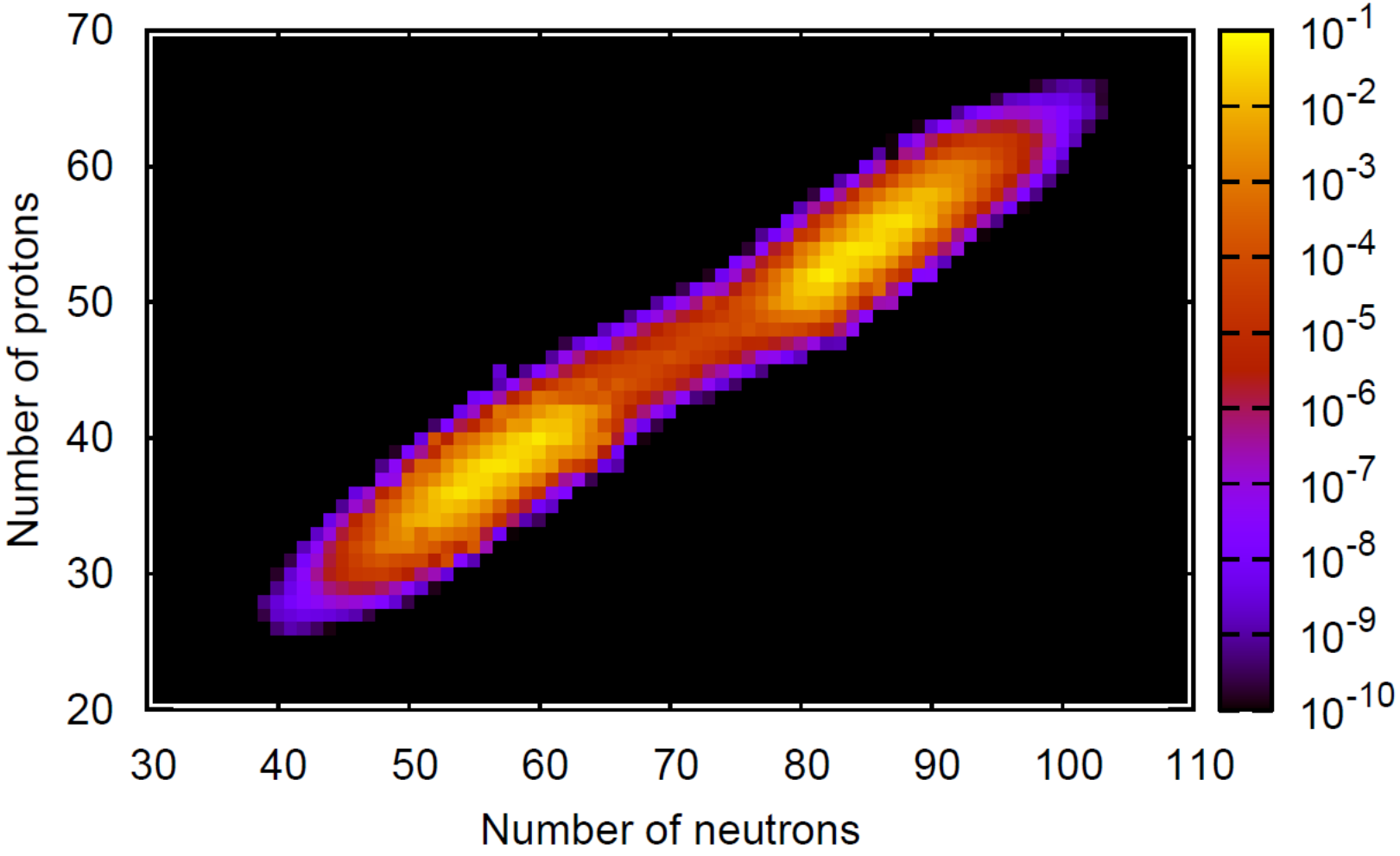
- **ENDF/B-VII depletion library is implemented in STREAM**



 # nuclides: 3837
 # transitions: 43416

Introduction (2/4)

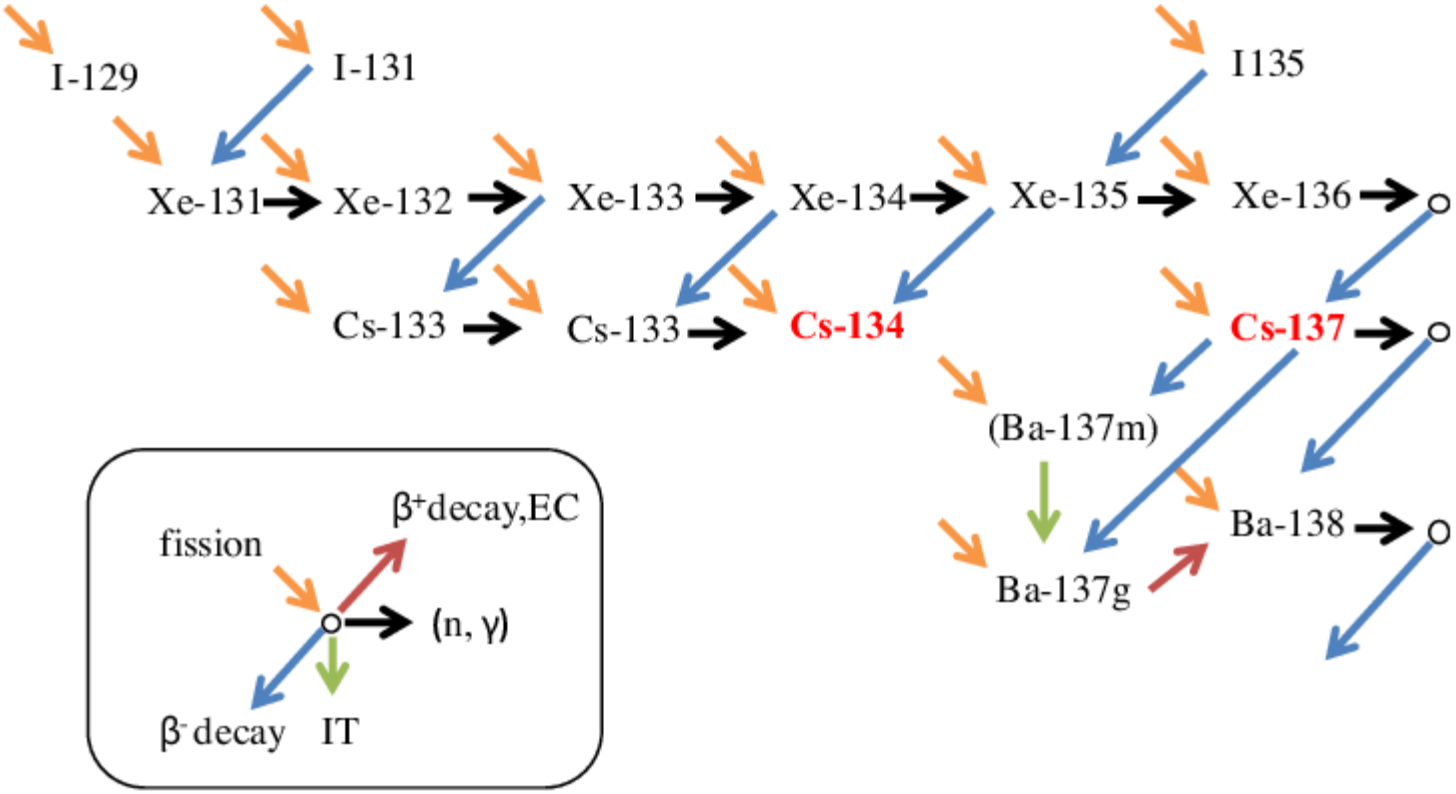
- **Over 1,000 FP nuclides are generated by a fission reaction.**



G. Chiba, M. Tsuji, T. Narabayashi, Y. Ohoka and T. Ushio, "Important fission product nuclides identification method for simplified burn up chain construction" *Journals of Nuclear Science and Technology*, **Vol 52** No. 7-8 (2015).

Introduction (3/4)

An example of "Burnup chain"



Evaluate the importance of a given nuclide to one nuclide !!!

Introduction (4/4)

- **STEP 1: Identify the relevant nuclides using Depletion Perturbed Theory (DPT)**
- **STEP 2: Redistribute the decay data and the fission yields**
- **STEP 3: Reconduct the depletion problem using optimized burnup chain**

II. Method and Materials

1. Overview of Depletion Perturbation Theory

Overview of DPT (1/6)

- **The burnup equation in matrix form:**

$$\frac{\partial \boldsymbol{n}(t)}{\partial t} = \boldsymbol{M}(t)\,\boldsymbol{n}(t) \qquad (1)$$

- **M** $\in \mathbb{R}^{n\times n}$ **is called the burnup matrix**

- **The adjoint burnup equation :**

$$-\frac{\partial \boldsymbol{n}^*(t)}{\partial t} = \boldsymbol{M}^*(t)\,\boldsymbol{n}^*(t) \qquad (2)$$

- **One can easily note that:**

$$\boldsymbol{M}^*(t) = \boldsymbol{M}^{\boldsymbol{T}}(t)$$

  - **"T" is the transpose operator.**

Overview of DPT (2/6)

- If $n_i(t)$ = the i^{th} component of the nuclide number density vector at the time t.
- Then $n_i^*(t)$ can be interpreted as the importance of nuclide i at the time t to the response at time t_{EOC}.
- Final response can be:
  - Neutron multiplication factor (k_{eff})
  - Number density of a specific nuclide
  - Reaction rate
- In our case: the number density of a specific nuclide k at the end of burn up process $n_k(t_{EOC})$.

Overview of DPT (3/6)

- **Multiply E.q (1) with $n^*(t)$ and E.q (2) with $n(t)$, then subtracting the result yields**

$$\boldsymbol{n}^*(t)\frac{\partial \boldsymbol{n}(t)}{\partial t} - \boldsymbol{n}^{\boldsymbol{T}}(t)\frac{\partial \boldsymbol{n}^*(t)}{\partial t} = \boldsymbol{n}^{*\boldsymbol{T}}(t)\boldsymbol{M}(t)\,\boldsymbol{n}(t) - \boldsymbol{n}^{\boldsymbol{T}}(t)\boldsymbol{M}^{\boldsymbol{T}}(t)\boldsymbol{n}^*(t) \quad (3)$$

- **Using the adjoint property:**

$$\boldsymbol{n}^{\boldsymbol{T}}\boldsymbol{M}^{\boldsymbol{T}}\boldsymbol{n}^* = \boldsymbol{n}^{*\boldsymbol{T}}\boldsymbol{M}\boldsymbol{n}$$

$$\Rightarrow \quad \boldsymbol{n}^*(t)\frac{\partial \boldsymbol{n}(t)}{\partial t} - \boldsymbol{n}^{\boldsymbol{T}}(t)\frac{\partial \boldsymbol{n}^*(t)}{\partial t} = 0 \qquad (4)$$

Overview of DPT (4/6)

- **Integrating Eq.(4) over the time period $[t, t_{EOC}]$ produces**

$$\int_{t}^{t_{EOC}} \boldsymbol{n}^{*T} \boldsymbol{n}\, dt = \mathbf{0} \tag{5}$$

$$\rightarrow \boldsymbol{n}^{*T}(t)\boldsymbol{n}(t) = \boldsymbol{n}^{*T}(t_{EOC})\boldsymbol{n}(t_{EOC})$$

- **If we define $n^*(t_{EOC})$ as a unit column-vector:**

$$\begin{cases} n_j^*(t_{EOC}) = 1 \\ n_i^*(t_{EOC}) = 0 \ (i \neq j) \end{cases}$$

- **Eq. (5) can be expressed as**

$$\sum_{i}^{N} n^{*T}_i(t) n_i(t) = n_j(t_{EOC}) \tag{6}$$

Overview of DPT (5/6)

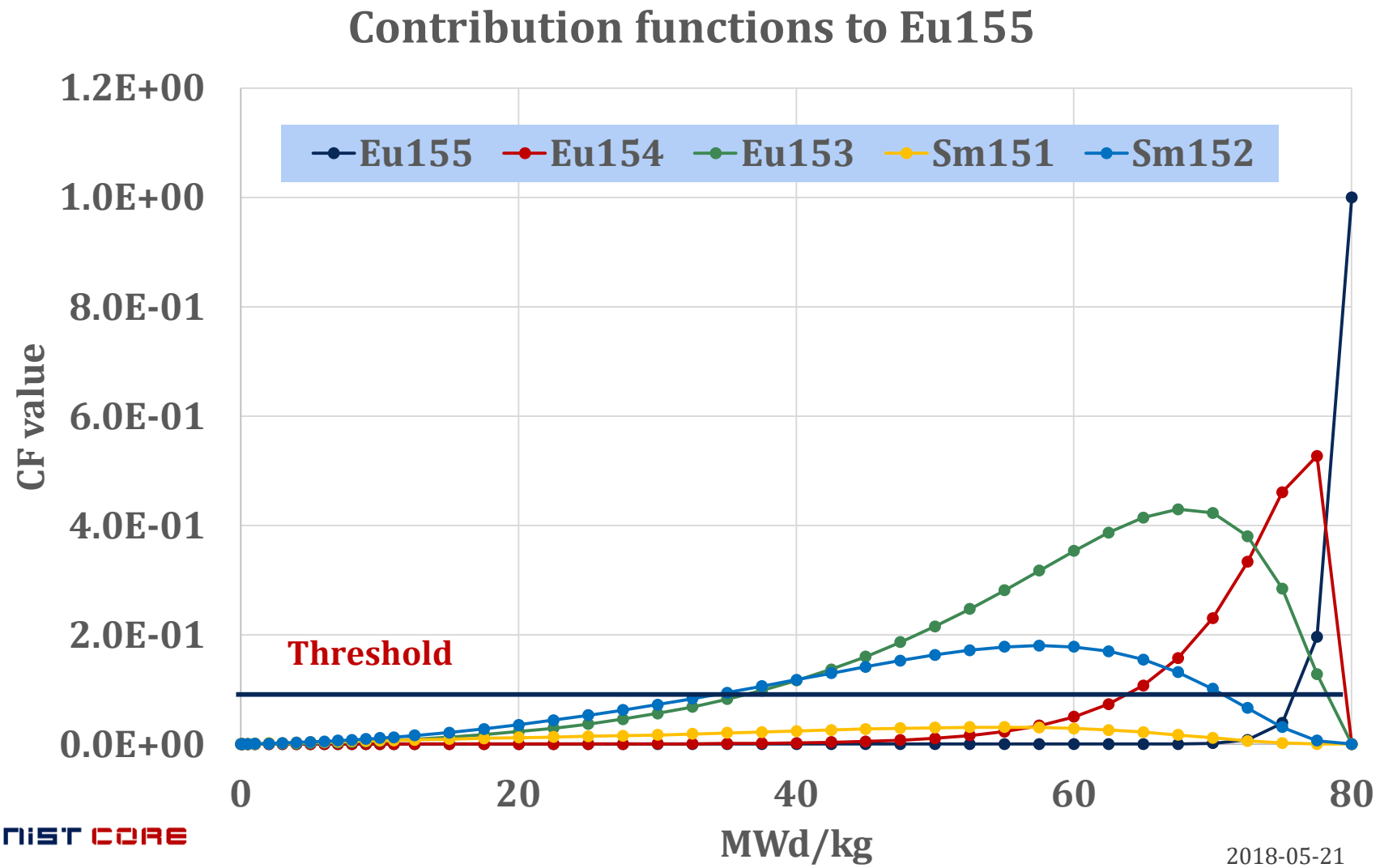
- **Then introduce the parameter so-called contribution function (CF):**

$$\boldsymbol{CF_{i\rightarrow j}(t)} = \frac{n^{*T}_i(t).n_i(t)}{n_j(t_{EOC})} \qquad (7)$$

- **Eq. (7) is the relative fraction at the time *t* that nuclide *i* will contribute to the number density of nuclide *j* at the end of burnup process.**

Overview of DPT (6/6)

- By setting threshold for the CF value, **the candidates for the simplified chain can be identified!**



II. Method and Materials

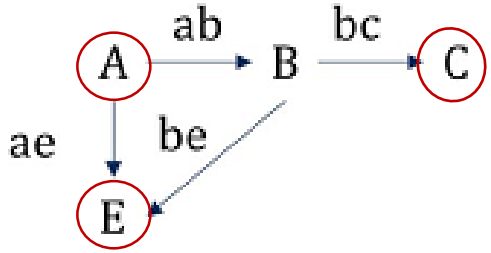
2. Simplification of the burnup matrix

Simplification of the burnup matrix (1/2)

- **Identify target nuclides:**
  - **Threshold for $\Sigma_f\phi$ and $\Sigma_c\phi$ for each depletion region (fuel, burnable absorber, etc..) in the problem.**
- **Identify candidate nuclides:**
  - **Calculate adjoint nuclides number density for target nuclides**
  - **Calculate CF for all nuclides to the target nuclides**
  - **Set threshold for the CF**
- **Redistribute the decay data and fission yield**

Simplification of the burnup matrix (2/2)

- **Redistribute the decay data and fission yield**
  - **Paths of radioactive decay are reorganized**



Transitional path for a nuclide A

$$TF(A \rightarrow E) = ae + ab \times be$$

$$TF(A \rightarrow C) = ab \times bc$$

  - **Independent fission yields of neglected precursors nuclides is added to the independent fission yields of the daughter nuclides**

A simplified burnup chain is constructed !

Constructing the simplified burnup chain

- **A mixed type fuel (Fuel, Gad fuel, IFBA,BP) fuel assembly 2D depletion problem is conducted.**

Burnup region	$\Sigma_f \phi$ threshold*	# target nuclide	$\Sigma_c \phi$ threshold	# target nuclide
Fuel	1.00E-6	30	1.00E-6	166
BP	1.00E-6	0	1.00E-6	67
IFBA	1.00E-6	0	1.00E-6	21

* Relative threshold (%)

→ 197 target nuclides !

- **Threshold for CF: 1.00E-7 (%)**

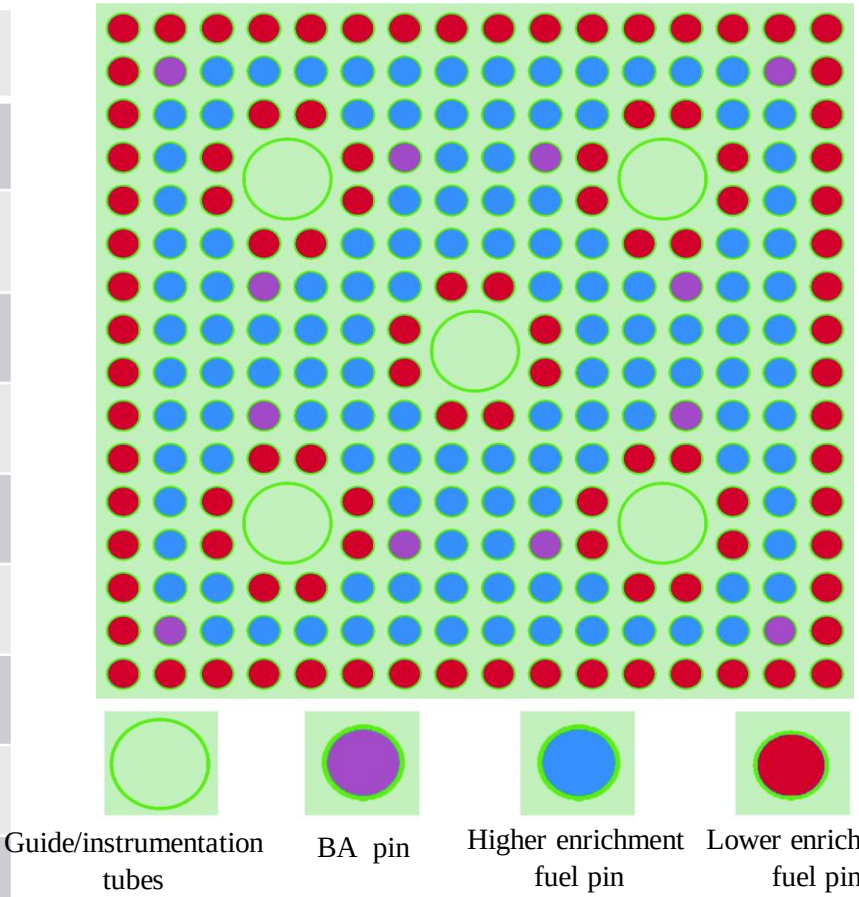
→ 464 candidate nuclides !

III. Numerical results

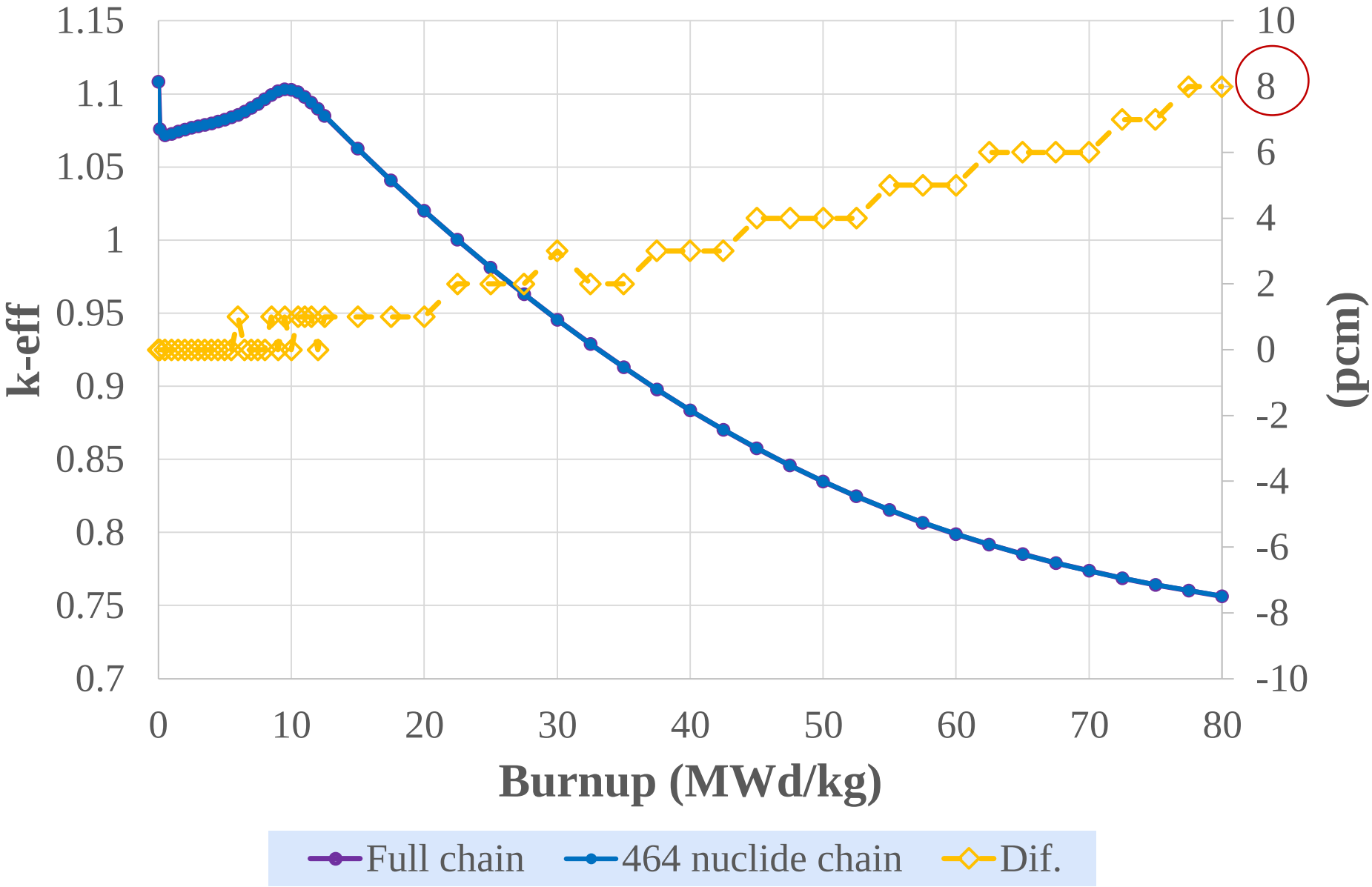
OPR-1000 FA depletion problem (1/2)

Fuel Assembly Composition and Specifications

Fuel type	Uranium oxide (UO2)
Enrichment (w/o)	3.42 / 2.92
Burnable Absorber (BA)	Gd_2O_3 (6 w/o)
Cladding material	Zircaloy-2
Coolant/Moderator	Borated Water
FA size	16 pins by 16 pins
Power Density	36.843 (W/gU)
Number of BA	12
Temperatures	Fuel - 900K
	Cladding – 600K
	Coolant/Moderator – 600K

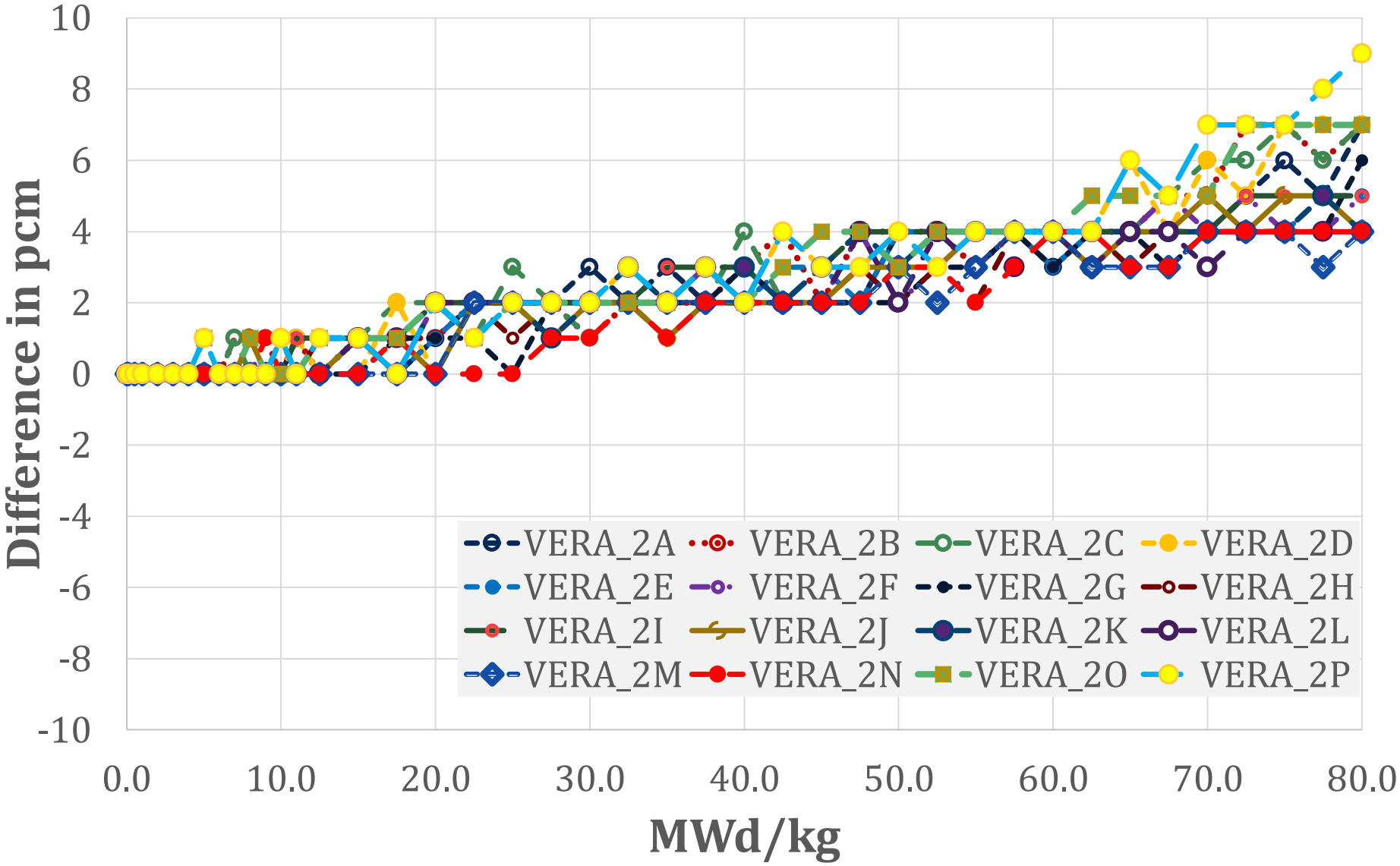


OPR-1000 FA depletion problem (2/2)

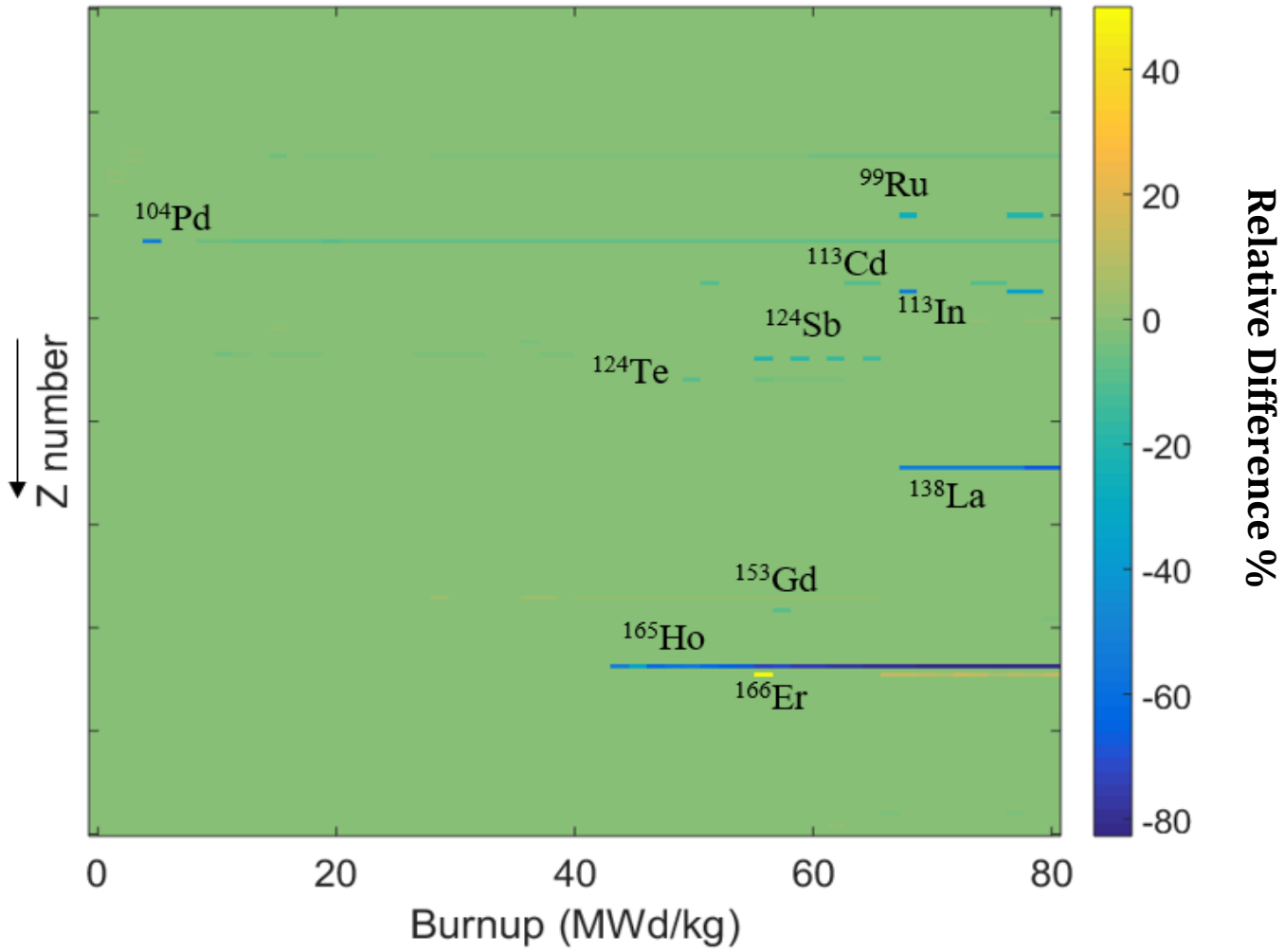


VERA Fuel Assembly 2D Depletion Problem

- **Geometry and Specification: "https://www.casl.gov/vera"**



Nuclide number density reproduction error



-Low concentration.

-Slight impact on reactivity (~0.3% difference):

^{104}Pd, ^{82}Kr, ^{96}Zr, ^{151}Pm, ^{165}Ho, ^{166}Er

Numerical Results in time reduction

	Total simulation time(s)			Depletion time(s)		
Problem	Full chain	464 chain	Ratio	Full chain	464 chain	Ratio
OPR-1000 FA	1736.4	539.9	3.2	1237.7	58.1	21.3
VERA_2A	1824.8	498.5	3.7	1358.2	34.8	39.0
VERA_2B	1792.9	474.9	3.8	1359.2	34.7	39.2
VERA_2C	1775.6	469.4	3.8	1337.8	34.4	38.8
VERA_2D	1790.1	490.6	3.6	1338.2	33.3	40.1
VERA_2E	1856.8	530.3	3.5	1357.0	33.3	40.7
VERA_2F	1869.3	543.8	3.4	1345.2	36.2	37.2
VERA_2G	1857.8	553.5	3.4	1340.9	34.0	39.4
VERA_2H	1816.5	523.7	3.5	1325.0	35.3	37.5
VERA_2I	1809.3	497.8	3.6	1357.1	34.3	39.5
VERA_2J	1849.0	548.6	3.4	1338.4	34.4	38.9
VERA_2K	1853.0	537.3	3.4	1343.1	37.6	35.7
VERA_2L	1802.9	514.0	3.5	1335.8	34.7	38.4
VERA_2M	1836.7	530.9	3.5	1343.7	34.0	39.6
VERA_2N	1829.3	541.7	3.4	1322.7	34.1	38.8
VERA_2O	1821.2	515.8	3.5	1343.6	36.5	36.8
VERA_2P	1819.0	532.9	3.4	1332.1	36.2	36.8

Conclusion

- Automatic method for building a compressed library
- Reduction of the burn up matrix size:
  - From 3837 nuclides to 464 nuclides
  - From 43416 transitions to 10638 transitions
  - Only ~10 pcm difference in k-eff for all cases
- Acceleration
  - speed-up factor of 20~40 in depletion time
  - speed-up factor of 3~4 in total simulation time

Future work

- **Generate reduced-order libraries for other purposes**
  - **decay heat / source term**
- **Consider the implicit effect**
- **Use pseudo nuclides to improve performance**
- **Implement on-the-fly nuclide tracking to adjust the size of the burnup matrix as the burnup increases**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