Analysis of the source term in circulating fuel reactors: burnup results of the SAMOSAFER Benchmark

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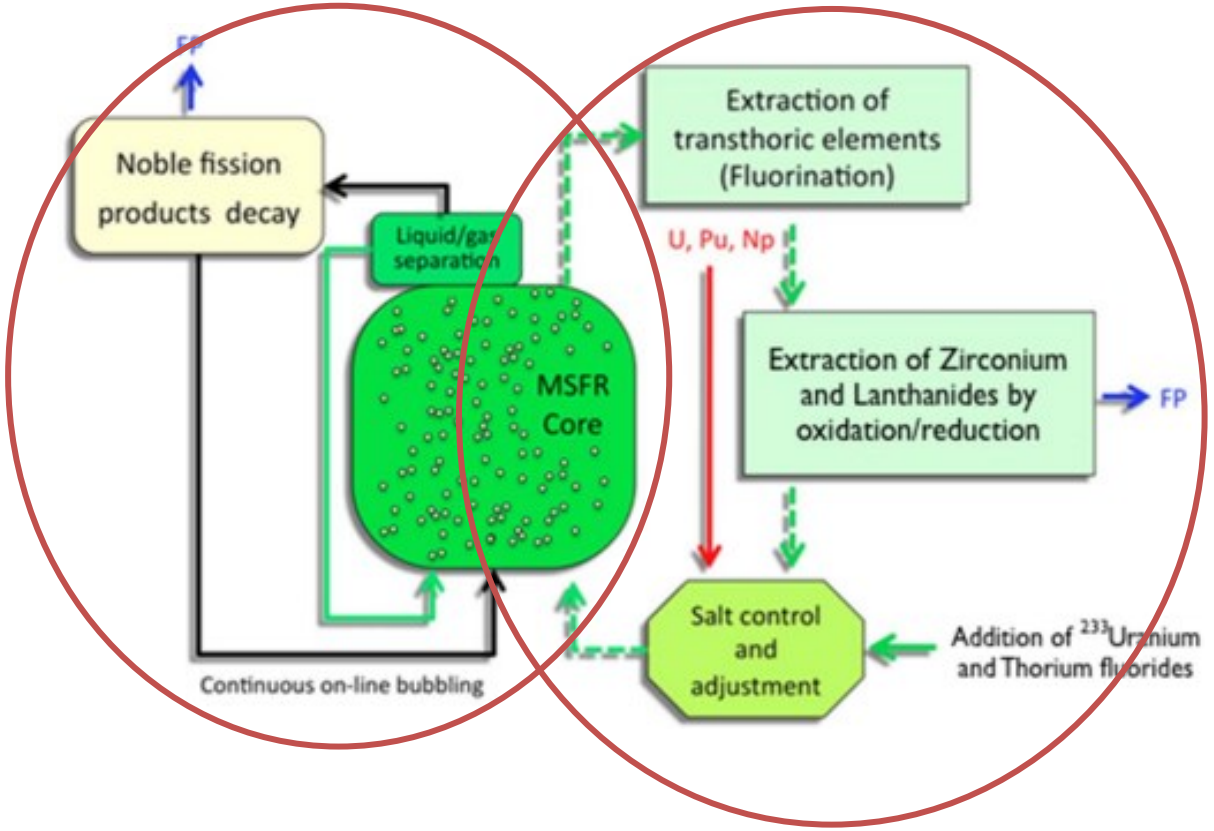
2. INTRODUCTION
MSFR and continuous reprocessing



MSFRs CONTINUOUS REPROCESSING:

- ✓ **On-line** reprocessing by **He bubbling.**
- ✓ **Off-line** reprocessing by **Fuel Treatment Unit.**

3. THESIS' STRUCTURE

Composition control and continuous reprocessing in depletion calculations

SERPENT-2 code extension — **UPG to SERPENT 2.1.32**

- FPs removal — **SotA**
- Eutectic composition control: — **SotA**
  - Continuous Thorium Mass Control
  - Molar Fraction Control
- Reactivity Control (semi-diagonal) — **SotA**

New features

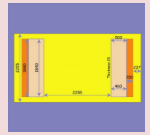
- Batch Thorium Mass Control — **NEW!**
- Effective decay constant verification — **NEW!**

SAMOSAFER benchmark

- Algorithms testing and verification
- Radioactive source term evaluation

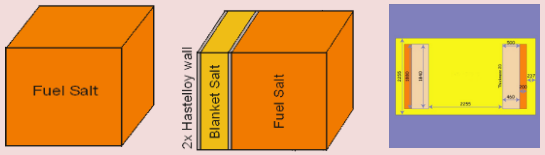
Verification case

- EVOL Benchmark geometry and compositions
- Comparison with SERPENT 2.1.17



SAMOSAFER benchmark simulations

- Incremental steps: Step 0, 3 and 4
- Fuel cube + blanket geometry and EVOL geometry for algorithms testing
- Fuel cube geometry for decay constants verification



4. BURNUP SIMULATIONS IN SERPENT-2

Bateman equations

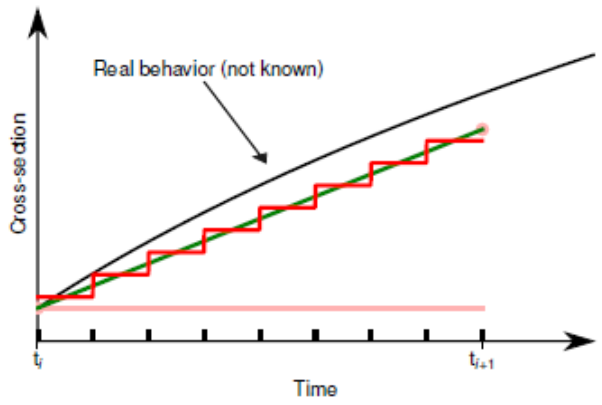
Monte Carlo transport calculation to evaluate **microscopic reaction rates**.

Bateman equations solved with time-averaged microscopic reaction rates:

$$\frac{dN_i^\alpha}{dt} = \sum_j \boldsymbol{\sigma_{j\to i}}\,\boldsymbol{\phi}\, N_j^\alpha + \sum_j \lambda_j\, b_{j\to i}\, N_j^\alpha - \sum_j \boldsymbol{\sigma_{i\to j}}\,\boldsymbol{\phi}\, N_i^\alpha - \lambda_i\, N_i^\alpha$$

Control strategies (**burnup matrix modification** and/or **batch** injection of **feed**). **Controls** also needed to achieve **equilibrium composition** rapidly.

Time steps, time substeps and **PCC** methods for better time-averaging:



5. FPs REMOVAL ALGORITHM

Introduction of effective decay constants

FPs removal needed to:

✓ Maintain composition **clean.**

✓ Remove neutron **poisons.**

✓ Avoid **bubble formation** and metal **particles deposition**.

FPs removal modeled in Bateman eq. with **effective decay constant**:

$$\frac{dN_i^\alpha}{dt} = \sum_j \sigma_{j\to i}\,\phi\,N_j^\alpha + \sum_j \lambda_j\,b_{j\to i}\,N_j^\alpha - \sum_j \sigma_{i\to j}\,\phi\,N_i^\alpha - \lambda_i\,N_i^\alpha - \boldsymbol{f_i\,\lambda_{repro}\,N_i^\alpha}$$

6. MOLAR FRACTION CONTROL ALGORITHM

Introduction of non-diagonal terms

Control of molar fraction to preserve eutectic composition

To control **heavy fraction**: Fissioned/reprocessed HM replaced with Th-232 **(feed):**

$$\frac{dN_{Th^{232}}^{\alpha}}{dt} = \sum_j \sigma_{j\to Th^{232}}\,\phi\,N_j^{\alpha} + \sum_j \lambda_j b_{j\to Th^{232}}\,N_j^{\alpha} - \sum_j \sigma_{Th^{232}\to j}\,\phi\,N_{Th^{232}}^{\alpha} - \lambda_{Th^{232}}\,N_{Th^{232}}^{\alpha} + \sum_{k=HM} \boldsymbol{\sigma_{k,fiss}\,\phi\,N_k^{\alpha}} + \sum_{k=HM} \boldsymbol{\lambda_{k,repro}\,\phi\,N_k^{\alpha}}$$

To control **light fraction**: Li-7 **removed** when FPs are produced, Li-7 **injected** when FPs are reprocessed:

$$\frac{dN_{Li-7}^{\alpha}}{dt} = \sum_j \sigma_{j\to Li-7}\,\phi\,N_j^{\alpha} + \sum_j \lambda_j b_{j\to Li-7}\,N_j^{\alpha} - \sum_j \sigma_{Li-7\to j}\,\phi\,N_{Li-7}^{\alpha} + \sum_{l=FP} \lambda_l\,N_l^{\alpha} - \sum_{k=HM} \sigma_{k,fiss}\,\phi\,N_k^{\alpha} \sum_{l=FP} Y_{k\to l}$$

7. REACTIVITY CONTROL

Semi-diagonal strategy

Tuning of fissile/fertile ratio to achieve target reactivity

Low feed:

$$\frac{dN_{Th^{232}}}{dt} = \sum_j \sigma_{j\to Th^{232}}\,\phi\,N_j + \sum_j \lambda_j b_{j\to Th^{232}}\,N_j - \sum_j \sigma_{Th^{232}\to j}\,\phi\,N_{Th^{232}}$$

$$-\lambda_{Th^{232}}\,N_{Th^{232}} + \sum_{k=HM} \boldsymbol{\sigma_{k,fiss}\,\phi\,N_k} + \sum_{k=HM} \boldsymbol{\lambda_{k,repro}\,\phi\,N_k} - \boldsymbol{\lambda_{rc}\,f_{rc}\,N_{Th^{232}}}$$

High feed:

$$\frac{dN_{U^{233}}}{dt} = \sum_j \sigma_{j\to U^{233}}\,\phi\,N_j + \sum_j \lambda_j b_{j\to U^{233}}\,N_j - \sum_j \sigma_{U^{233}\to j}\,\phi\,N_{U^{233}}$$

$$-\lambda_{U^{233}}\,N_{U^{233}} + \boldsymbol{\lambda_{rc}\,f_{rc}\,N_{Th^{232}}}$$

Independent from Molar Fraction Control algorithm, **coupling** possible.

8. SERPENT 2.1.32 UPDATE

Implementation of the algorithms in Serpent 2.1.32

SERPENT
Monte Carlo burnu
extensions for MSF
- ✓ **FPs** removal.
- ✓ **MFC** algorithm.
- ✓ **RC** algorithm.

CHANGELOG:
- ✓ **Adaptation** of control algorithms in the new burnup routine of Serpent 2.1.32.
- ✓ **Bug fix:** burning of actinides with **isomeric branching ratio** now works properly.
- ✓ Other **minor bug fix** in MFC and RC algorithms.

2.1.32
o code +
R:

Mass Control

nd errors.

9. THORIUM MASS CONTROL ALGORITHM

Continuous/Batch

Constant thorium mass to preserve eutectic composition.

Continuous strategy: $\frac{dN^{\alpha}_{Th^{232}}}{dt} = 0$

If time discretization is fine enough, results obtained with batch algorithm should approach continuous ones.

Batch strategy: refill of consumed Th-232 at end of substep. **More realistic**. May face issues if **time steps are too long.**

- ✓ **Simple** and effective.
- ✓ Thorium control leads to slight **increase of actinides mol% in long simulations**.

10. EFFECTIVE DECAY CONSTANT VERIFICATION

Analytical solutions

How to check if the correct **effective decay constant** is correctly used in the calculations?

Comparison could be made in Step 0 (**Decay only**):

- ✓ avoid the **contribution due to the irradiation**
- ✓ starting from an **already irradiated composition** allows catching the short cycle time in the very first steps of the history.

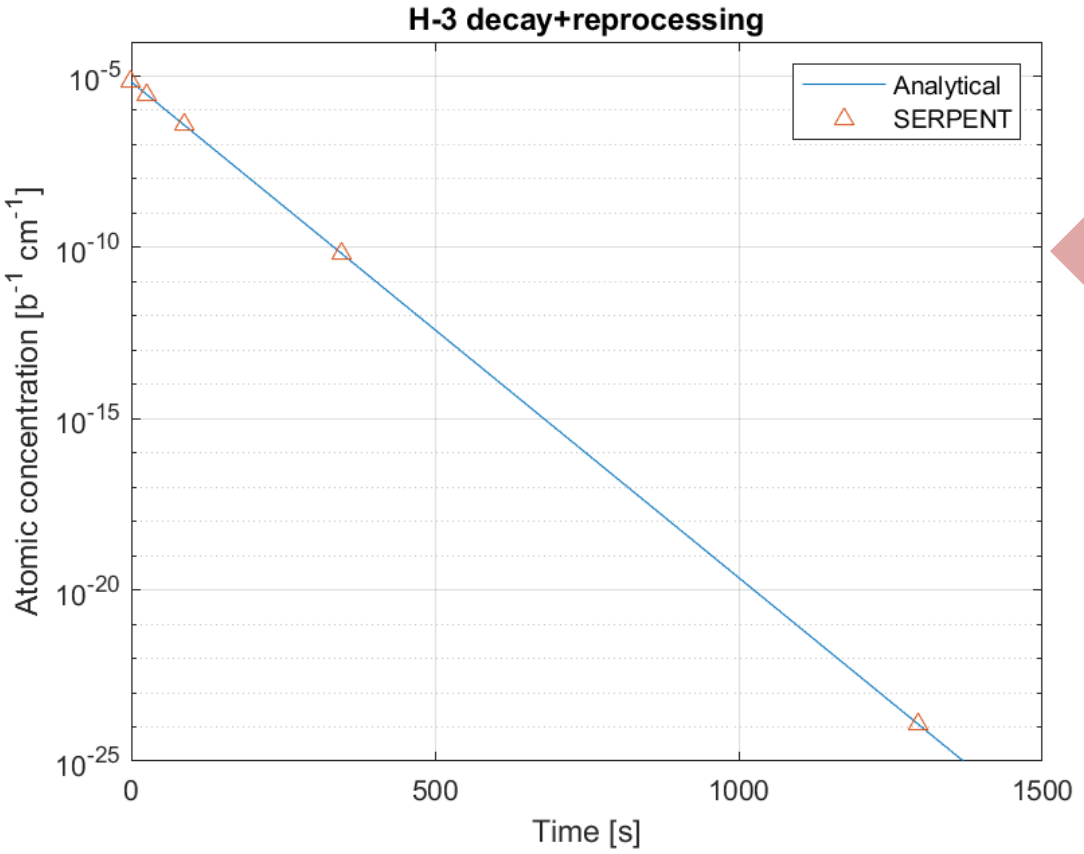
Bateman equations in this case become:

$$\frac{dN_i^\alpha}{dt} = +\sum_j \lambda_j \, b_{j\to i} \, N_j^\alpha \; - \lambda_i \; N_i^\alpha \; - \lambda_{repro} \, N_i^\alpha$$

Analytical solutions - exponential law with a specific decay constant - for some nuclides in the burnup matrix can be used **as a comparison (verification) wrt numerical results.**

11. EFFECTIVE DECAY CONSTANT VERIFICATION

Specific nuclides option



1st option: comparison with nuclides which are **not the product of radioactive decay** of any nuclide in BU matrix:

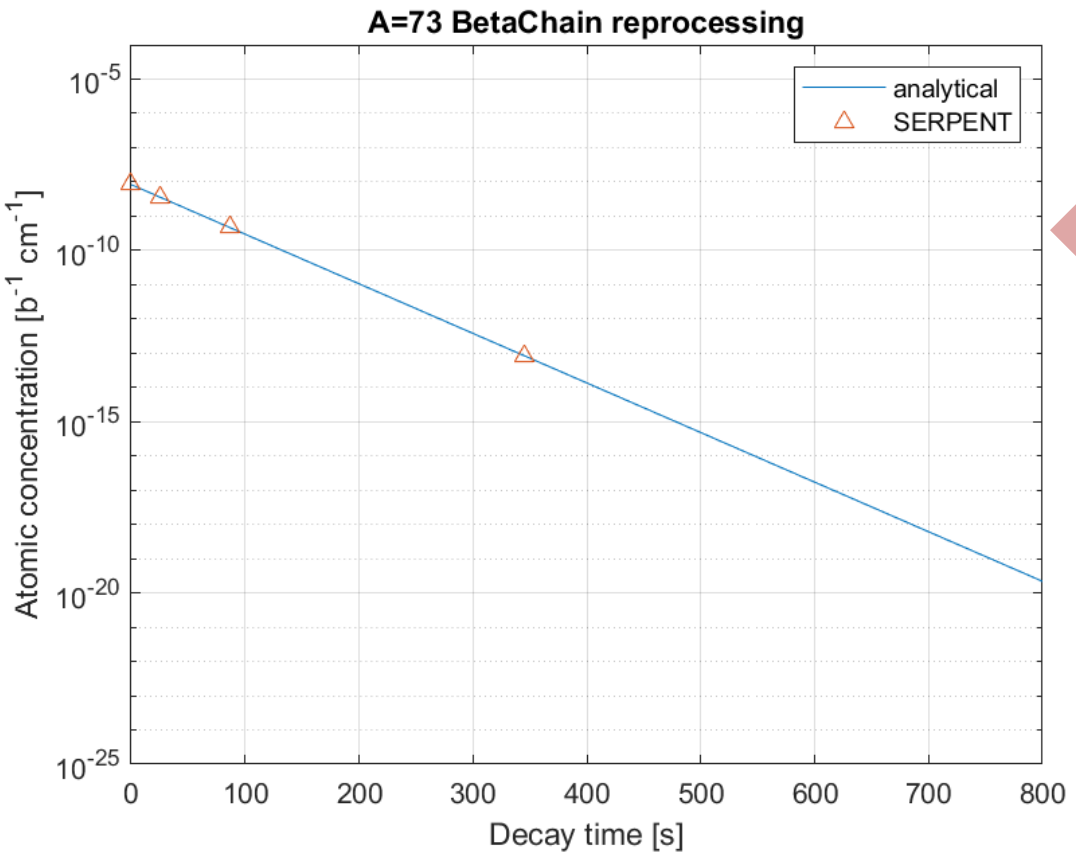
$$\frac{dN_i}{dt} = -(\lambda_{repro} + \lambda_i) N_i$$

$$N_i(t) = N(0) \exp\left[-(\lambda_{repro} + \lambda_i)\, t\right]$$

Pros: simple and immediate.
Cons: Very few are present with relevant concentrations, i.e., noise issues.

12. EFFECTIVE DECAY CONSTANT VERIFICATION

Beta decay chain option



2nd option: **β chain** comparison. The overall concentration of nuclides belonging to a beta decay chain follows a simple exponential behavior:

$$\frac{d}{dt}(N_1 + N_2 + \cdots) = -(\lambda_{repro})(N_1 + N_2 + \cdots)$$

$$(N_1 + N_2 + \cdots)(t) = (N_1(0) + N_2(0) + \cdots)\exp[-(\lambda_{repro}t)]$$

Pros: higher densities, i.e., less noise issues.
Cons: cannot be used if **other decay modes** are present in β chain.

13. SAMOSAFER BENCHMARK DEFINITION

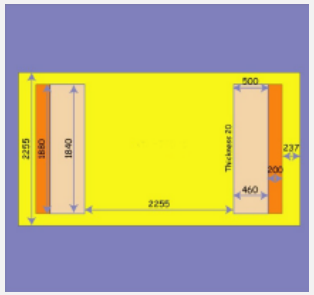
Incremental steps

1. **Upgrade** t[illegible] implementation of Th mass control algorithm.

2. **EVOL be**[illegible]s verification.

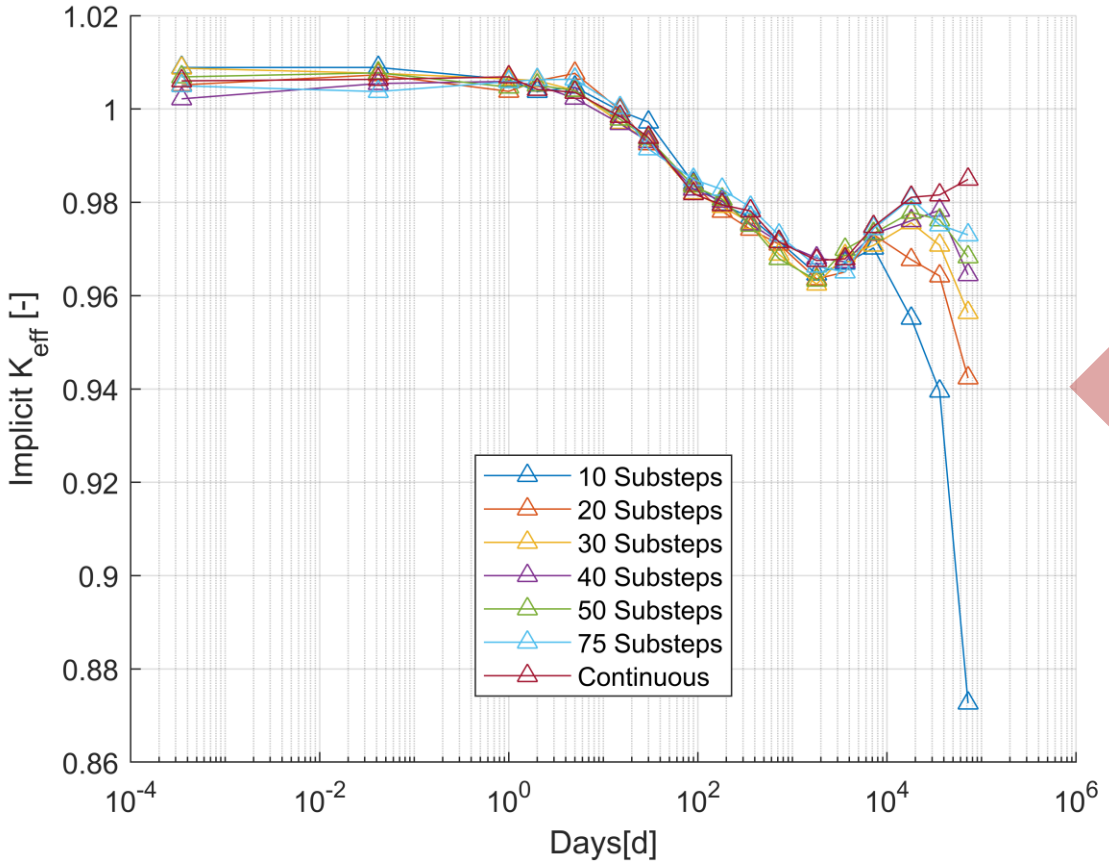
STEP 3.05

- ✓ **Th mass control**
- ✓ **Off-gas + FTU + BTU** treatments.
- ✓ **EVOL** benchmark geometry and compositions.



14. SAMOSAFER BENCHMARK RESULTS

Batch thorium mass control verification



Results **converge** towards the ones obtained with **continuous** algorithm **as the number of substeps increases**.

15. CONCLUSIONS AND FUTURE DEVELOPMENTS

The algorithms can control **eutectic composition and reactivity** effectively. **Equlibrium** is reached by FPs and main actinides.

The algorithms have been successfully implemented in **Serpent 2.1.32**, the results obtained with it are **compatible** with EVOL simulations with **Serpent 2.1.17**. Moreover, the tool has also been successfully verified by means of the comparison with **analytical solutions** of Bateman equations.

Future developments:

- ✓ **RESULTS COMPARISON WITH THE PARTNERS.**
- ✓ **EXPERIMENTAL VALIDATION.**

New **Batch thorium mass control** algorithm allows maintaining the mass of Th-232 constant and the results **approach the continuous ones** if time substeps are small enough.

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Thanks for your attention