Comparison Between Continuous and Batchwise Online Reprocessing in Serpent2

Luke Seifert, Madicken Munk

University of Illinois at Urbana-Champaign, Department of Nuclear, Plasma, and Radiological Engineering, Urbana, IL 61801

Introduction

Molten Salt Reactor Online Reprocessing

- Depletion of a reactor provides useful data on safety parameter and fuel cycle evolution
- Depletion of Molten Salt Reactors requires accounting for reprocessing
- Batchwise modeling of Molten Salt Reactors is common [6, 2]
- Continuous modeling offers unique advantages over batchwise modeling

Table 1: Online Reprocessing Cycle Times [4]

Reprocessing Group	Element(s)	Cycle Time
Rare Earths	Y, La, Ce, Pr, Nd, Pm, Sm, Gd	50 days
Rare Earths	Eu	500 days
Noble Metals	Se, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Sb, Te	20 seconds
Seminoble Metals	Zr, Cd, In, Sn	200 days
Gases	Kr, Xe	20 seconds
Volatile Fluorides	Br, I	60 days
Discard	Rb, Sr, Cs, Ba	3435 days
Salt Discard	Th, Li, Be, F	3435 days
Protactinium	Pa	3 days
Higher Nuclides	Np, Pu	16 years

Comparison of Methods

- An identical toy model is implemented for both methods in Serpent2 [3]
- Continuous model uses varying number of steps
- Multiple approaches are implemented for the continuous model

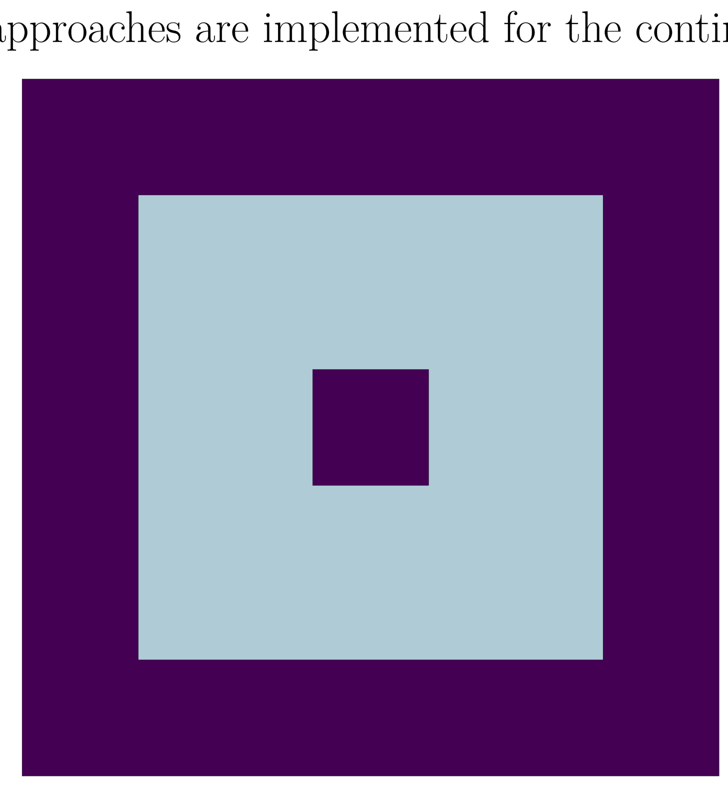

Figure 1: Geometry of toy model used in serpent2 for continuous and batchwise reprocessing models. Composed of a cube of fuel salti (cyan) with a graphite log in the center and a graphite shell (purple).

Table 2: Approach Acronyms and Descriptions

Approach	Description
SP pre	SaltProc steady batch pre-depletion
SP post	SaltProc steady batch post-depletion
CR	Cycle Rate continuous approach
SPCR	SaltProc Cycle Rate continuous approach
CTD	Cycle Time Decay continuous approach
CTRL	Control method (no reprocessing feeds or removal)

Objectives

- Capture the precise differences in continuous and batchwise models
- Determine effective depletion step sizes for continuous reprocessing
- Investigate validity of using average feed rates during depletion

Contact Information

- Email: seifert5@illinois.edu
- Phone: +1 865 279 0603

Reprocessing Models

Batchwise Reprocessing

- Iteratively perform depletion with external adjustments
- ***Steady Batch*** uses small removals each depletion step.

$$X = \frac{1}{T_{cyc}} \tag{1}$$

- T_{cyc} is the cycle time
- X is the fractional removal rate

- ***Bulk Batch*** uses full removal after a set number of depletion steps.
- SaltProc is used to run batchwise reprocessing for Serpent2 [5]
- The current version of SaltProc uses the Steady Batch method

Table 3: Batchwise Reprocessing Methods

Approach	Cycle Time	X [s^{-1}]	Step Removal
Bulk Batch [3d]	20 s	-	1
Bulk Batch [3d]	30 d	-	0*
Steady Batch [3d]	20 s	3.86E-6	1
Steady Batch [3d]	3 d	3.86E-6	1
Steady Batch [3d]	30 d	3.86E-7	0.1

* Bulk removal occurs after 30 days, so the step fractional removal becomes 1 at 30 day step.

Continuous Reprocessing

- Adds 'decay-like' term to Bateman equation, less iterative [1]

$$\left.\frac{dN_j}{dt}\right|_{base} = \sum_{i \neq j} \left[\left(\gamma_{i\rightarrow j}\sigma_{f,i}\Phi + \lambda_{i\rightarrow j} + \sigma_{i\rightarrow j}\Phi \right) N_i \right] - \left(\lambda_j + \sigma_j \Phi \right) N_j \tag{2}$$

$$\left.\frac{dN_j}{dt}\right|_{net} = \left.\frac{dN_j}{dt}\right|_{base} - \lambda_{r,j} N_j + \sum_{mat} \lambda_{r,i\rightarrow j} N_i \tag{3}$$

The symbols given in the equations are defined as follows:

- N_j is the atomic density of isotope j.
- $\gamma_{i\rightarrow j}$ is the fractional fission product yield of j in the fission of isotope i.
- $\sigma_{f,i}$ is the microscopic fission cross section of isotope i.
- Φ is the spectrum-averaged scalar flux in the fuel region.
- $\lambda_{i\rightarrow j}$ is the decay constant of decay $i \rightarrow j$.
- $\sigma_{i\rightarrow j}$ is the microscopic transmution cross section of reaction $i \rightarrow j$.
- N_i is the atomic density of isotope i.
- λ_j is the decay constant of isotope j.
- $\lambda_{r,j}$ is the reprocessing constant for removal of isotope j.
- σ_j is the microscopic total transmutation cross section of isotope j.
- $\lambda_{r,i\rightarrow j}$ is the reprocessing constant for feed of material $i \rightarrow j$.

- ***Cycle Time Decay*** (CTD) model treats reprocessing as decay

$$\tau_{1/2} = \frac{1}{2} T_{cyc} \tag{4}$$

$$\lambda_r = \frac{ln(2)}{\tau_{1/2}} \tag{5}$$

- ***Cycle Rate*** (CR) treats as linear fractional removal, same as Steady Batch

$$\lambda_r = ln\left(\frac{1}{1-X}\right) \tag{6}$$

- ***SaltProc Cycle Rate*** (SPCR) mimics batchwise reprocessing with continuous model

Table 4: Continuous Reprocessing Methods

Approach	Cycle Time	$\tau_{1/2}$	X [s^{-1}]	λ_r [s^{-1}]
Cycle Time Decay	20 s	10 s	6.70E-2	6.93E-2
Cycle Time Decay	3 d	1.5 d	5.35E-6	5.35E-6
Cycle Rate	20 s	-	0.05	5.13E-2
Cycle Rate	3 d	-	3.86E-6	3.86E-6
SaltProc Cycle Rate	20 s	-	3.86E-6	3.86E-6
SaltProc Cycle Rate	3 d	-	3.86E-6	3.86E-6
SaltProc Cycle Rate	30 d	-	3.86E-7	3.86E-7

Results

Multiple Steps

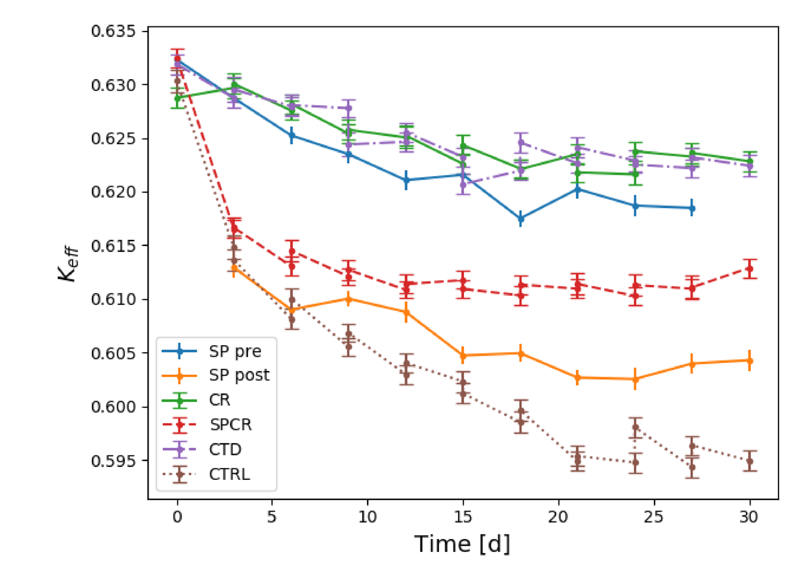

Figure 2: Continuous and batch models k_{eff} over time when using the matching depletion steps and feed rates.

Single Step

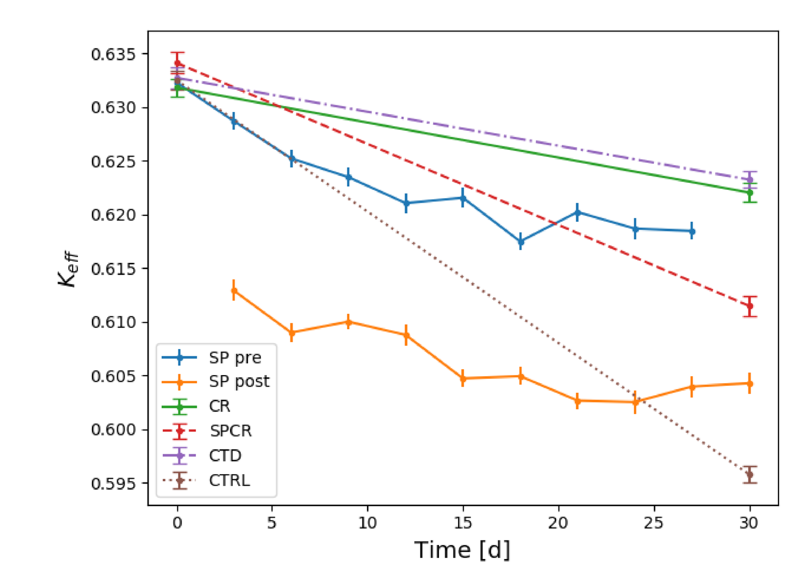

Figure 3: Continuous and batch models k_{eff} over time when continuous uses a single step and average feed rates.

Overall Results

Table 5: k_{eff} at 30 Days for 3 and 30 Day Steps

Approach	3d Step k_{eff}	30d Step k_{eff}	Diff [pcm]
CR	0.622815	0.622043	77
SPCR	0.612871	0.611481	140
CTD	0.62241	0.623246	84
CTRL	0.594924	0.595784	86

Key Takeaways

- Continuous with same depletion steps results in higher k_{eff}
- Step size order of magnitude increase and average feed rate usage resulted in 100 pcm difference in final k_{eff}
- Step size increase reduces computational cost by a factor of 10
- Average feed rate use eliminates double running, making depletion twice as efficient

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