



# Comparison Between Continuous and Batchwise Online Reprocessing in Serpent2



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## 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 [3, 2]
- Continuous modeling offers unique advantages over batchwise modeling

### Comparison of Methods

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

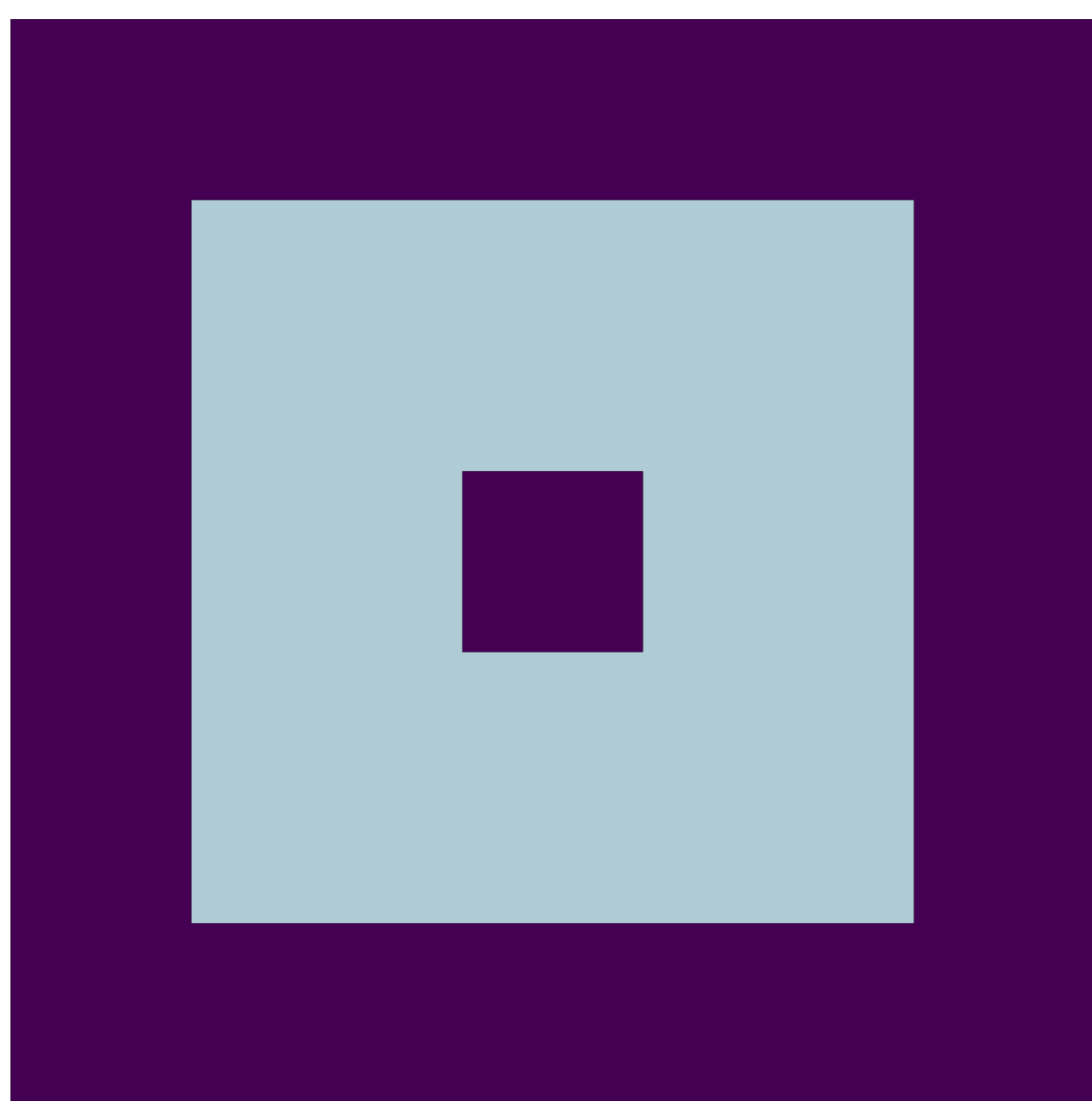


Figure 1: Geometry of toy model used in serpent2 for continuous and batchwise reprocessing models. Composed of a cube of fuel salt with a graphite log in the center and a graphite shell.

Table 1: 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

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## Reprocessing Models

### Batchwise Reprocessing

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

$$X = \frac{1}{T_{cyc}} \quad (1)$$

- $T_{cyc}$  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
- The current version of SaltProc uses the Steady Batch method

Table 2: Batchwise Reprocessing Methods

Approach	Cycle Time	X [s <sup>-1</sup> ]	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]

$$\frac{dN_j}{dt_{base}} = \sum_{i \neq j} [(\gamma_{i \rightarrow j} \sigma_{f,i} \Phi + \lambda_{i \rightarrow j} + \sigma_{i \rightarrow j} \Phi) N_i] - (\lambda_j + \sigma_j \Phi) N_j \quad (2)$$

$$\frac{dN_j}{dt_{net}} = \frac{dN_j}{dt_{base}} - \lambda_{r,j} N_j + \sum_{mat} \lambda_{r,i \rightarrow j} N_i \quad (3)$$

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  $i$ .
- $\Phi$  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 transmutation cross section of reaction  $i \rightarrow j$ .
- $N_i$  is the atomic density of isotope  $i$ .
- $\lambda_j$  is the decay constant of isotope  $j$ .
- $\lambda_{r,j}$  is the reprocessing constant for removal of isotope  $j$ .
- $\sigma_j$  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

$$\tau_{1/2} = \frac{1}{2} T_{cyc} \quad (4)$$

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

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

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

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

Table 3: Continuous Reprocessing Methods

Approach	Cycle Time	$\tau_{1/2}$	X [s <sup>-1</sup> ]	$\lambda_r$ [s <sup>-1</sup> ]
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

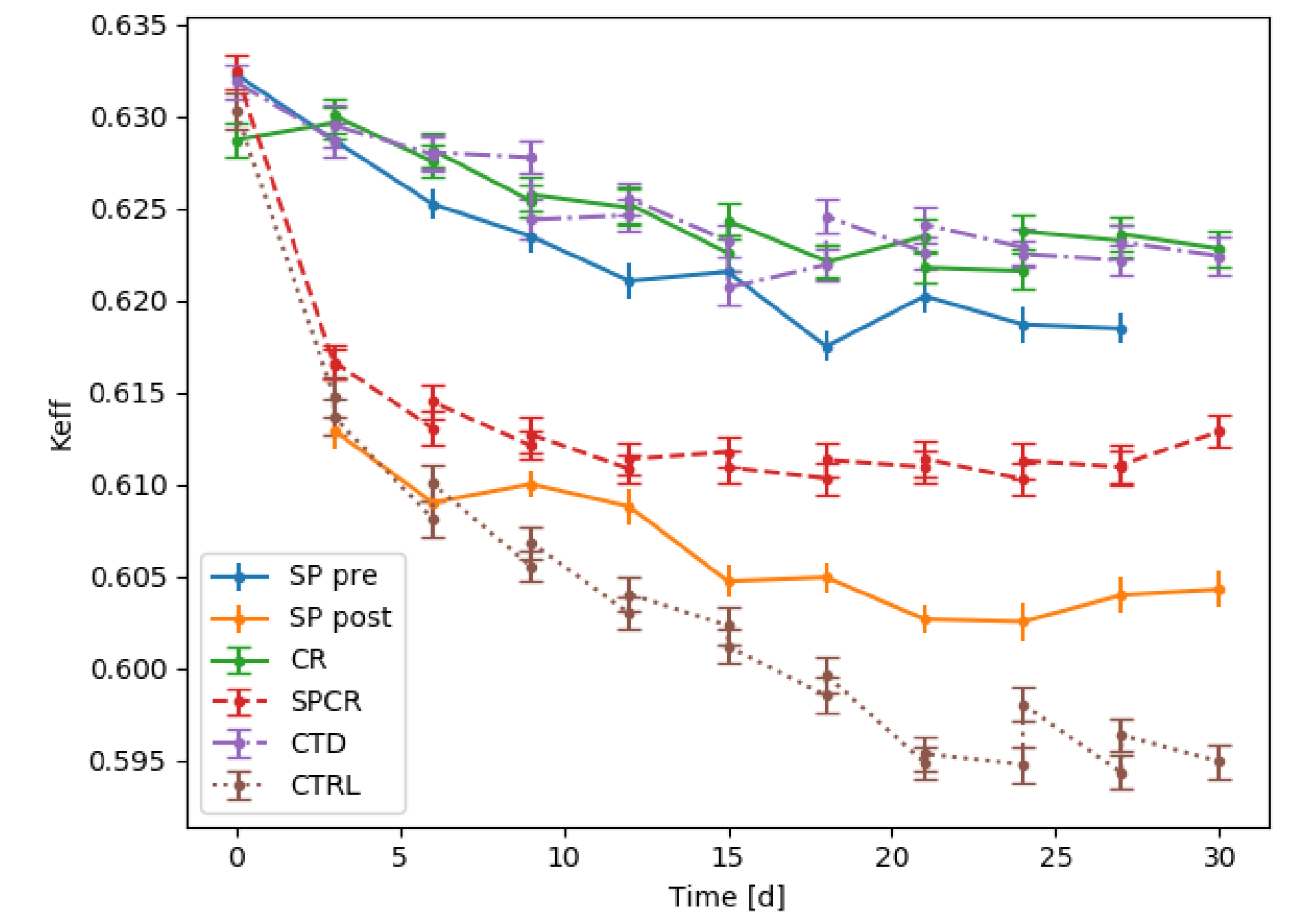


Figure 2: Continuous and batch models  $k_{eff}$  over time when using the matching depletion steps and feed rates.

### Single Step

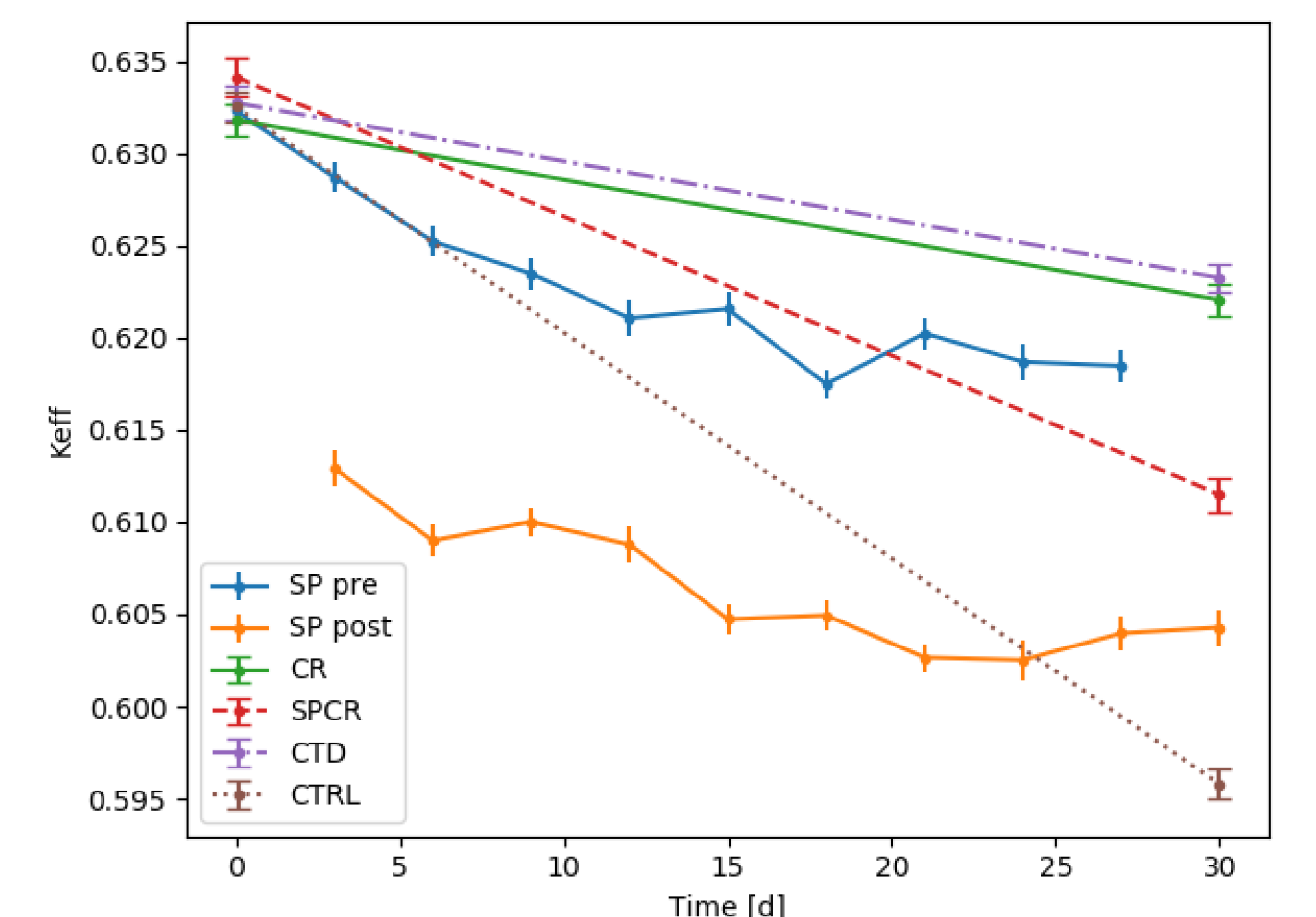


Figure 3: Continuous and batch models  $k_{eff}$  over time when continuous uses a single step and average feed rates.

### Overall Results

Table 4:  $k_{eff}$  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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## References

- [1] M. Aufiero, A. Cammi, C. Fiorina, J. Leppänen, L. Luzzi, and M. Ricotti. An extended version of the SERPENT-2 code to investigate fuel burn-up and core material evolution of the Molten Salt Fast Reactor. *Journal of Nuclear Materials*, 441(1-3):473-486, Oct. 2013.
- [2] B. R. Betzler, J. J. Powers, and A. Worrall. Molten salt reactor neutronics and fuel cycle modeling and simulation with SCALE. *Annals of Nuclear Energy*, 101:489-503, Mar. 2017.
- [3] A. Rykhlevskii, J. W. Bae, and K. D. Huff. Modeling and simulation of online reprocessing in the thorium-fueled molten salt breeder reactor. *Annals of Nuclear Energy*, 128:366-379, June 2019.