Depletion of molten salt reactor with online salt conditioning in the Monte Carlo iMC code

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Introduction

- Molten salt reactor, MSR
  - One of the Gen IV advanced reactor systems
  - Utilize liquid fuel in the form of salt
  - Using liquid fuel enables unique concepts
    - Helium bubbling
    - Off-gas system
    - Online refueling

- Considering the systems is necessary for accurate MSR simulation
  - Material composition change affects depletion calculation

- Implementation of the systems is studied

Method

Fictitious decay constant

- Circulation time and removal efficiency given
  - Circulation time: Δt, removal efficiency: ϵ
  - Removal is proportional to concentration N
    - Adopt fictitious decay constant
      - Decay rate is proportional to concentration

- Applying fictitious decay constant λ_R to represent removal:

$$\frac{dN}{dt} = -\lambda_R N \ \rightarrow N(t) = N(0)\exp[-\lambda_R t]$$

- Let removal occurs when nuclide reaches certain point in the reactor (i.e. top)
  - Number of removed nuclides

$$\epsilon \equiv \frac{[removed]}{[reached]} = \frac{Rate\ of\ removal}{Rate\ of\ reaching\ top} = \frac{R}{Rate\ of\ volume\ reaching\ top} \times \frac{1}{Number\ density} \ \rightarrow R = \epsilon A v N$$

- Number of removed nuclide until time t

$$Removed\ in\ time\ t = V\big(N(0) - N(t)\big) = VN(0)\big(1 - e^{-\lambda_R t}\big) = \epsilon A v t N(0)$$

$$1 - e^{-\lambda_R \Delta t} = \epsilon \ \rightarrow \lambda_R = -\frac{\ln(1-\epsilon)}{\Delta t}$$

Method

Applying to burnup calculation

- Typical ODE regarding nuclide production/loss

$$\frac{dN_i}{dt} = \sum_{j \neq i} \left(l_{ij}\lambda_j + f_{ij}\sigma_j\phi\right)N_j(t) - (\lambda_i + \sigma_i\phi)N_i(t)$$

- Using fictious decay constant to consider removal

$$\frac{dN_i}{dt} = \sum_{j \neq i} \left(l_{ij}\lambda_j + f_{ij}\sigma_j\phi\right)N_j(t) - (\lambda_i + \boldsymbol{\lambda_{Ri}} + \sigma_i\phi)N_i(t)$$

$$\lambda_{Ri} = -\frac{\ln(1-\epsilon_i)}{T_i}$$

where ϵ_i is removal efficiency and T_i is circulation time of nuclide i

Method

Continuous refueling scheme

- During burnup, fissionable nuclides removed due to fission reaction
- Continuous refueling aims to compensate fissionable nuclide loss
  - Feed fissionable material with rate identical to fission rate

$$\Delta\frac{dN_i}{dt} = +r_i R_{fission}$$

where r_i is fraction of nuclide i in the feed

  - Rate of fission is summation of all fissionable material's fission rate

$$\Delta\frac{dN_i}{dt} = +\sum_{j=fiss.} r_i \sigma_{j,f} \phi N_j$$

- Fission rate is proportional to neutron flux
  - Fictitious cross-section can be applied to consider neutron flux

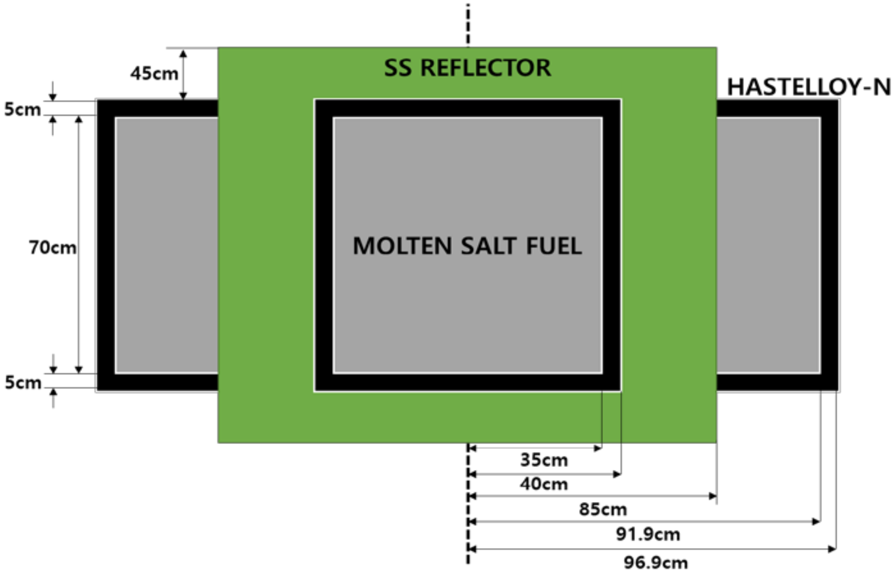
$$\frac{dN_i}{dt} = \sum_{j\neq i}\left(l_{ij}\lambda_j + f_{ij}\sigma_j\phi\right)N_j(t) - (\lambda_i + \boldsymbol{\lambda_{Ri}} + \sigma_i\phi)N_i(t) + \sum_{j=fiss.} r_i \boldsymbol{\sigma_{j,f}}\phi N_j$$

Validation

Validation problem

- Molten salt reactor model
  - 67KCl-33TRUCl fuel
  - Hastelloy-n cylindrical containment
  - SS reflector
  - 100MWth

- Monte Carlo simulation done with iMC code
  - 100 inactive cycles, 200 active cycles
  - 20,000 histories per cycle
    - Standard deviation ~ 30pcm



Validation

Validation problem

- Off-gas system
  - Applied for only noble gas and noble metals
    - Noble metal: Mo, Tc, Se, …
    - Noble gas: Kr, Xe
  - Varied removal efficiency and circulation time T

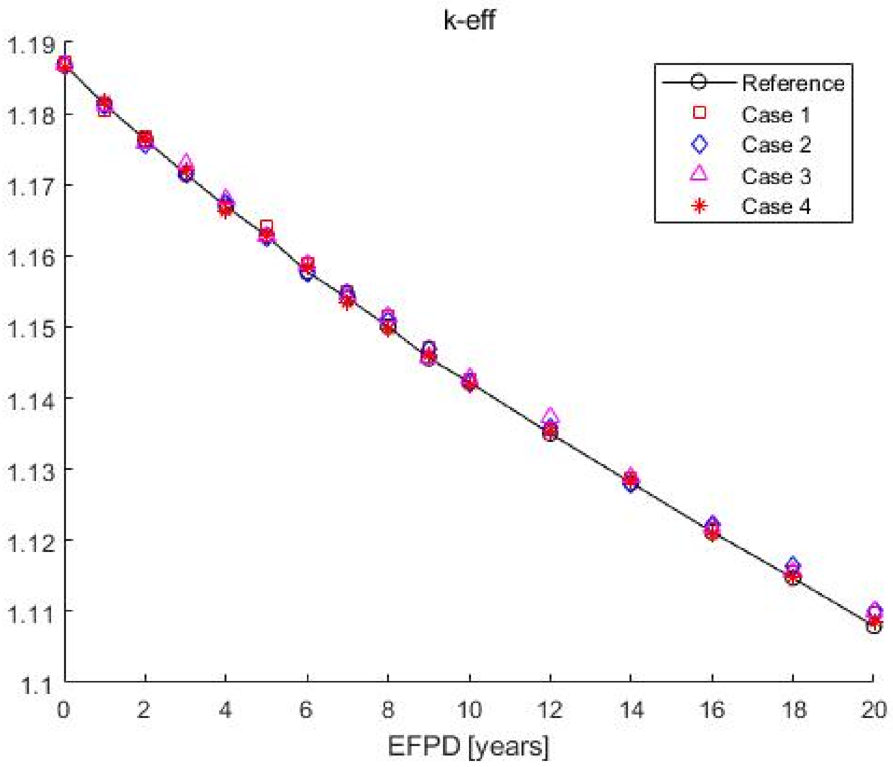
Case #	**Noble metal**	**Noble gas**	**Circulation time**
Reference	0 %	0 %	10s
Case 1	90 %	90 %	
Case 2	50 %	50 %	
Case 3	90 %	50 %	
Case 4	90 %	0 %	

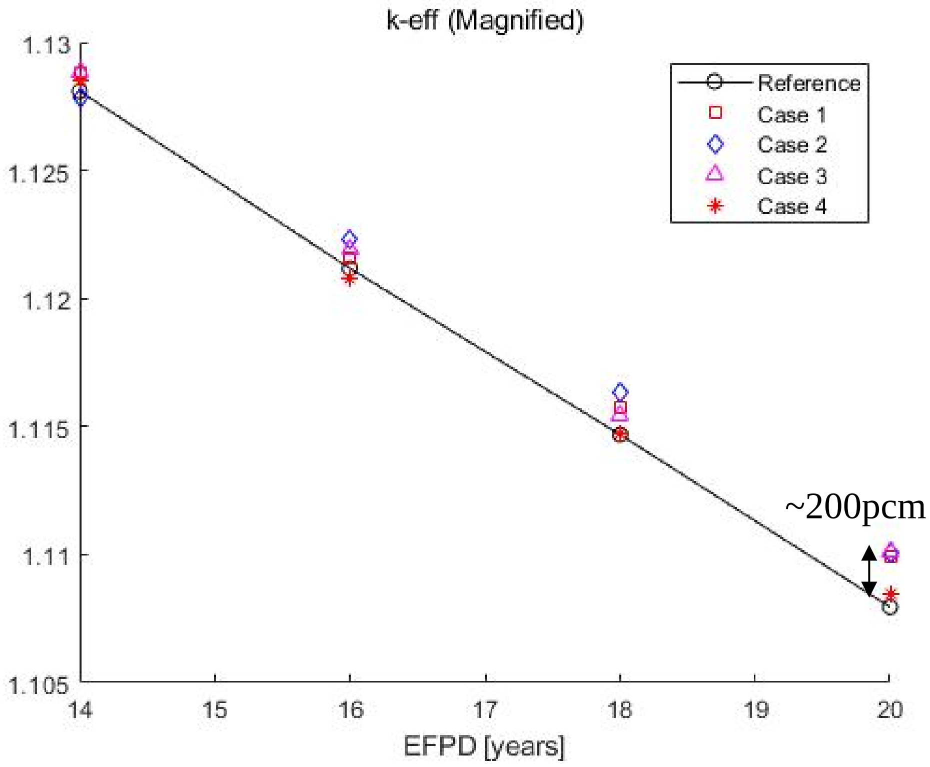
- Online refueling
  - Tested continuous refueling
    - Refuel with fresh fuel (67KCl-33TRUCl)

Result

Nuclide removal

- k-eff comparison
  - k-eff increased in case 1-3
    - Reactor removal efficiency merely affects reactor performance since $t_{circulation} \ll burnup\ step$
  - Case 4 agrees with reference
    - Solely removing noble gas does not affect reactivity



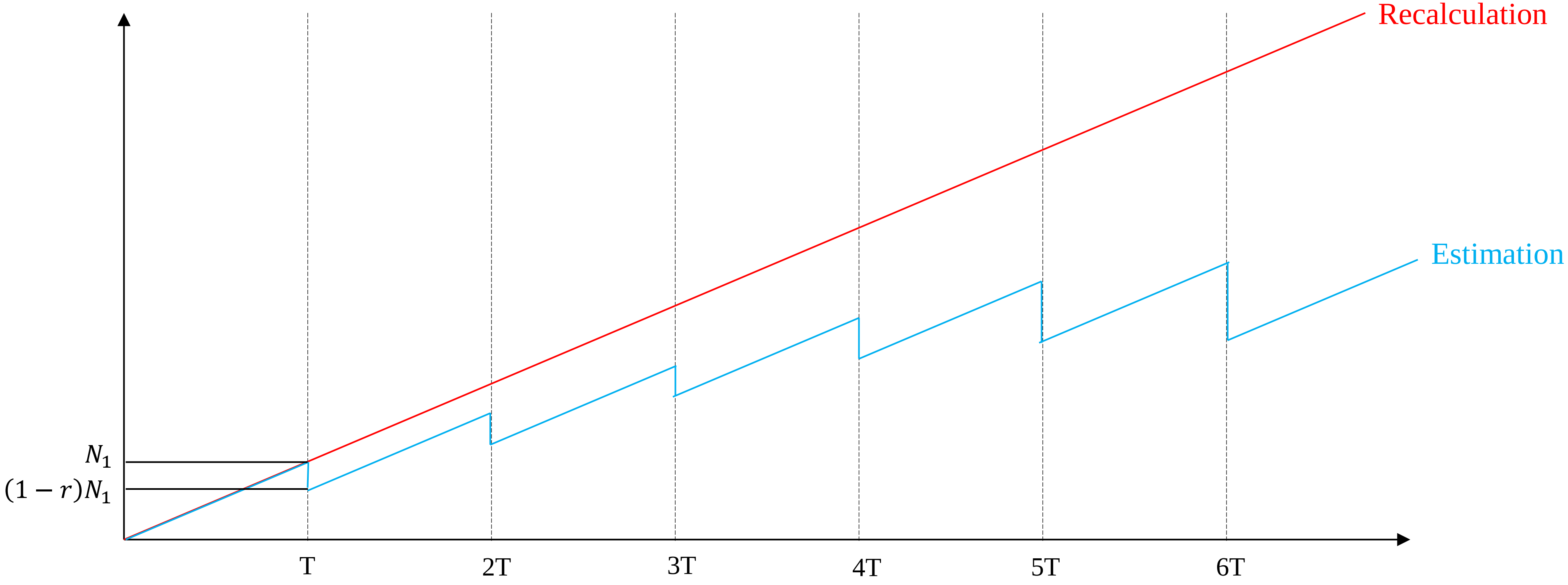


~200pcm

Result

Nuclide removal

- Nuclide concentration
  - Nuclide concentration estimation
    - Recalculate with identical removal coefficient except target nuclide
    - Estimate target nuclide concentration with removal efficiency and circulation time.
    - Since T << burnup step, for stable nuclide, equilibrium will be obtained
    - Assumption: target fission product accumulation merely affect reactor performance



Result

Nuclide removal

- Equilibrium

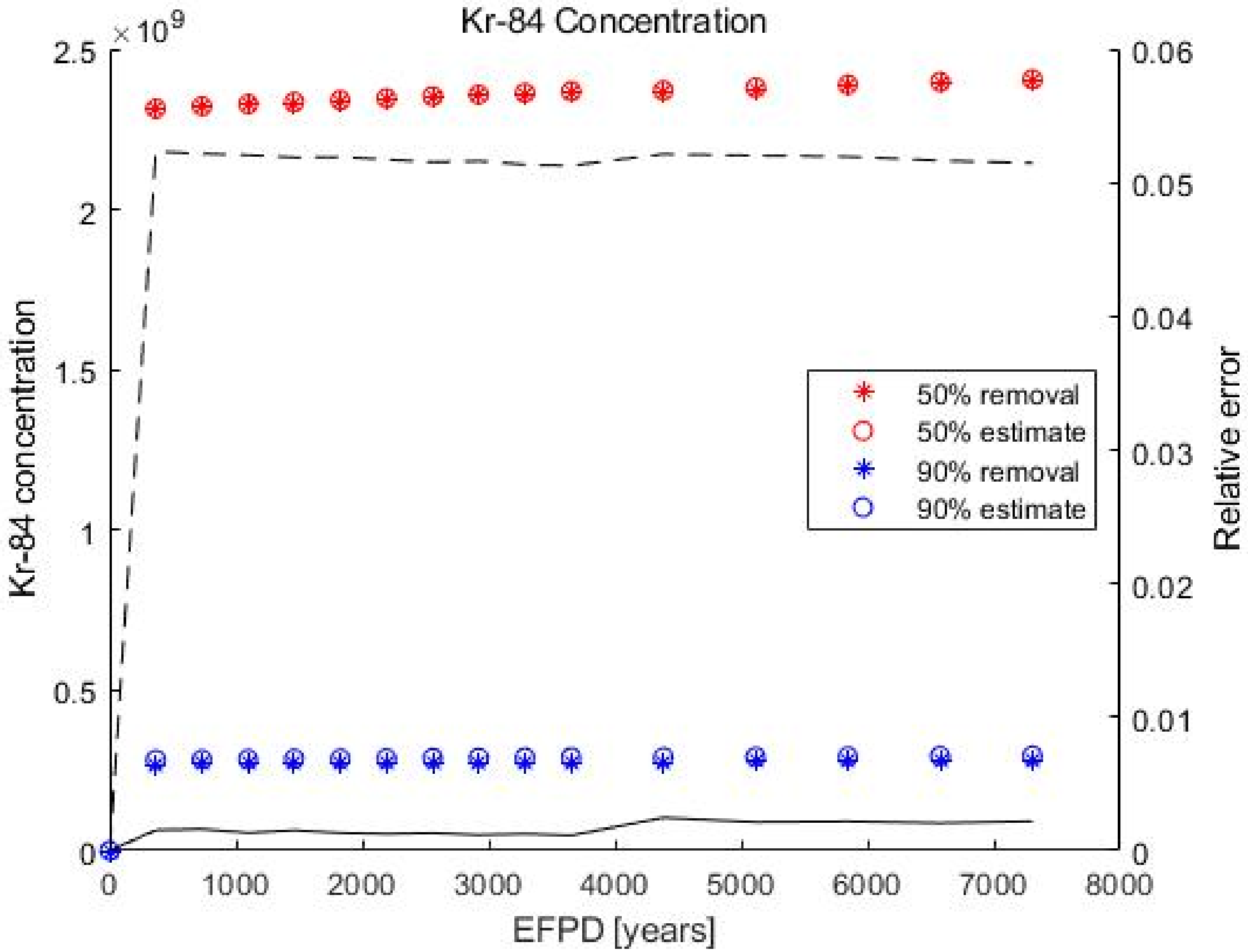
$$N_{eq} = \left([Prod.rate] \times T + N_{eq}\right) \times (1 - \epsilon_i) \ \rightarrow N_{eq} = \frac{1-\epsilon}{\epsilon}[Prod.in\ T]$$

- Method
  - Assume production rate is constant in each burnup steps
  - N_i^{rec}: Concentration of target nuclide from recalculated result at burnup step i.
  - $N_{i+1}^{rec} - N_i^{rec} = Prod.rate \times (t_{i+1} - t_i) \rightarrow Prod.rate = \frac{N_{i+1}^{rec} - N_i^{rec}}{\Delta t_i}$

Result

Nuclide removal

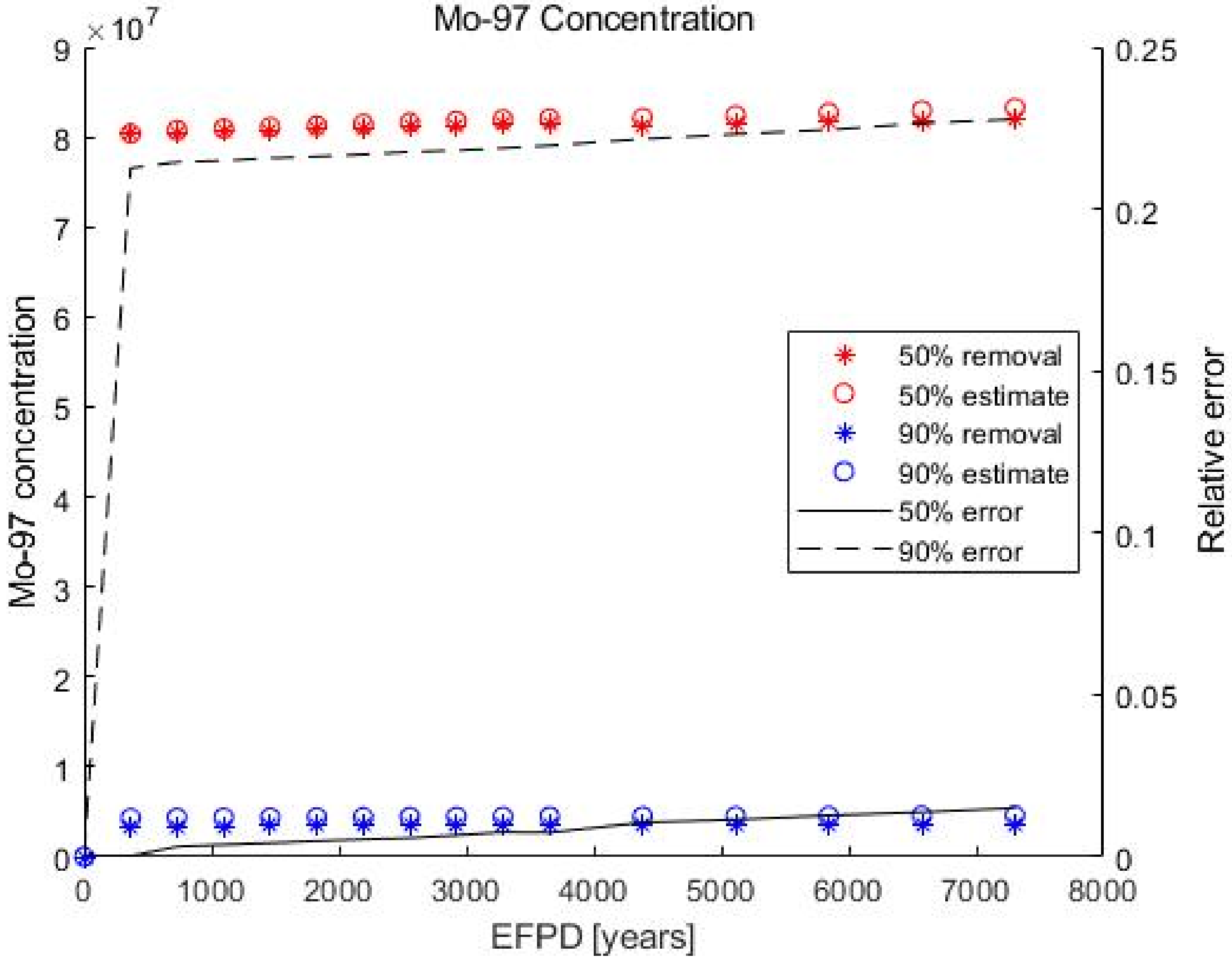
- Noble gas removal: Kr-84 (stable)



Result

Nuclide removal

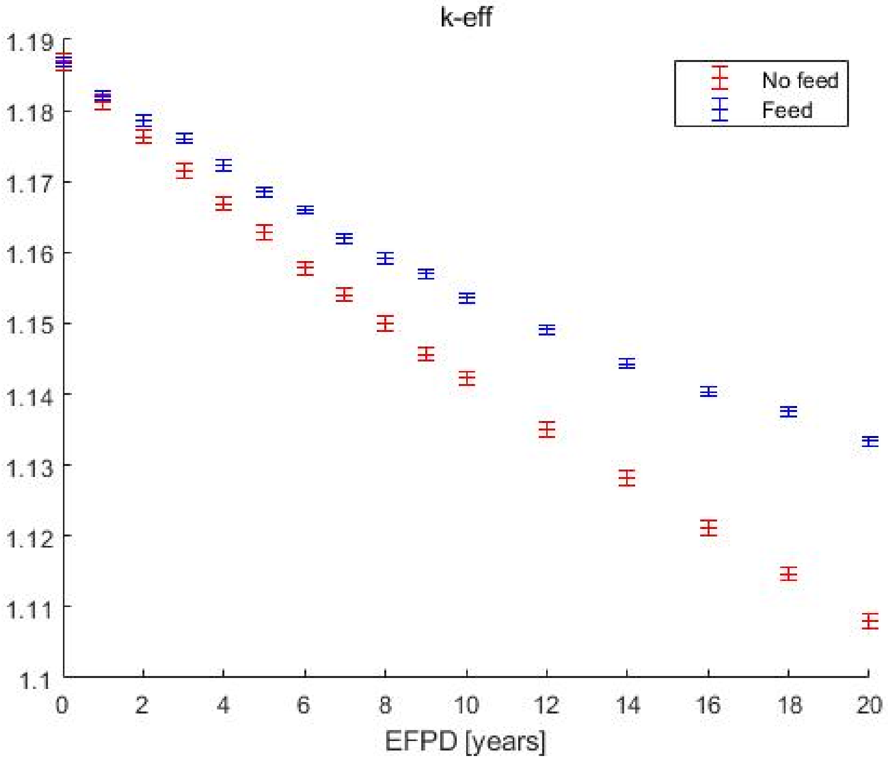
- Noble metal removal: Mo-97 (stable)

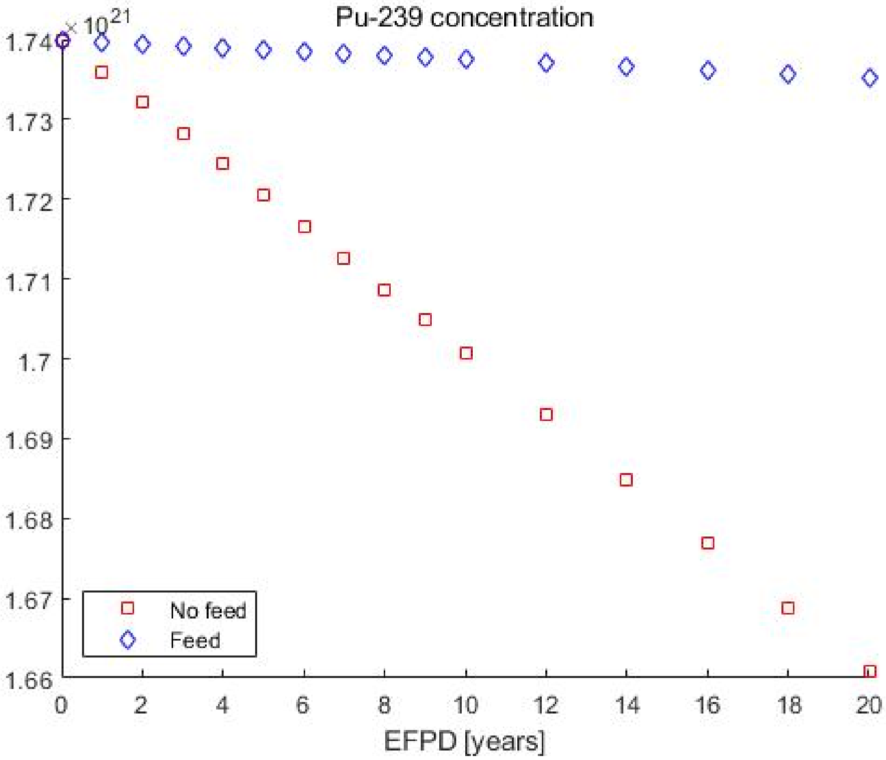


Result

Refueling

- k-eff loss is partly compensated due to continuous refueling
- Loss of fissionable may be originated from other reactions
- Pu-239 is conserved, while reactivity decline is noticeable.





Conclusion

- Nuclide removal and online refueling is implemented in iMC
  - Both system affects reactor performance significantly
  - Applied to the reactor model and compared to conventional depletion calculation.
    - Nuclide removal showed clear performance improvement
    - Furthermore, material-wise comparison agreed with removal scheme

    - Continuous refueling showed increase in reactor performance
    - Pu-239 depletion compensated

- Further research is required to contemplate more realistic MSR reactor system.

Thank you for your attention!