

Neutronic Feasibility of a Breakeven Molten Salt Fast Reactor Starting with HALEU



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Introduction

Nuclear trilemma

- Enhancing the safety → Adopting the concept of MSFR
- Preventing accumulation of spent fuel → Reutilizing the spent fuel
- Securing uranium resources → Reutilizing the spent fuel

Energy potential

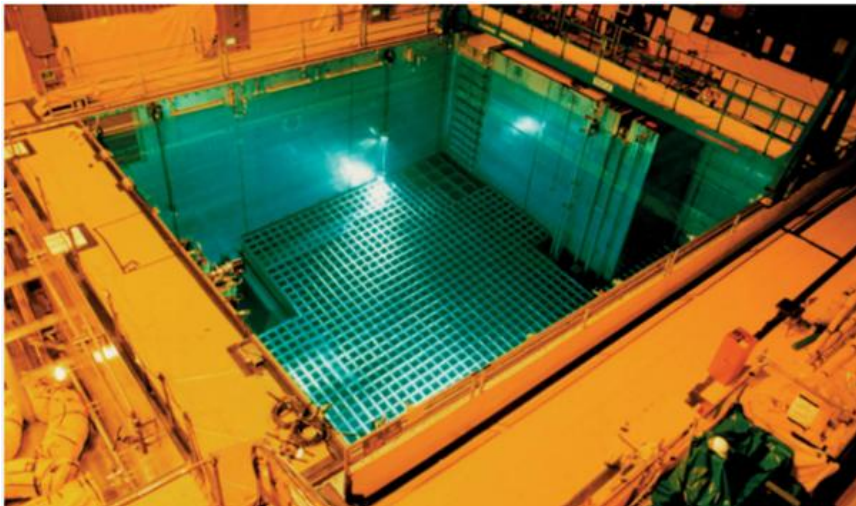
- Spent fuel in Korea: ~9,000 tons from LWR & ~9,400 tons from HWR
 - Equivalent to total electricity in Korea over 300 years
- Spent fuel in U.S.: ~90,000 tons from PWR and BWR
 - Equivalent to total electricity in USA over several hundreds years as well!



Accumulated amount of SNF and Saturation point of storage tank

Power plant	Expected SNF accumulation	Storage tank saturation point
Kori	12,290 FA	2032
Hanbit	13,051 FA	2030
Hanul	27,401 FA	2031
Saeul	15,660 FA	2066
Shin Wolsong	3,633 FA	2042
Wolsong	721,920 FA	2037

<Reference: Ministry of Trade, Industry and Energy>



Introduction

Breakeven Molten salt Fast Reactor (BeMFR)

– MSFR concept

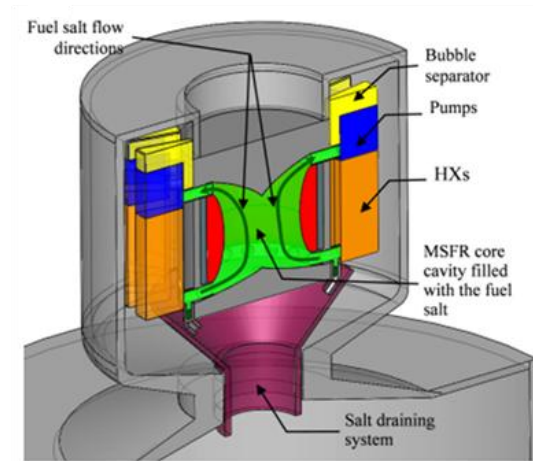
- Passive safety, convenient decay heat removal, atmospheric pressure operation
- Reduced spent fuel buildup, proliferation resistance

– Reutilizing the spent fuel as a energy resource

- Requiring U and TRU from spent fuel at the startup

→ Another option: starting with HALEU

- During operation, spent fuel is consumed as make-up fuel
- Other Properties:
 - Enables long-term operation by spent fuel feeding
 - Chloride salt → compact, high-density core
 - Minimal pyro-processing (output: small fraction of TRU) → high proliferation resistance



European MSFR

BeMFR pursues addressing nuclear trilemma though adopting MSFR concept and reutilizing spent fuel.

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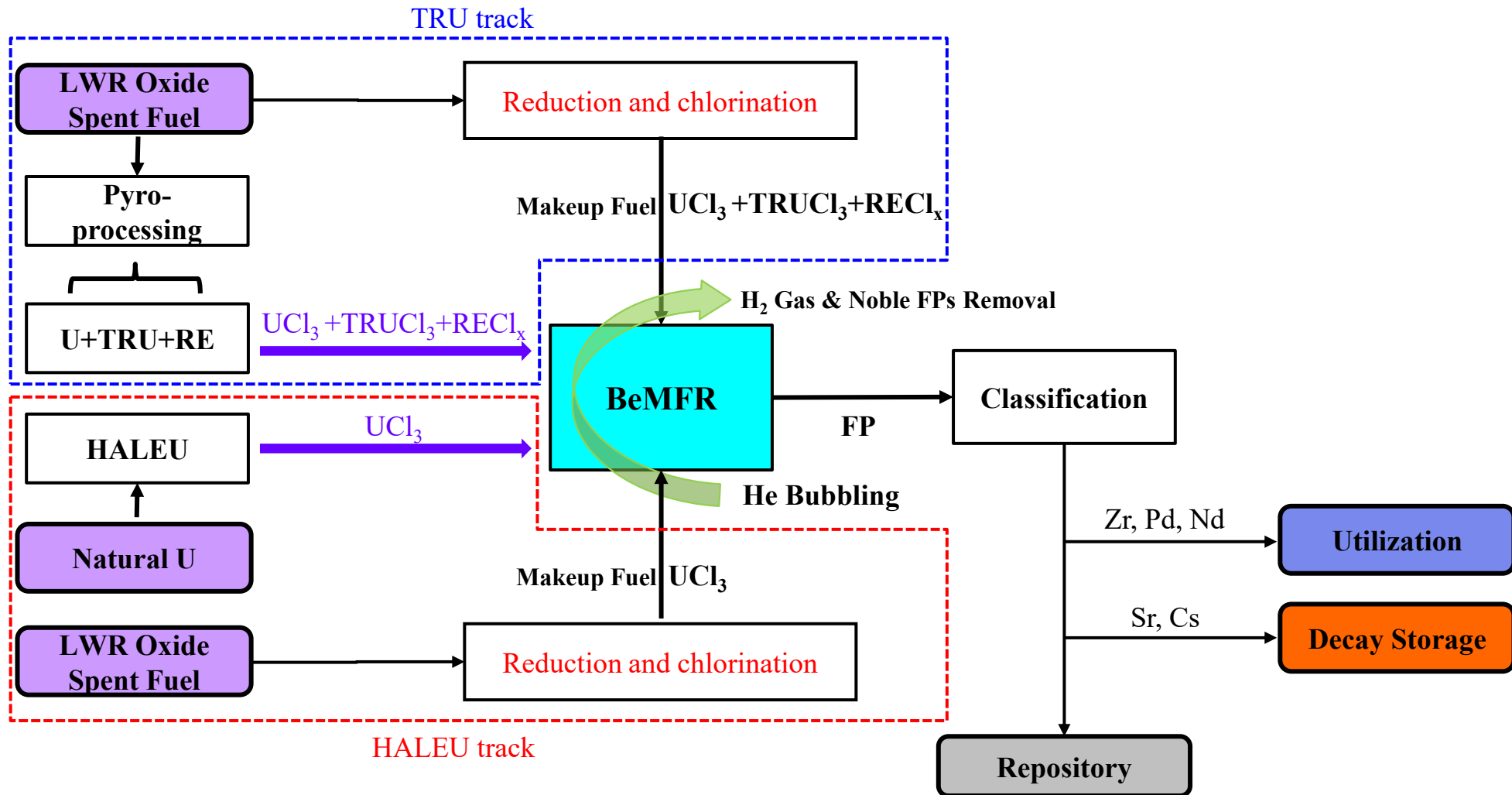
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Closed fuel cycle

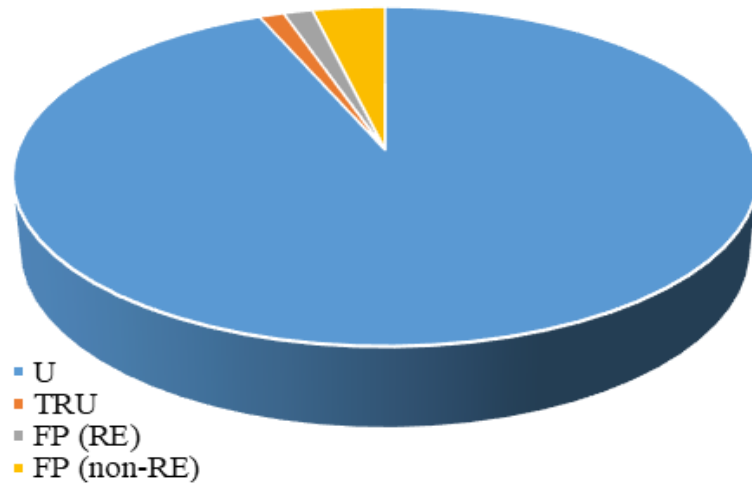
- TRU track and HALEU track



Fuel Cycle and Reactor Model

Spent fuel composition

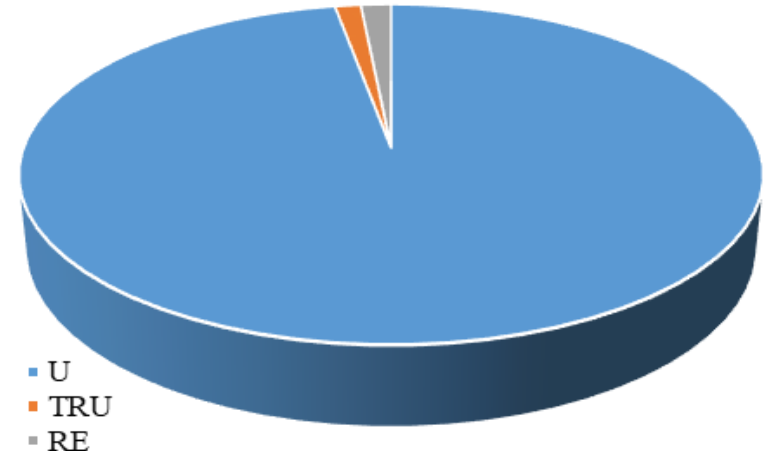
- From the depletion calculation of APR1400 lattice by Serpent 2.1
- Burnup: 50,000 MWd/MTU, Cooling period: 10 years



U : TRU : FP
= 93.60 : 1.26 : 5.14

Raw spent fuel

Non-RE FPs are
removed from
reduction and
chlorination



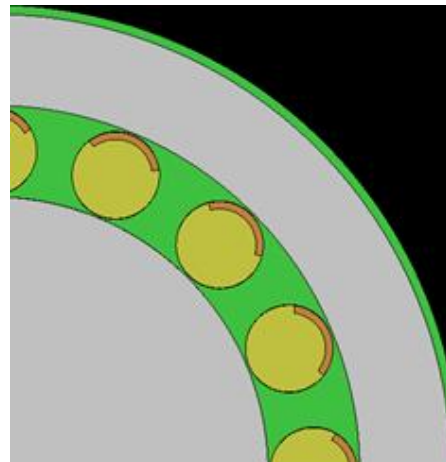
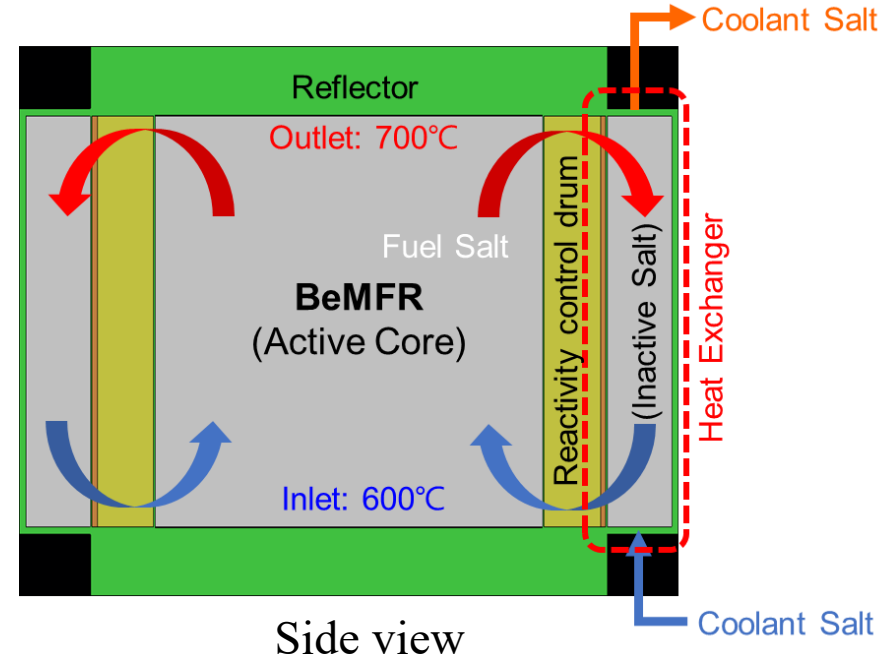
U : TRU : RE
= 97.17 : 1.31 : 1.52

Make-up fuel

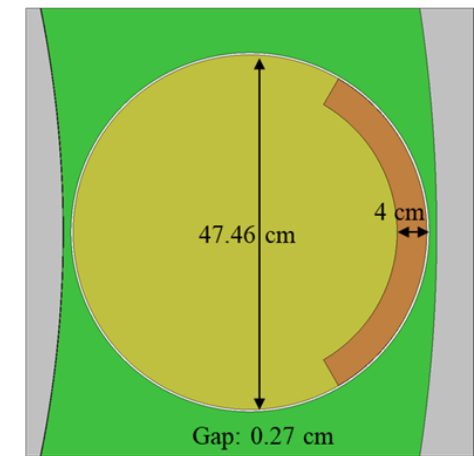
Fuel Cycle and Reactor Model

Cylindrical Reactor Layout

- Power: 3,000 MWth
 - Active core: cylindrical geometry
 - Diameter = Height = 3.0 m
- Reflector:
 - Stainless steel of 50 cm
- Inactive salt is placed around reflector
 - $V_{\text{inactive}} = 15 \text{ m}^3$
- Reactivity devices in reflector
- Operating temperature: 650°C



Top view (1/4)



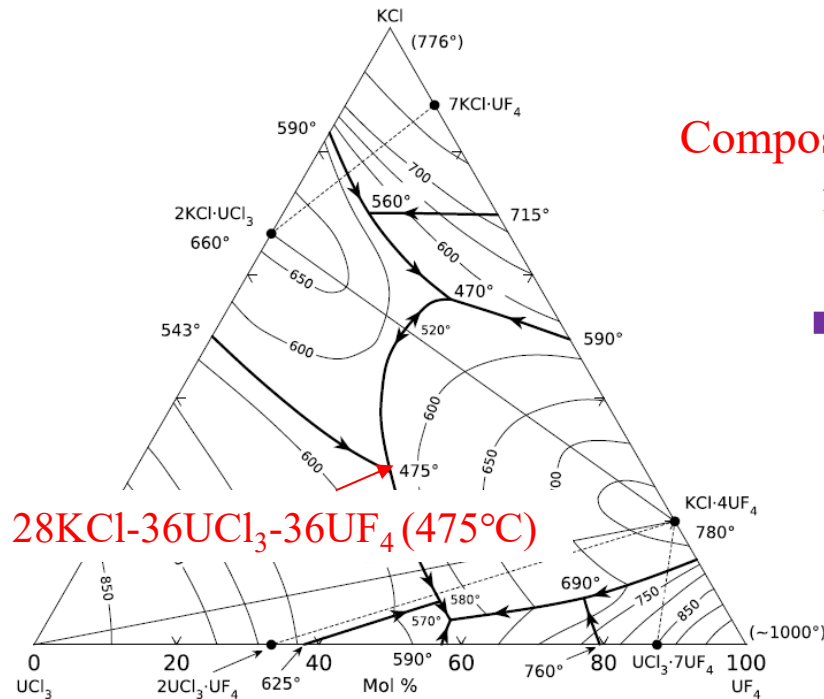
Reactivity control device

Fuel Cycle and Reactor Model

Two Cases of fuels:

- Case A: $\text{KCl-UCl}_3\text{-UF}_4$
- Case B: $\text{KCl-UCl}_3\text{-RECl}_3\text{-UF}_4\text{-REF}_4$

Phase diagram of $\text{KCl-UCl}_3\text{-UF}_4$



Composition of KCl has been fixed as 28.0%



Compositions of $\text{UCl}_3\text{-RECl}_3$ and $\text{UF}_4\text{-REF}_4$ could be changed to make initial criticality

Final composition of Case B about $\text{KCl-UCl}_3\text{-RECl}_3\text{-UF}_4\text{-REF}_4$: 28.0-34.0-2.0-34.0-2.0

This composition used for Case A as it is

Fuel Cycle and Reactor Model

Design parameters

	Case A	Case B
Power	3,000 MWth	3,000 MWth
Initial molar composition of KCl- UCl_3 - RECl_3 - UF_4 - REF_4	28-36-0-36-0	28-34-2-34-2
Uranium enrichment	19.75 wt.%	19.75 wt.%
Chlorine enrichment	99.0 at.%	99.0 at.%
Density (650°C)	4.768 g/cm ³	4.696 g/cm ³
Diameter	300 cm	300 cm
Height	300 cm	300 cm
Active core volume	21.2 m ³	21.2 m ³
Inactive salt volume	15.0 m ³	15.0 m ³
U mass	113,762 kg	107,422 kg
RE mass	0 kg	3,739 kg
Average fuel temperature	923.15 K	923.15 K
Pressure of the system	1 atm	1 atm

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Numerical Results

Fission products

Group	Solubility	Behavior in salt	Removal rate
Noble gas	Insoluble	Escape	1 %/s
Noble metal	Insoluble	Precipitation	60%/y
Soluble FPs	Soluble	Remain	0-6 %/y

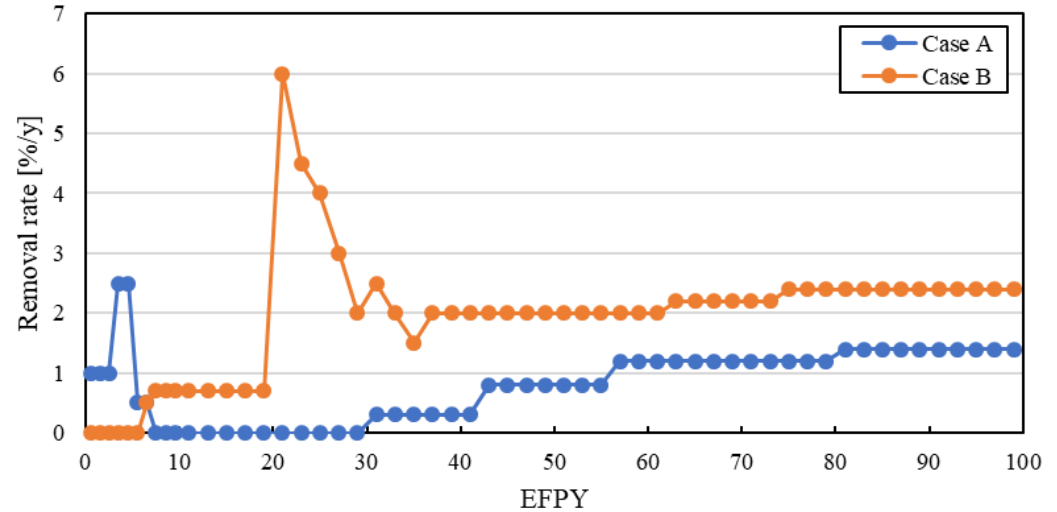
Other conditions:

- Makeup fuel feeding rate: 0-3.074 kg/d
- Hydrogen removal rate: 90%/y
- RE feeding rate: 0.0474-0.6 kg/d

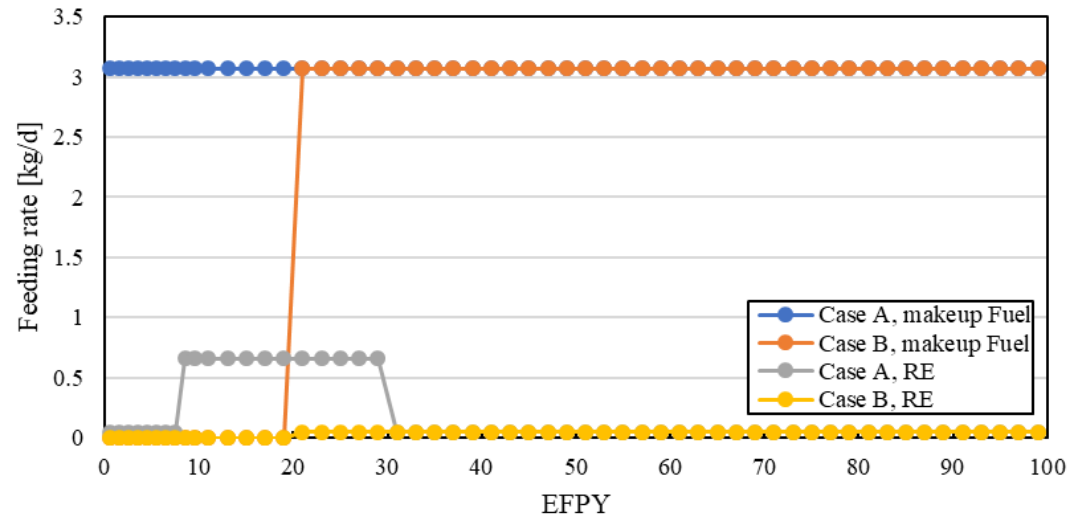
Calculation condition

- Program: Serpent 2.1.31
- Library: ENDF/B-VII.1
- History: 100,000, inactive cycle: 100, active cycle: 300

Soluble FP removal rate

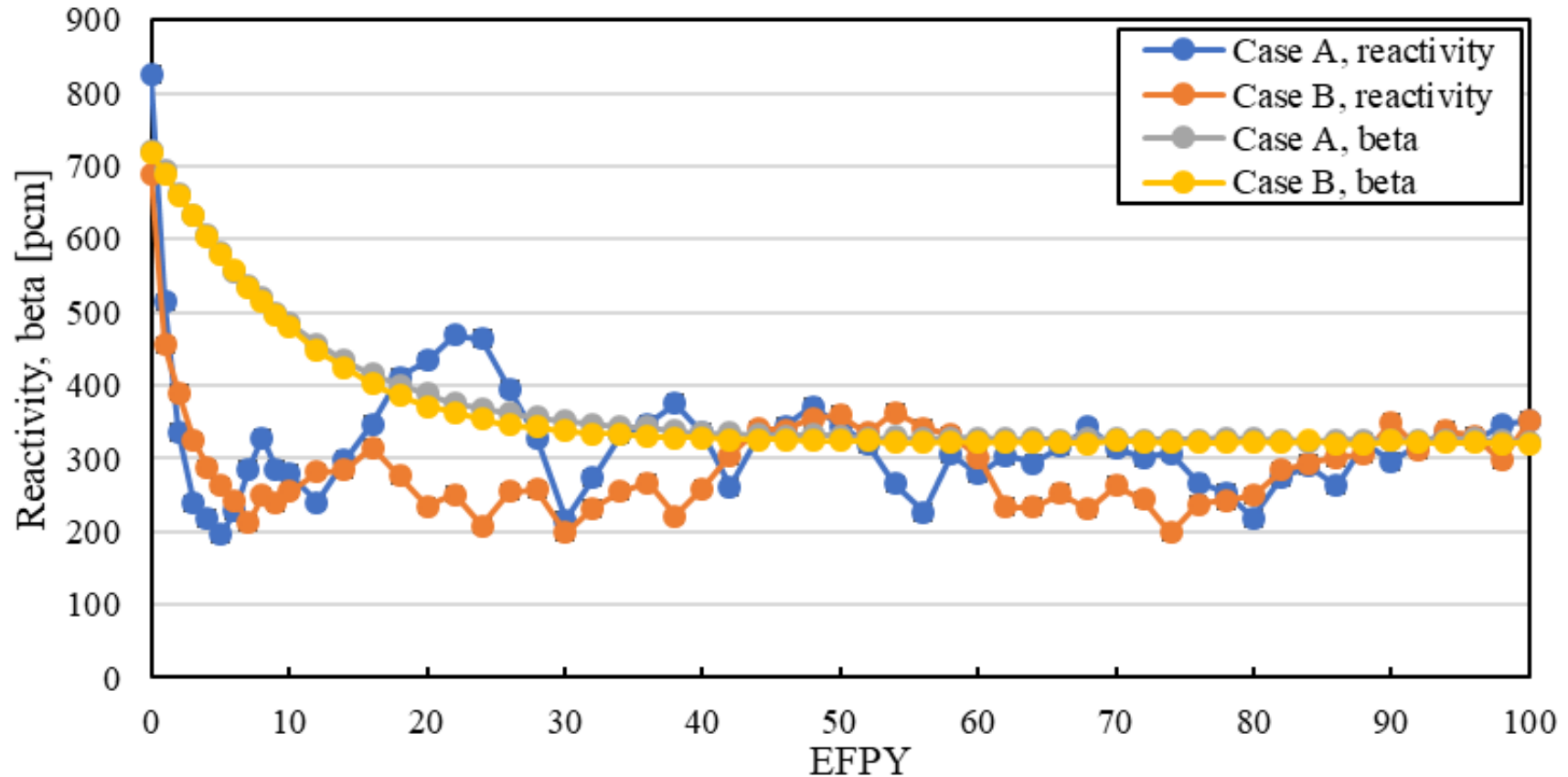


Make-up fuel and RE feeding rates



Numerical Results

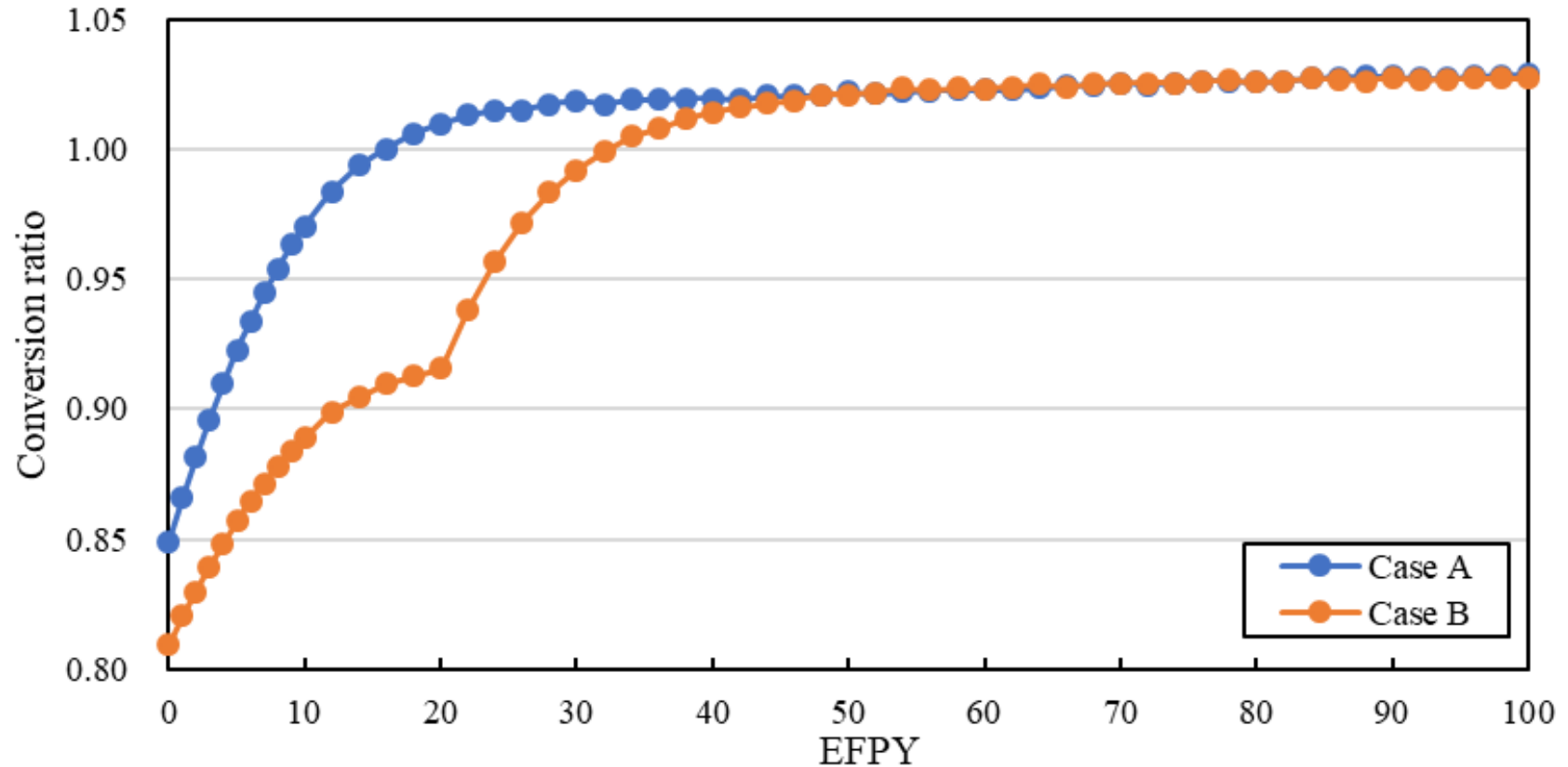
Reactivity, effective delayed neutron fraction .vs. 3 GWth Full-power operation time



The excess reactivity can be maintained below prompt criticality for most of the period.

Numerical Results

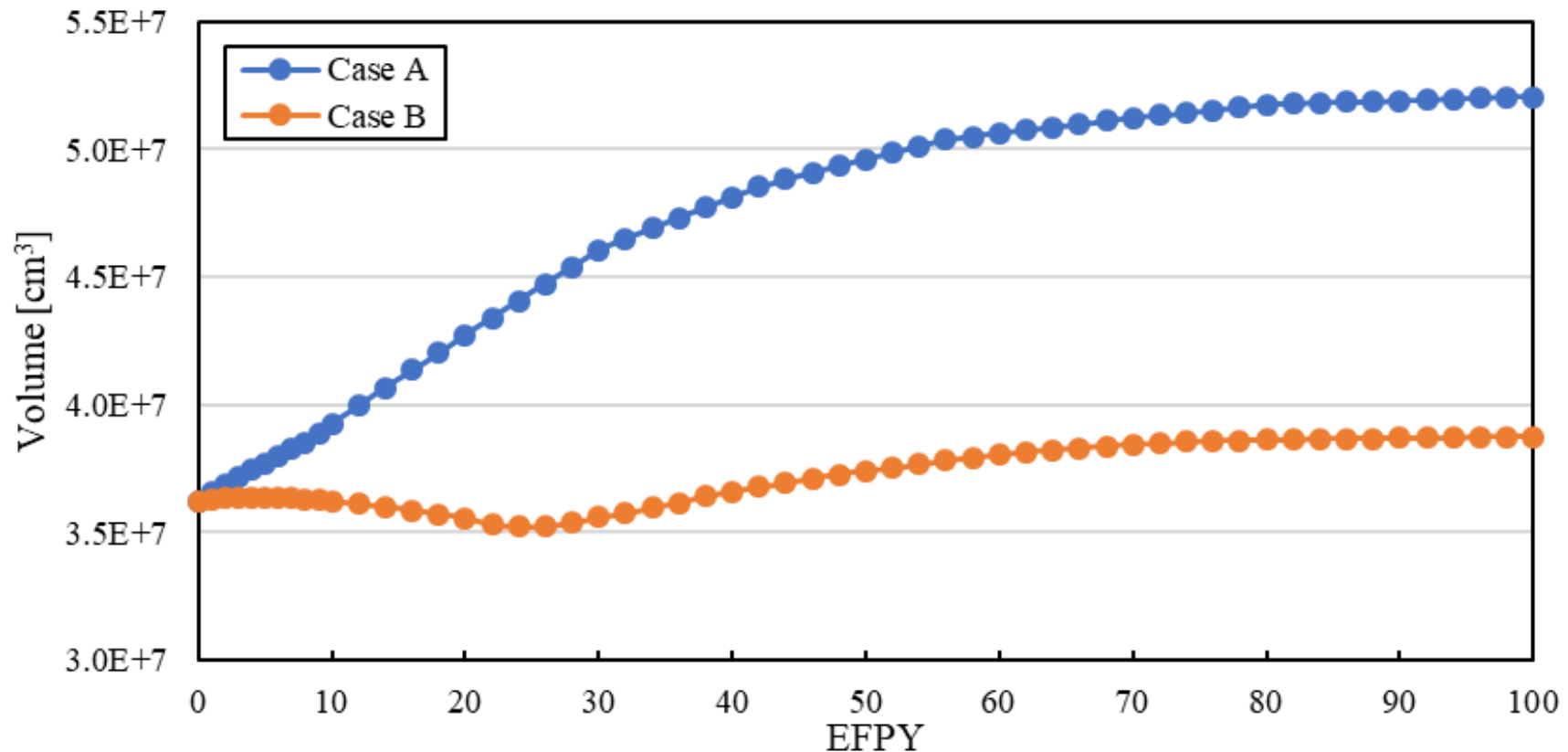
Conversion ratios .vs. 3 GWth Full-power operation time



The reactivity can be maintained through fuel conversion.

Numerical Results

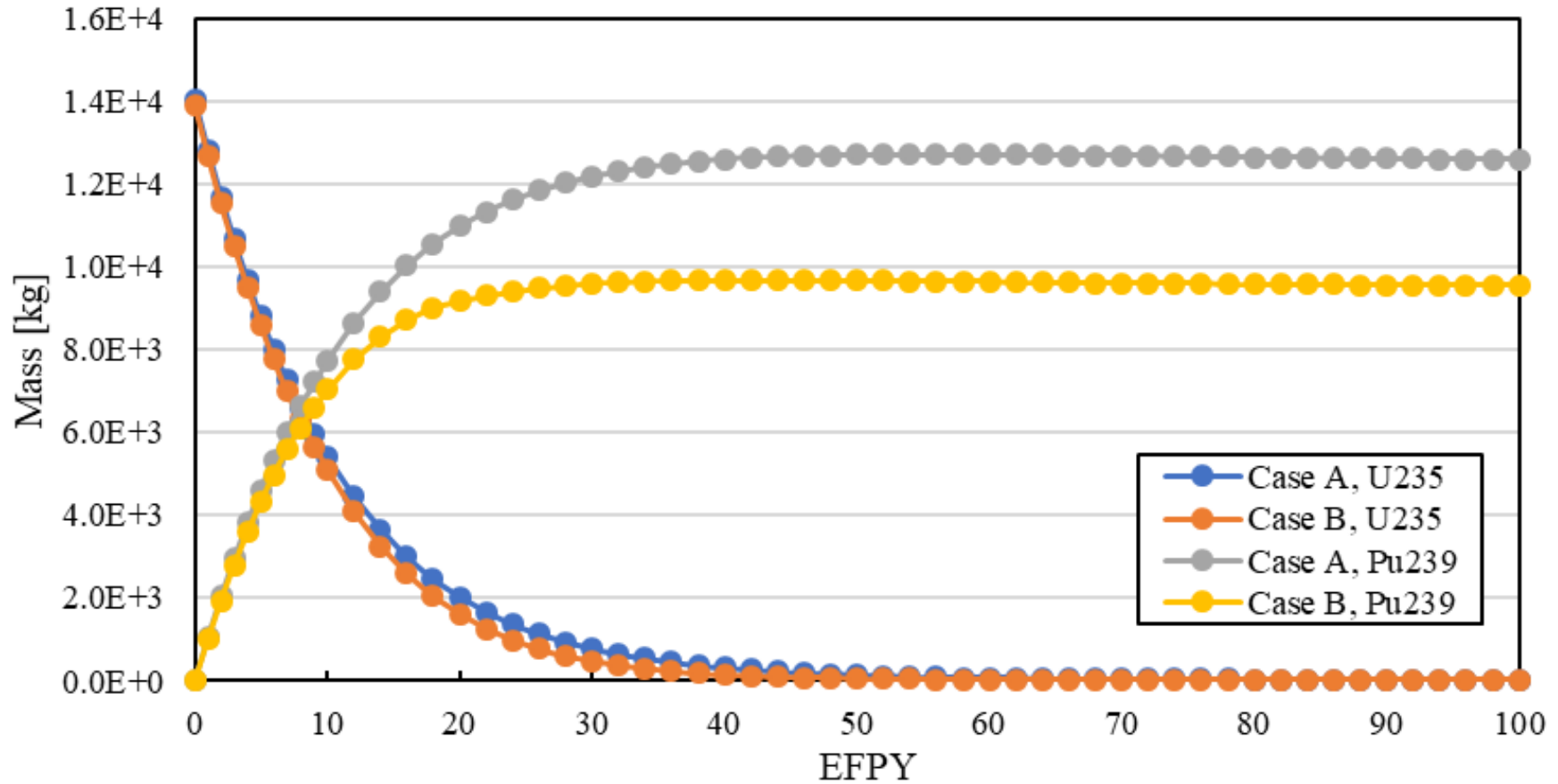
Fuel volumes .vs. 3 GWth Full-power operation time



Incorporating RE in the initial fuel can serve as an effective strategy to stabilize fuel volume

Numerical Results

U-235 and Pu-239 masses .vs. 3 GWth Full-power operation time



Inclusion of RE in initial fuel → Lower conversion ratio → Lower fissile amount

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Conclusions

- This study demonstrates the **feasibility of using HALEU as the initial fissile material** in breakeven molten salt fast reactors (BeMFRs)
- The analysis shows that HALEU can successfully initiate criticality and support long-term operation, even when immediate access to spent fuel is limited.
- Incorporating RE in the initial fuel composition can serve as an effective strategy to stabilize fuel volume
- These results indicate that HALEU-fueled BeMFRs provide a viable approach to sustainable and resilient nuclear energy
- By utilizing spent fuel exclusively, it has the **potential to provide clean energy** for centuries in nuclear-advanced countries, such as the United States or Korea.

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Fission products

Group	Elements
Noble gas	Kr, Xe, Rn
Noble metal	Co, Ni, Cu, Ge, As, Se, Mo, Tc, Ru, Rh, Pd, Ag, Sn, Sb, Te, W, Re, Os, Ir, Au, Hg, Bi, Po
Soluble FPs	Cr, Mn, Fe, Zn, Ga, Br, Rb, Sr, Y, Zr, Nb, Cd, In, I, Cs, Ba, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Ta, Pt, Tl, Pb, At, Fr, Ra