Online Reprocessing Simulation for Thorium-Fueled Molten Salt Breeder Reactor

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Outline

Reactor systems potentially meeting the Generation IV goals

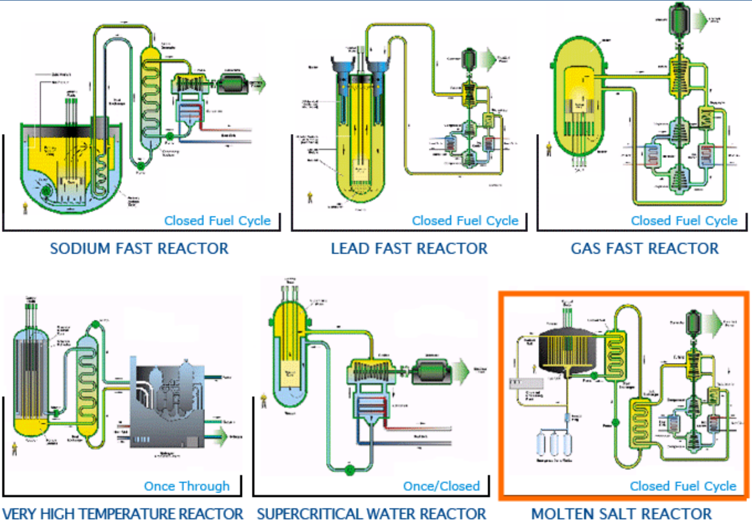


Figure 1: Potential Generation IV reactors [1].

Why Molten Salt Reactors?

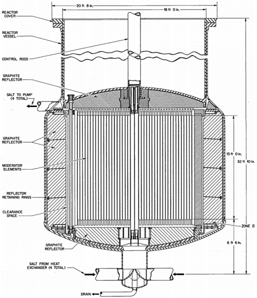
Main advantages of liquid-fueled Molten Salt Reactors (MSRs)[2]

1. High average coolant temperature (600-750°C) ⇒ high thermal efficiency.
2. May operate with epithermal or fast neutron spectrums.
3. Various fuels can be used (^{235}U, ^{233}U, Thorium, U/Pu).
4. Liquid fuel has strong negative temperature feedback.
5. Liquid fuel drains into tanks in emergency.
6. High fuel utilization ⇒ less nuclear waste generated.
7. Online reprocessing and refueling.

Main advantages of Molten Salt Breeder Reactor (MSBR)[3]

1. Breed fissile ^{233}U from ^{232}Th (breeding ratio 1.06).
2. ^{233}U, ^{235}U, or ^{239}Pu for the initial fissile loading.
3. Thorium cycle limits plutonium and minor actinides.
4. Could transmute Light Water Reactor (LWR) spent fuel.

Molten Salt Reactor Experiment vs Molten Salt Breeder Reactor



Molten Salt Reactor Experiment (MSRE)

1. 8 MW_{th}
2. Fuel salt
   - ^{7}LiF-BeF_2-ZrF_4-UF_4
   - ^{7}LiF-BeF_2-ZrF_4-UF_4-PuF_3
3. First use of ^{233}U and mixed U/Pu
4. Single region core
5. Operated: 1965-1969 at ORNL

Molten Salt Breeder Reactor (MSBR) [3]

1. 2.25GW_{th}, 1GW_e
2. Fuel salt
   - ^{7}LiF-BeF_2-ThF_4-$^{233}UF_4$
   - ^{7}LiF-BeF_2-ThF_4-$^{233}UF_4$-$^{239}PuF_3$
3. Breeding ratio 1.06
4. Single fluid/two-region core design
5. Chemical salt processing plant

Research objectives

Goals of current study

1. Develop simplified single-cell MSBR model using the continuous-energy SERPENT 2 Monte Carlo reactor physics software [4].
2. Using the built-in SERPENT 2 depletion capabilities simulate online reprocessing and refueling regime.
3. Find the equilibrium core composition for the MSBR.

What is next?

1. Depletion simulation using a full-core, 3-D, high-fidelity MSBR model.
2. Additional SERPENT 2 flow control system will evaluate material flows.
3. Optimization of reprocessing parameters and reactor design.
4. Determine and compare major safety characteristics for initial and equilibrium fuel composition.

Outline

Input data

Table 1: Summary of principal data for MSBR [3]

Thermal capacity of reactor	2250 MW(t)
Net electrical output	1000 MW(e)
Net thermal efficiency	44.4%
Salt volume fraction in central core zone	0.132
Salt volume fraction in outer core zone	0.37
Fuel-salt inventory (Zone I)	8.2 m^3
Fuel-salt inventory (Zone II)	10.8 m^3
Fuel-salt inventory (annulus)	3.8 m^3
Fuel salt components	LiF-BeF_2-ThF_4-${}^{233}UF_4$-${}^{239}PuF_3$
Fuel salt composition	71.767-16-12-0.232-0.0006 mole%

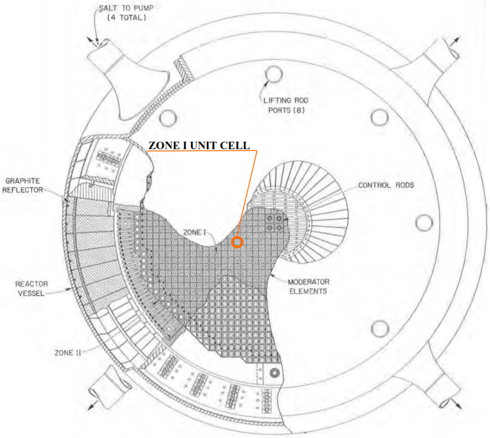


Figure 2: Plan view of MSBR vessel [3].

Graphite unit cell geometry

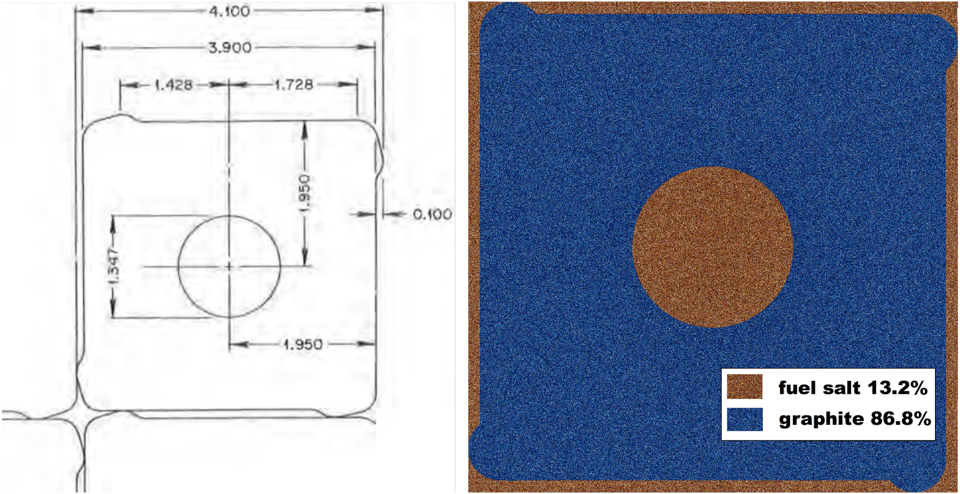


Figure 3: Molten Salt Breeder Reactor Zone I unit cell geometry from the reference [3] (left) and SERPENT 2 (right).

Online reprocessing method

- Currently, researchers typically develop custom scripts to simulate online reprocessing and refueling using stochastic (i.e. MCNP) or deterministic (i.e. SCALE) codes [5, 6].

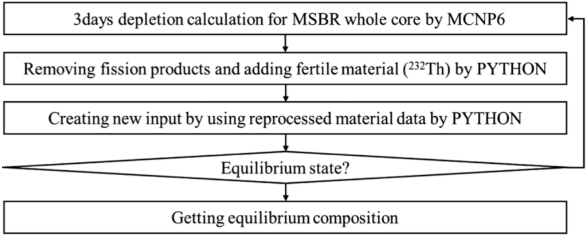


Figure 4: Depletion calculation principal scheme [7].

- SERPENT 2 allows the user to define multiple material flows into and out of the fuel and applies batchwise reprocessing and refueling at each step.

Online reprocessing method

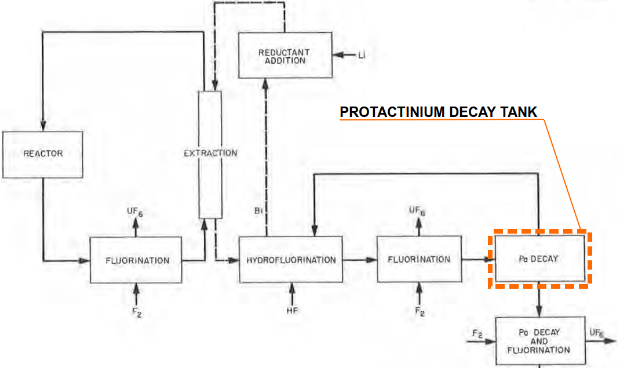


Figure 5: Protactinium isolation with uranium removal by fluorination [3].

Online reprocessing approach

- Continuously removes all poisons, noble metals, and gases.
- ^{233}Pa is continuously removed from the fuel salt into a decay tank.

$$^{232}_{90}\text{Th} + ^{1}_{0}\text{n} \rightarrow ^{233}_{90}\text{Th} \xrightarrow[22.3\text{ min}]{\beta^-} ^{233}_{91}\text{Pa} \xrightarrow[26.967\text{ d}]{\beta^-} ^{233}_{92}\text{U}$$

Approximations and assumptions

Model simplifications and assumptions

1. Single cell model of MSBR with periodic boundary conditions.
2. Delayed neutron precursor drift is neglected.

Simulation conditions and nuclear data

1. $T_{fuel} = T_{graphite} = 908K$.
2. ρ_{fuel}=3.33 g/cm^3 and $\rho_{graphite}$=1.843 g/cm^3.
3. 10^4 neutrons per cycle for a total of 500 cycles, the first 20 are inactive.
4. ENDF/B-VII cross sections were used [8].

Outline

Infinite multiplication factor for unit cell model

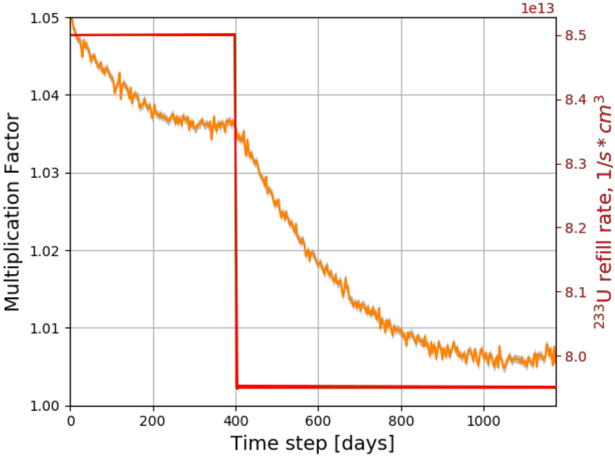


Figure 6: Infinite multiplication factor during a 1200 day depletion simulation. The confidence interval $\pm\sigma$ is shaded.

- Strong absorbers (^{233}Th,^{234}U) accumulating in the begining of cycle.
- Fissile materials other than ^{233}U are bred into the core (^{235}U, ^{239}Pu).
- Fresh fuel refill rate was changed after 400 days of operation to adjust these effects.
- The multiplication factor stabilizes after approximately 950 days.

Fuel salt composition evolution

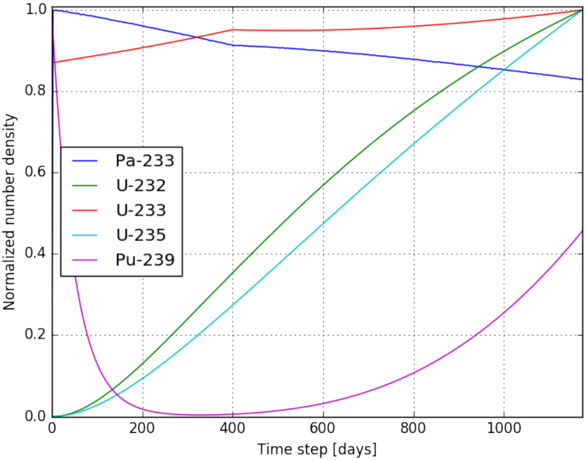


Figure 7: Normalized number density of major isotopes during 1200 day of depletion.

- Number density of ^{233}Pa is negligible (10^{16} $1/cm^3$) but some small amount of it is produced during the 3-day reprocessing period.
- Fissile materials other than ^{233}U are produced in the core (^{235}U, ^{239}Pu).
- ^{239}Pu from initial fissile loading fully depleted after 250 days but then slowly produced from ^{238}U.

Rate of change ^{232}Th and ^{233}U in the core

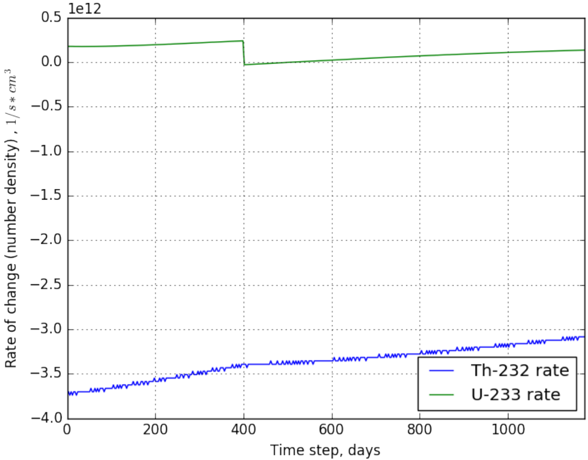


Figure 8: Rate of change of major isotopes during online reprocessing.

- To keep the reactor critical, a higher ^{233}U flow rate from the protactinium decay tank is required for the first 400 days.
- The ^{232}Th loss rate slightly decreases over 4 years of operation due to fissile material accumulation.

Rate of change ^{233}Pa, ^{233}U from the protactinium decay tank

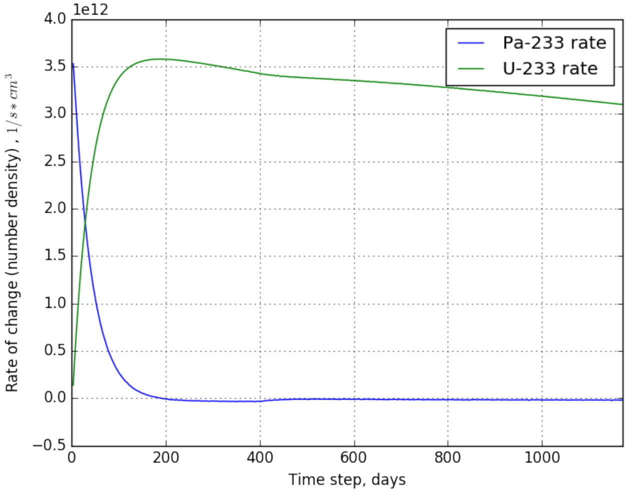


Figure 9: Isotopic rate of change for the protactinium decay tank during MSBR online reprocessing.

- Protactinium accumulated for approximately 200 days.
- Fresh fissile ^{233}U fuel flow established after 200 days.

Neutron spectrum

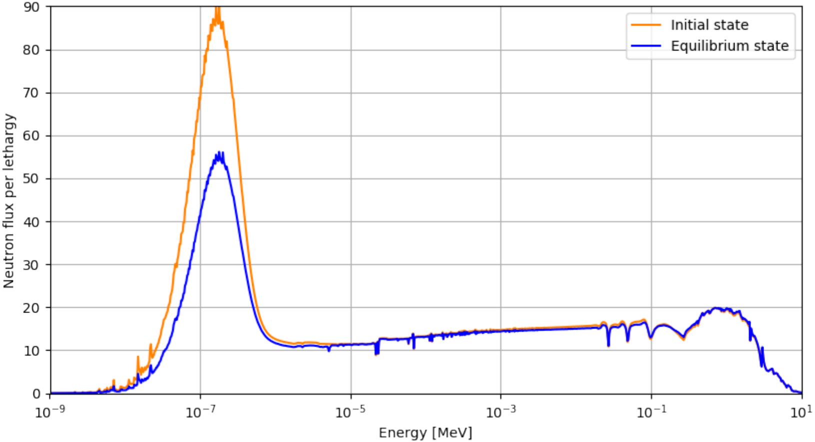


Figure 10: Neutron spectrum for initial and equilibrium composition (normalized per lethargy).

- MSBR has a epithermal spectrum which is perfect for thorium fuel cycle.
- Spectrum becomes harder due to fission product accumulation.

Outline

Conclusions

This study outcomes

- MSBR unit cell online reprocessing simulation was performed using the SERPENT 2 Monte Carlo code to find equilibrium fuel composition.
- Infinite multiplication factor slowly decreases and reaches the equilibrium state after 950 days of operation.
- To achieve equilibrium state and maintain criticality, the material flow rate should be adjusted, ideally, for each 3-day step.
- The neutron energy spectrum is harder for the equilibrium state because a significant amount of fission products were accumulated in the MSBR core.

Future research

Future research effort

1. Depletion simulation using a full-core, 3-D, high-fidelity MSBR model.
2. Additional SERPENT 2 flow control system development to simulate adjusting material flows depending upon the instantaneous reactivity.
3. Reprocessing parameters (e.g. time step, feeding rate, protactinium removal rate) optimization will be performed to achieve maximum fuel utilization, breeding ratio or safety characteristics.
4. Temperature coefficients of reactivity, rod worth, power density will be computed for initial and equlibrium fuel composition to determine influence of fuel depletion on MSBR safety.
5. LWR fuel transmutation study.

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Generation IV Reactors

Goals for Generation IV Nuclear Energy Systems [1]

1. Sustainability
2. Economics
3. Safety and Reliability
4. Proliferation Resistance and Physical Protection

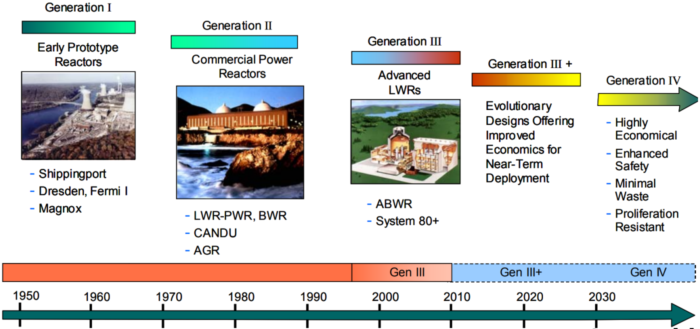

Figure 11: A Technology Roadmap for Gen IV Nuclear Energy Systems [1].

MSBR plain view