Advanced Online Reprocessing Simulation for Thorium-Fueled Molten Salt Breeder Reactor

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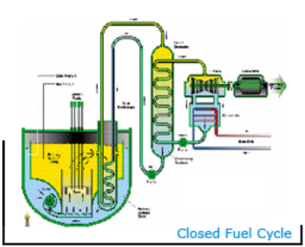
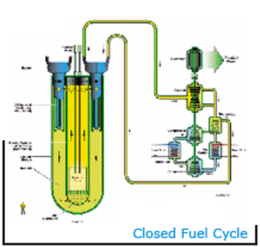
Outline

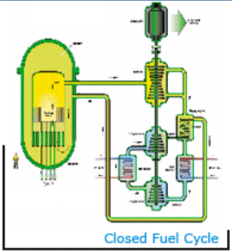
Potential Generation IV reactor systems



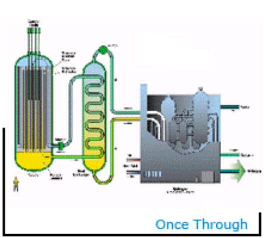
SODIUM FAST REACTOR



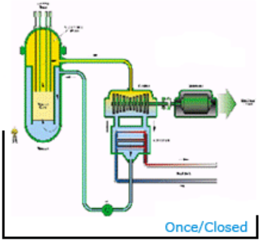
LEAD FAST REACTOR



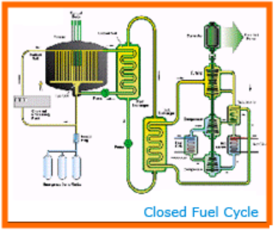
GAS FAST REACTOR



VERY HIGH TEMPERATURE REACTOR



SUPERCRITICAL WATER REACTOR



MOLTEN SALT REACTOR

Why Molten Salt Reactors?

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

1. High average coolant temperature (600-750°C) $\Rightarrow$ high thermal efficiency, hydrogen production, cheap heat energy for chemical industry.
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 $\Rightarrow$ less nuclear waste generated.
7. Online reprocessing and refueling.

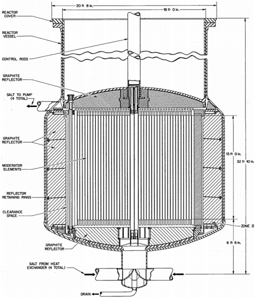
Main advantages of Molten Salt Breeder Reactor (MSBR) [3]

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. Create high-fidelity full-core 3-D model of MSBR without any approximations using the continuous-energy SERPENT 2 Monte Carlo physics software [4].
2. Develop online reprocessing simulation code, SaltProc, which expands the capability of SERPENT for simulation liquid-fueled MSR operation [5].
3. Analyse MSBR neutronics and fuel cycle to find the equilibrium core composition and core depletion.
4. Compare predicted operational and safety parameters of the MSBR at both the initial and equilibrium states.

Outline

1. Background
   - Motivation
   - Objectives
2. Methodology
3. Results and discussion
4. Conclusions

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-$^{233}UF_4$
Fuel salt composition	71.75-16-12-0.25 mole%

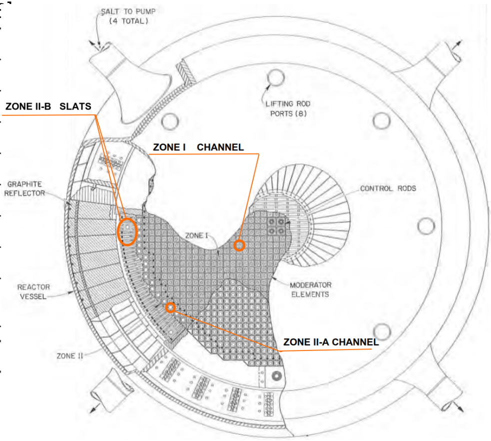
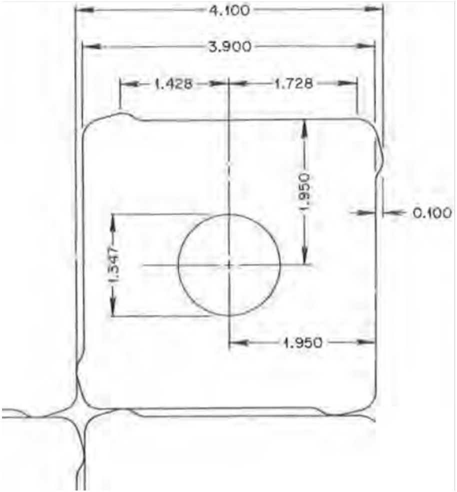


Figure 2: Plan view of MSBR vessel [3].

Moderator element geometry (Zone I)



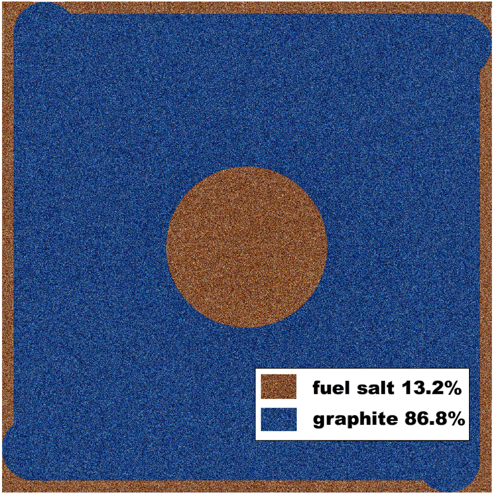


Figure 3: Molten Salt Breeder Reactor Zone I unit cell geometry from the reference [3] (left) and SERPENT 2 (right).

Full-core SERPENT model of MSBR

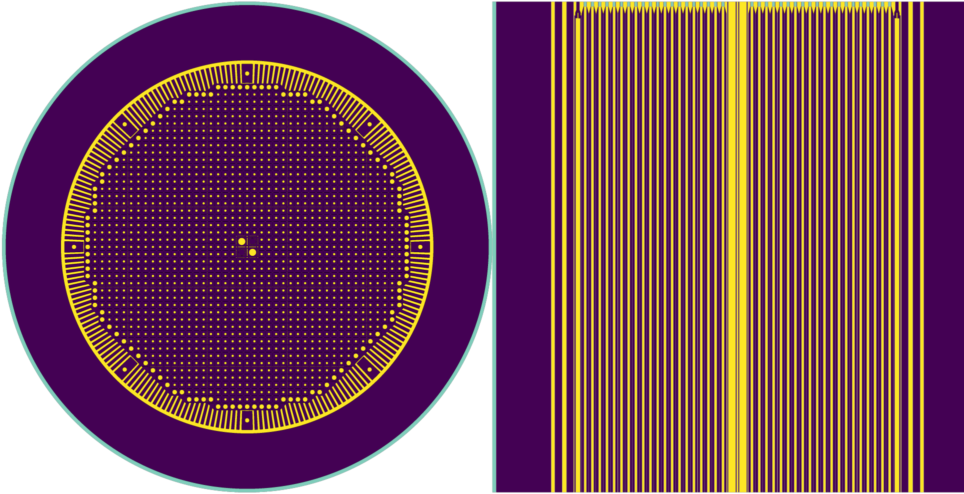


Figure 4: Plan (left) and elevation (right) view of MSBR model.

Core Zone II

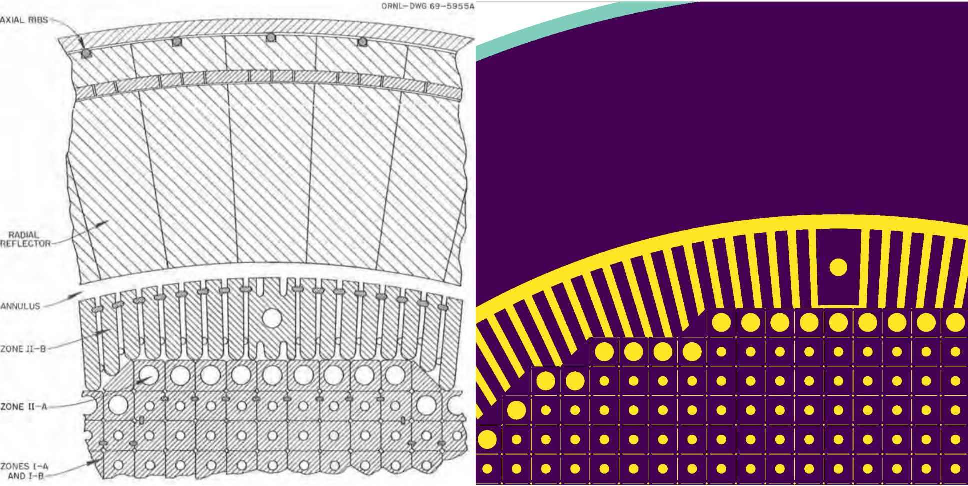


Figure 5: Detailed plan view of graphite reflector and moderator elements.

Online reprocessing method

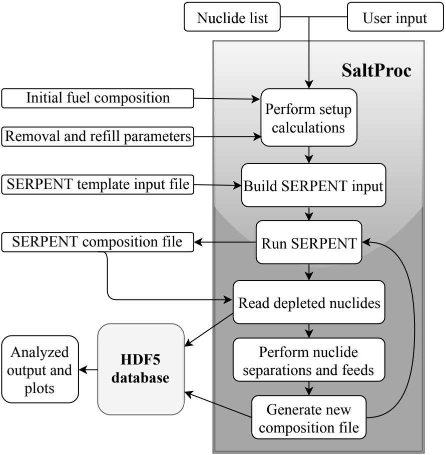


Figure 6: Flow chart for the SaltProc.

SaltProc capabilities

- Remove specific isotopes from the core with specific parameters (reprocessing interval, mass rate, removal efficiency)
- Add specific isotopes into the core
- Maintain constant number density of specific isotope in the core
- Time-dependent material feed and removal rates
- Store stream vectors in an HDF5 database for further analysis or plots
- Generic geometry: an infinite medium, a unit cell, a multi-zone simplified assembly, or a full-core

Online reprocessing method

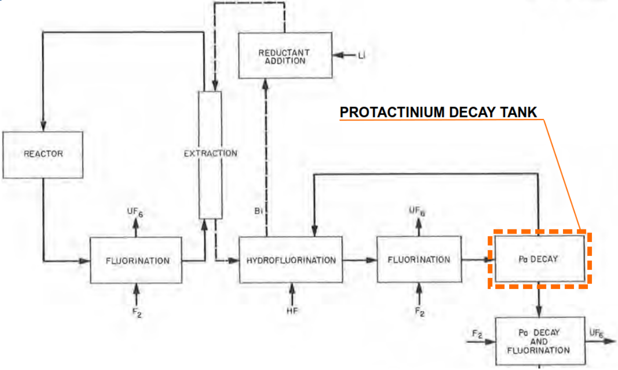


Figure 7: Protactinium isolation with uranium removal by fluorination [3].

Online reprocessing approach

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

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

The effective cycle times for protactinium and fission products removal [3]

Processing group	Nuclides	Cycle time
Rare earths	Y, La, Ce, Pr, Nd, Pm, Sm, Gd	50 days
	Eu	500 days
Noble metals	Se, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Sb, Te	20 sec
Seminoble metals	Zr, Cd, In, Sn	200 days
Gases	Kr, Xe	20 sec
Volatile fluorides	Br, I	60 days
Discard	Rb, Sr, Cs, Ba	3435 days
Protactinium	^{233}Pa	3 days
Higher nuclides	^{237}Np, ^{242}Pu	16 years

Feeds

- ^{232}Th (maintained constant)
- ^{233}U returned from Pa decay tank (the feed rate assumed equal to ^{233}Pa removal rate)

Removals

- ^{233}Pa separated into a decay tank
- 100% of other poisons removed

Outline

Effective multiplication factor for full-core MSBR model

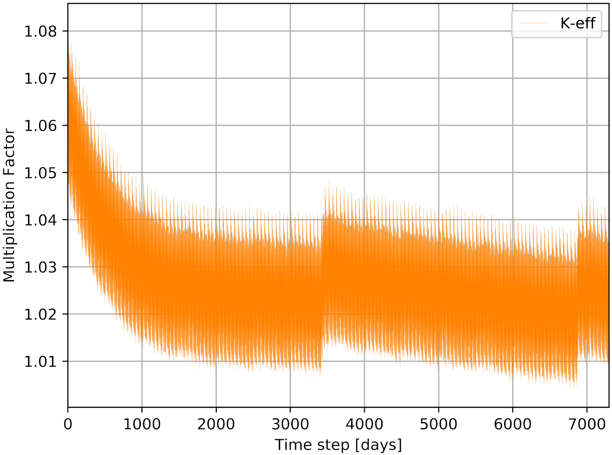


Figure 8: k_{eff} during a 20 years depletion simulation.

- Strong absorbers (^{233}Th,^{234}U) accumulating in the core
- Fissile materials other than ^{233}U are bred into the core (^{235}U, ^{239}Pu)
- The multiplication factor stabilizes after approximately 6 years

Fuel salt composition evolution

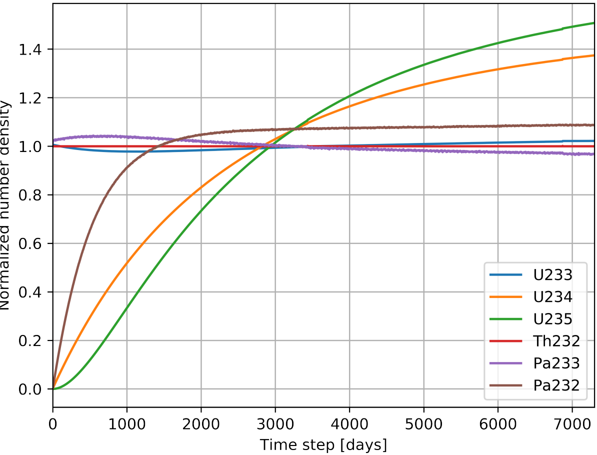


Figure 9: Normalized number density of major isotopes in the core during 20 years of operation.

- 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)
- ^{233}U number density fluctuates less than 0.8% in the time interval from 16 to 20 years of operation

Neutron spectrum

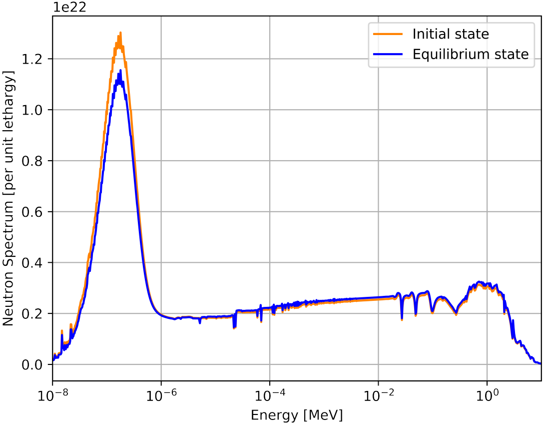


Figure 10: Neutron spectrum for startup and equilibrium composition (normalized per lethargy)

- MSBR has a epithermal spectrum which is perfect for thorium fuel cycle
- Spectrum becomes harder due to Pu isotopes accumulation in the core

Power and breeding distribution

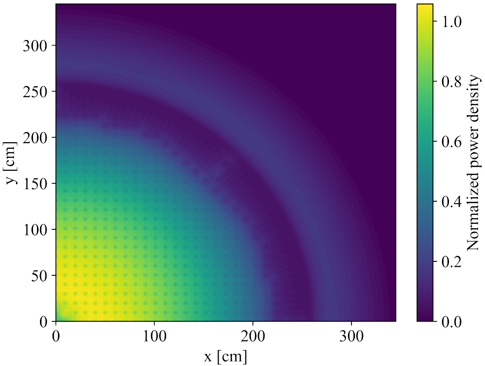


Figure 11: Normalized power density

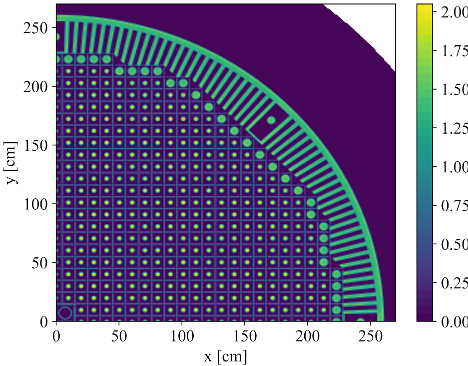


Figure 12: ^{232}Th neutron capture reaction rate normalized by total flux

Temperature coefficients and control rod worth

Table 2: Temperature coefficients of reactivity for initial and equilibrium state

Reactivity coefficient [pcm/K]	**Initial**	**Equilibrium**	**Reference** [3]
Fuel salt	-3.22 ± 0.044	-1.53 ± 0.046	-3.22
Moderator	$+1.61 \pm 0.044$	$+0.97 \pm 0.046$	$+2.35$
Total	-3.1 ± 0.04	-0.97 ± 0.046	-0.87

Table 3: Control system rod worth for initial and equilibrium fuel composition

Reactivity parameter	**Initial**	**Equilibrium**
Control (graphite) rod integral worth (cents)	28.215 ± 0.825	28.991 ± 0.773
Safety (B_4C) rod integral worth (cents)	251.805 ± 0.825	210.992 ± 0.774
Total reactivity control system worth (cents)	505.762 ± 0.720	424.882 ± 0.805

^{232}Th refill rate

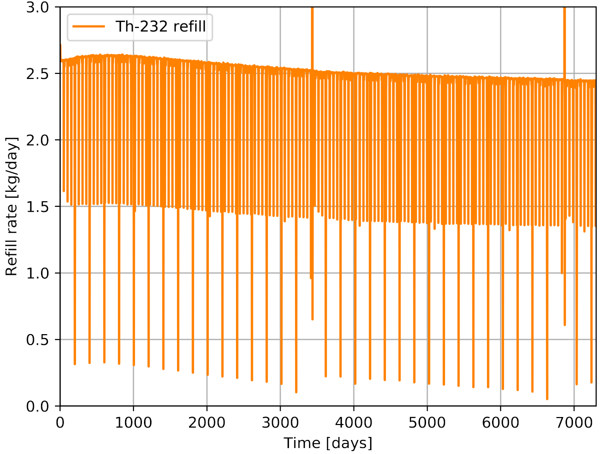


Figure 13: ^{232}Th feed rate over 20 years of MSBR operation

- Fluctuation with various interval and amplitude due to batch-wise removal of strong absorbers
- Feed rate increases during the first 500 days of operation and than steadily reduces due to spectrum hardening and accumulation of absorbers in the core
- Average ^{232}Th refill rate throughout 20 years of operation is approximately 2.39 kg/day or 100 g/GWh$_e$

Outline

Conclusions

This study outcomes

- Full-core fidelity model instead of simplified single-cell model [6] was implemented to precisely describe the two-region MSBR concept design sufficiently to accurately represent breeding in the “blanket”
- Effective multiplication factor slowly decreases from 1.075 and reaches 1.02 at equilibrium after approximately 6 years of operation
- Wide diversity of nuclides, including fissile isotopes (e.g. ^{233}U, ^{239}Pu) and non-fissile strong absorbers (e.g. ^{234}U) keep accumulating in the core
- The neutron energy spectrum is harder for the equilibrium state because a significant amount of fission products were accumulated in the MSBR core
- The total temperature coefficient and reactivity control system efficiency decreases throughout reactor operation
- Average ^{232}Th refill rate throughout 20 years of operation is approximately 2.39 kg/day or 100 g/GWh$_e$ which is a good agreement with online reprocessing analysis by Oak Ridge National Laboratory (ORNL)

Future research

Future research effort

1. Reprocessing parameters (e.g. time step, feeding rate, protactinium removal rate) optimization to achieve maximum fuel utilization, breeding ratio or safety characteristics
2. Verify SaltProc against SERPENT 2 extended for trully continuous online fuel reprocessing simulation
3. Develop a multi-physics model of the MSBR in the coupled neutronics/ thermal-hydraulics code, Moltres [7]

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Foresight Sustainable Energy Management and the Built Environment Project.

[2] Badawy M. Elsheikh.
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[3] R. C. Robertson.
Conceptual Design Study of a Single-Fluid Molten-Salt Breeder Reactor.
Technical Report ORNL–4541, comp.; Oak Ridge National Lab., Tenn., January 1971.

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Serpent – a Continuous-energy Monte Carlo Reactor Physics Burnup Calculation Code.
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[5] Andrei Rykhlevskii, Jin Whan Bae, and Kathryn Huff.
arfc/saltproc: Code for online reprocessing simulation of Molten Salt Reactor with external depletion solver SERPENT, March 2018.

References II

[6] Andrei Rykhlevskii, Alexander Lindsay, and Kathryn D. Huff.
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[7] Alexander Lindsay, Gavin Ridley, Andrei Rykhlevskii, and Kathryn Huff.
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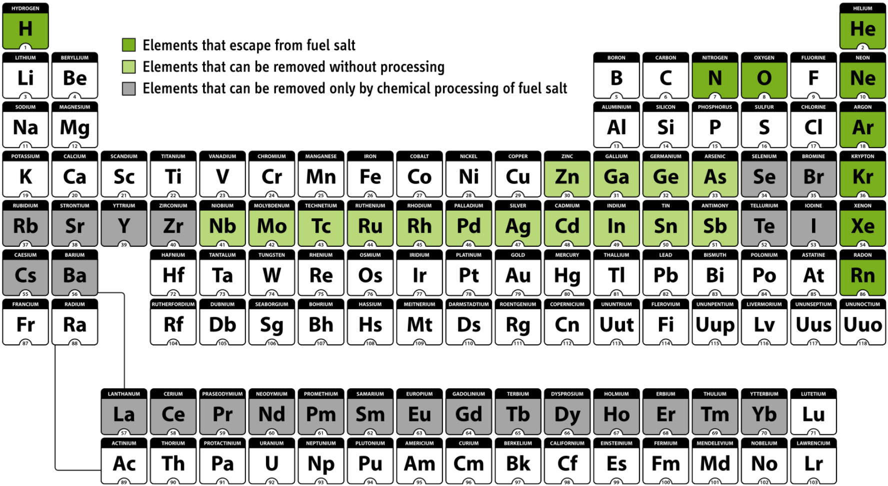
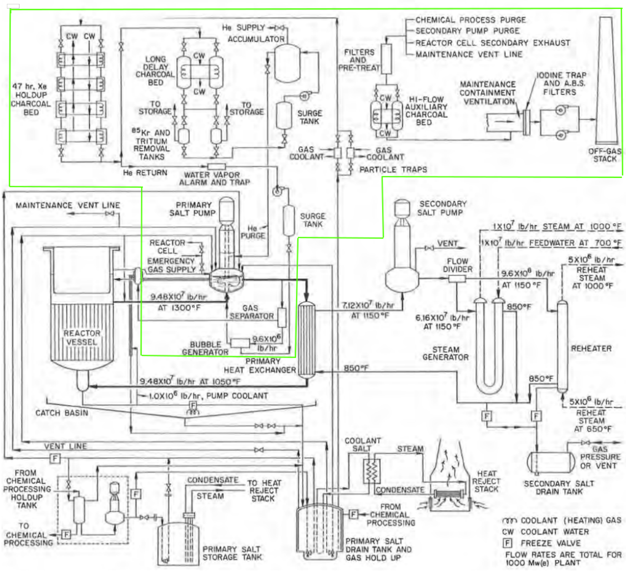
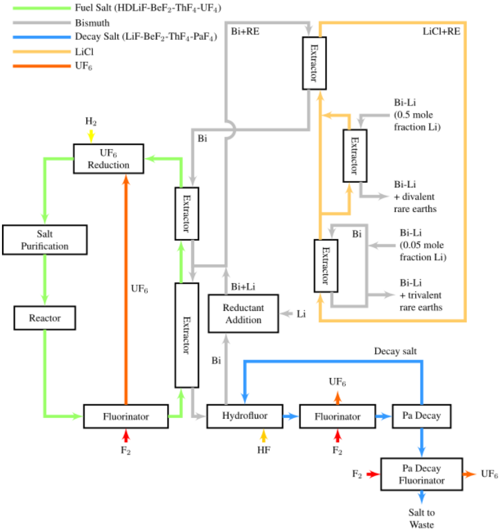
Processing options for MSR fuels



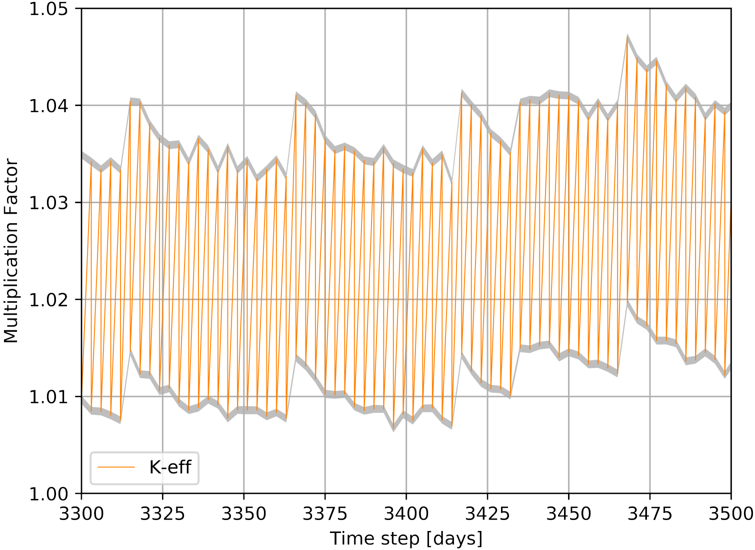
BUBBLE GENERATOR AND GAS SEPARATOR for MSBR



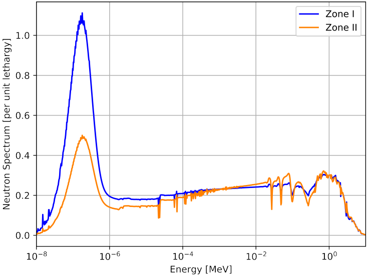
Chemical processing facility for MSBR

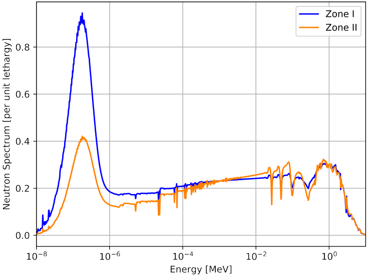


Multiplication factor dynamics during Rb, Sr, Cs, Ba removal (3435days)

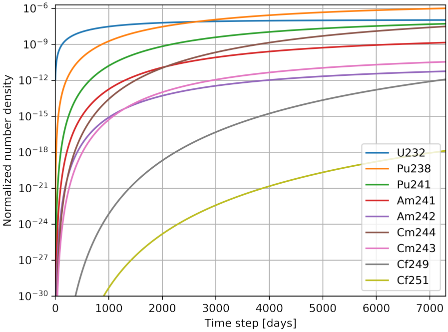


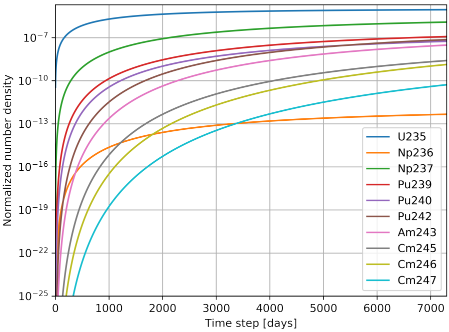
MSBR neutron energy spectrum for different regions



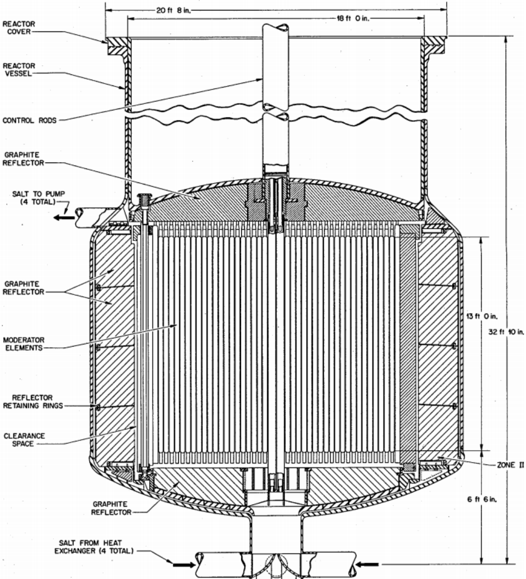


Fissile isotopes producing in MSBR core





MSBR plain view



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

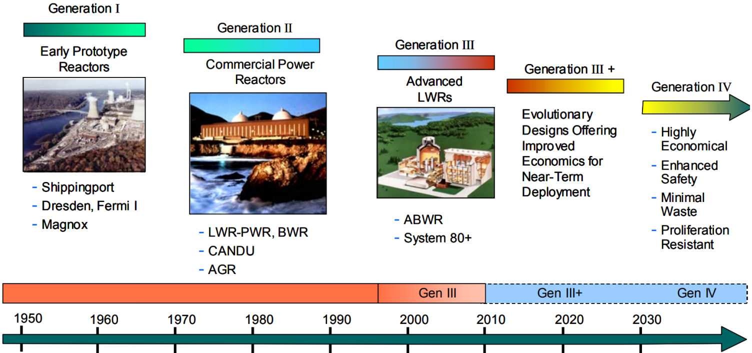


Figure 14: A Technology Roadmap for Gen IV Nuclear Energy Systems [1].