Fuel Cycle Performance of Fast Spectrum Molten Salt Reactor Designs

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Outline

Research objectives and motivation

Motivation

- Fuel cycle performance analysis for four Fast Molten Salt Reactor (MSR) concepts requires a depletion simulation over the system lifetime (60 years)
- Full-core 3D 60-year depletion calculations for MSRs using Monte Carlo code (Serpent/Shift) are computationally prohibitive
(16 mln neutron histories per state point to obtain uncertainty $\pm 7 pcm$)
- We want to reduce the cost by performing depletion simulations for representative simplified unit cells using deterministic code (TRITON)

Depletion calculations of MSR with continuous fuel reprocessing

1. Develop high-fidelity 3D models of four different Fast Spectrum MSRs using Monte Carlo code Serpent 2 [1]
2. Create and validate simplified 2D (XY) models for SCALE [2] with optimal cost/accuracy ratio
3. Perform depletion simulation with on-line continuous feeds and removals to estimate fuel cycle performance of selected designs

MSR (Molten Salt Reactor) types

Stationary Fuel

1. Graphite block with TRISO fuel, clean salt works as coolant (Fluoride-Salt-Cooled High-Temperature Reactor (FHR))
2. Plate Fuel: hexagonal fuel assembly is similar in shape to a typical sodium-cooled reactor
3. Fuel Inside Radial Moderator (FIRM)
4. Liquid fuel salt inside fuel rods cooled by clean salt (Moltex Stable Salt Reactor)

Mobile Fuel

1. Mobile solid fuel elements (pebbles) cooled by clean salt (PB-FHR)
2. **Circulating molten fuel salt** which also works as coolant (Molten Salt Breeder Reactor (MSBR), Molten Salt Fast Reactor (MSFR))

Stationary and Mobile Solid fuel

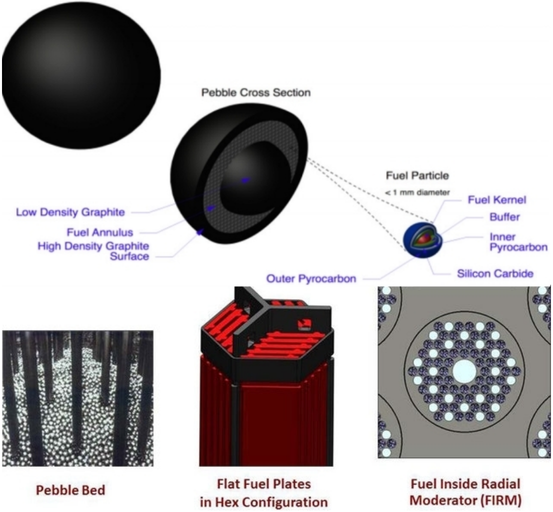

Figure 1: TRISO fuel particle (top) and FHR fuel designs (bottom). Source [3] .

Mobile, Circulating, Liquid Fuel

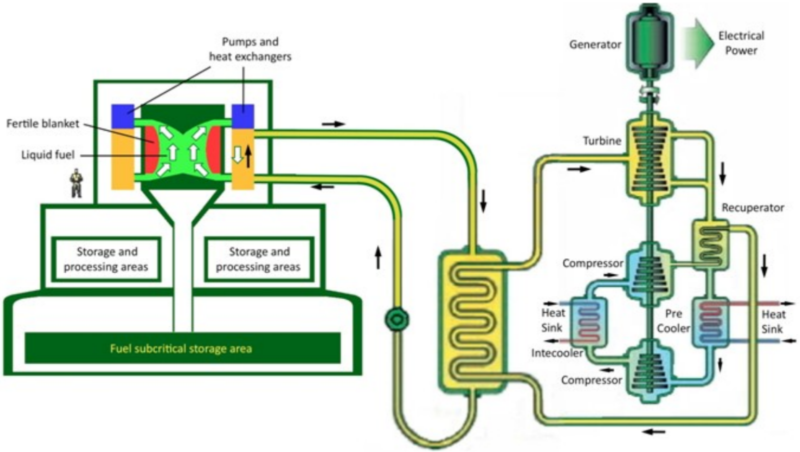

Figure 2: EVOL MSFR is an example of reactor design with **liquid, mobile, circulating** fluoride salt fuel (Image courtesy of Elsa Merle-Lucotte, 2015).

Why Molten Salt Reactors with circulating fuel?

Liquid-fueled MSR designs have following potential advantages:

1. High coolant temperature (600-750°C) ⇒ potentially high thermal efficiency, process heat for chemical industry
2. Fuel diversity (^{235}U, ^{233}U, Thorium, U/Pu)
3. Strong negative temperature feedback of liquid fuel
4. Passive safety ⇒ fuel drains into tanks in emergency
5. High fuel utilization ⇒ less nuclear waste generated
6. On-line (continuous) fuel reprocessing and refueling
7. Can produce more fissile material than it consumes (breeder)
8. Nuclear Spent Fuel Transmuter
9. Unmoderated ⇒ no replacement of an irradiated moderator needed

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Fast Spectrum MSR depletion simulation

Depletion simulations were performed using SCALE/TRITON 6.2.4 Alpha [4]:

- Truly continuous (online) salt reprocessing (removals and feeds)
- Supports only constant or piecewise feed and removal rates
- Depletion over the system lifetime (60 years)
- Simplified geometry (unit cell), a 16×16 spatial mesh
- 238-group ENDF-B/VII.0 cross-section library

Four different fast MSR designs:

1. European MSFR [5]
2. Molten Chloride Salt Fast Reactor (MCSFR) [6]
3. REBUS-3700 [7]
4. Molten Salt Actinide Recycler and Transmuter (MOSART) [8]

Selected Fast Spectrum MSR designs

Table 1: Principal data of selected fast spectrum MSR designs.

Parameter	MSFR	MCSFR	REBUS-3700	MOSART
P [MW_{th}]	3,000	6,000	3,700	2,400
V_{fuel} [m^3]	18	38	55.6	49.05
$V_{fertile}$ [m^3]	7.3	75	—	—
Fuel salt	LiF-ThF_4-$^{233}UF_4$	$NaCl$-UCl_3-$^{239}PuCl_3$	$NaCl$-$TRUCl_3$	LiF-BeF_2-ThF_4-$TRUF_3$
Fertile salt	LiF-ThF_4	$NaCl$-UCl_3	—	—
Fuel cycle	$Th/^{233}U$	U/Pu	U/TRU	$Th/^{233}U$
$m_{init\ fissile}$ [t]	7.726	9.400	18.061	9.637

Geometry approximation

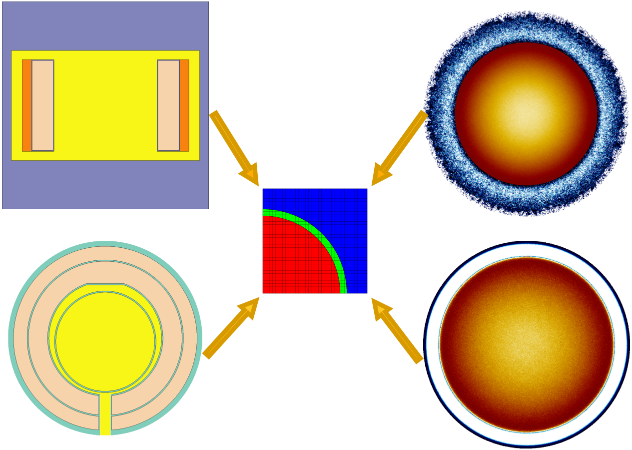
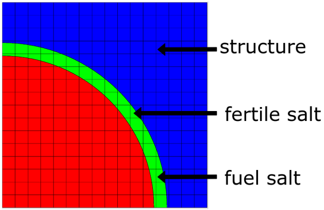


Figure 3: Full-core 3D models of MSFR (upper left), MCSFR (lower left), REBUS-3700 (upper right), and MOSART (lower right) and 2D representative unit cell model (center) showing fuel salt (red), fertile salt (green), and structural material (blue).

Unit cell model construction



Simplified unit cell geometry for each MSR concept was selected as follows:

1. Fuel-to-fertile salt ratio for unit cell was consistent with full-core model:

$$\frac{V^f_{core}}{V^f_{blanket}} = \frac{A^u_{core}}{A^u_{blanket}}$$

2. Size of unit cell was adjusted to obtain k^u_∞ as close to k^f_{eff} as possible
3. Structural material volume for unit cell was varied to get neutron energy spectrum shape close to full-core spectrum

Accuracy validation for simplified model

The geometry and size for unit cell are optimized using specific rules:

1. Multiplication factor has less than 300*pcm* difference between approximated and full-core geometry
2. Pearson correlation coefficient r for neutron spectrum:

$$r = \frac{\sum_{i=1}^{N}(\Phi_i^f - \overline{\Phi^f})(\Phi_i^u - \overline{\Phi^u})}{\sqrt{\sum_{i=1}^{N}(\Phi_i^f - \overline{\Phi^f})^2 \sum_{i=1}^{N}(\Phi_i^u - \overline{\Phi^u})^2}} > 0.995$$

3. Approximation error δ in total neutron flux:

$$\delta = \left| \frac{\sum_{i=1}^{N}(\Phi_i^f - \Phi_i^u)}{\sum_{i=1}^{N} \Phi_i^f} \right| \times 100\% < 3\%$$

Fuel Cycle Performance Evaluation Metrics

Nuclear Fuel Cycle Evaluation and Screening

- The DOE-NE funded a study to conduct an evaluation and screening of nuclear fuel cycle options
- The study formulated sixteen Evaluation Metrics (EM)

Evaluation metrics calculated based on continuous reprocessing depletion herein:

1. Natural uranium per energy generated (for MCSFR, REBUS-3700)
2. Natural thorium per energy generated (for MSFR, MOSART)
3. Mass of spent nuclear fuel (SNF)+high level waste (HLW) disposed per energy generated
4. Mass of depleted uranium (DU) + recovered uranium (RU) + recovered thorium (RTh) disposed per energy generated

Outline

1. Introduction
   - Motivation
   - Fast Molten Salt Reactors
2. Methodology
3. Results
4. Conclusions
5. Acknowledgements

Accuracy of unit cell geometry (1/2)

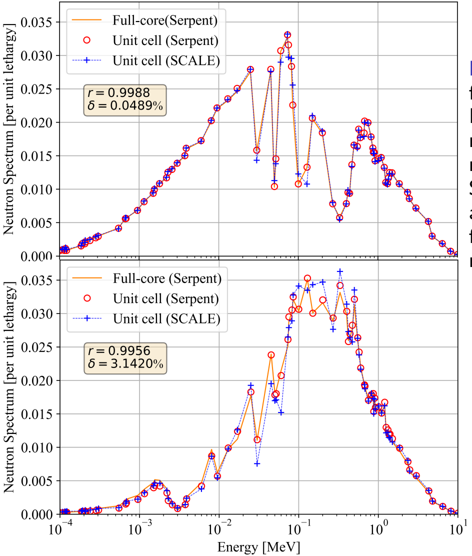


Figure 4: Neutron flux energy spectrum for full-core and unit cell models for two-fluid MSFR (top) and MCSFR (bottom). The neutron population per cycle and the number of active/inactive cycles for Serpent simulations were chosen to obtain a balance between reasonable uncertainty for a transport problem ($\pm 10pcm$ for multiplication factor).

Accuracy of unit cell geometry (2/2)

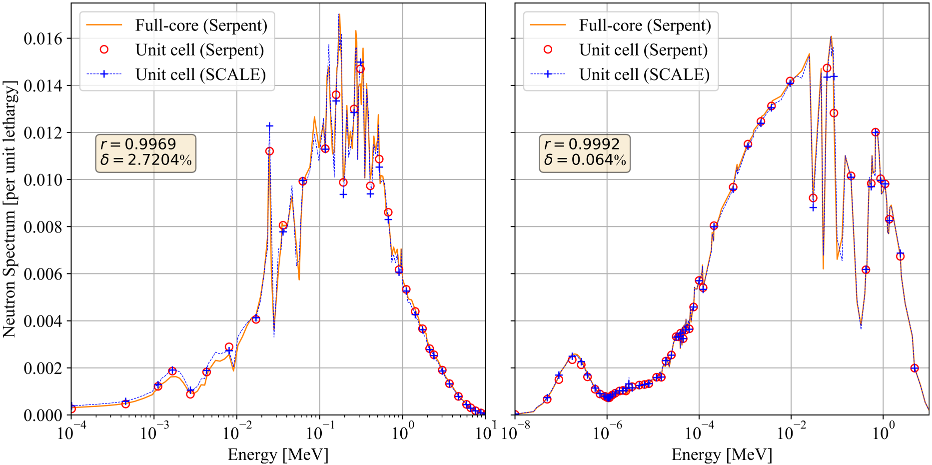


Figure 5: Neutron flux energy spectrum for full-core and unit cell models for single-fluid REBUS-3700 (left) and MOSART (right). Uncertainty for multiplication factor is $\pm 10 pcm$.

Approximation accuracy for depletion calculations

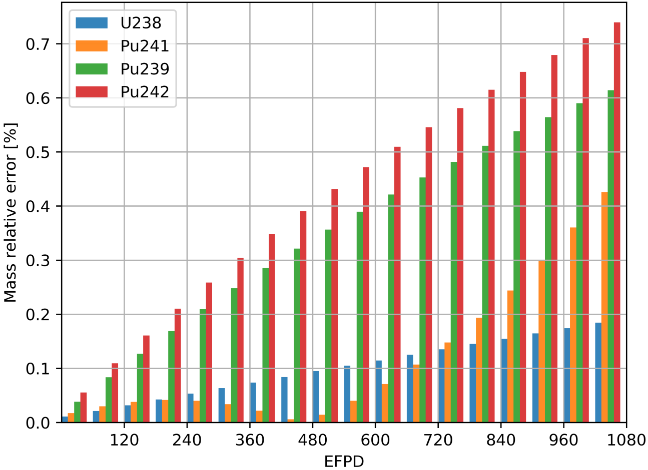


Figure 6: Discrepancy in mass of important isotopes in REBUS-3700 for full-core and unit cell depletion calculations using SERPENT2 without reprocessing.

Multiplication factor for four MSR designs

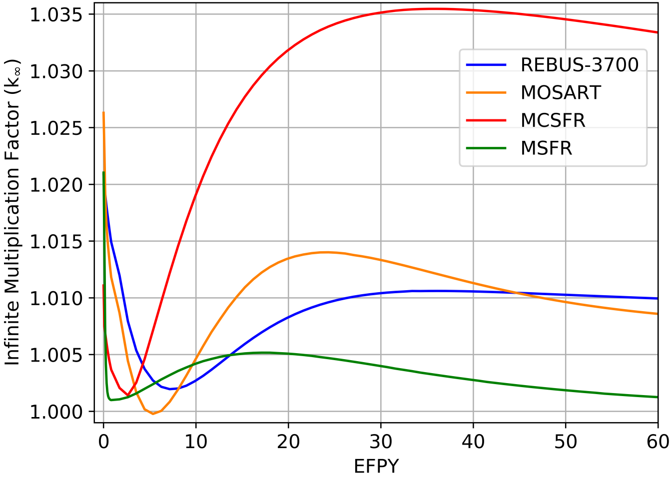


Figure 7: Infinite multiplication factor for four reactor designs during 60 years of operation.

Evolution of heavy metal inventory: MSFR and MCSFR

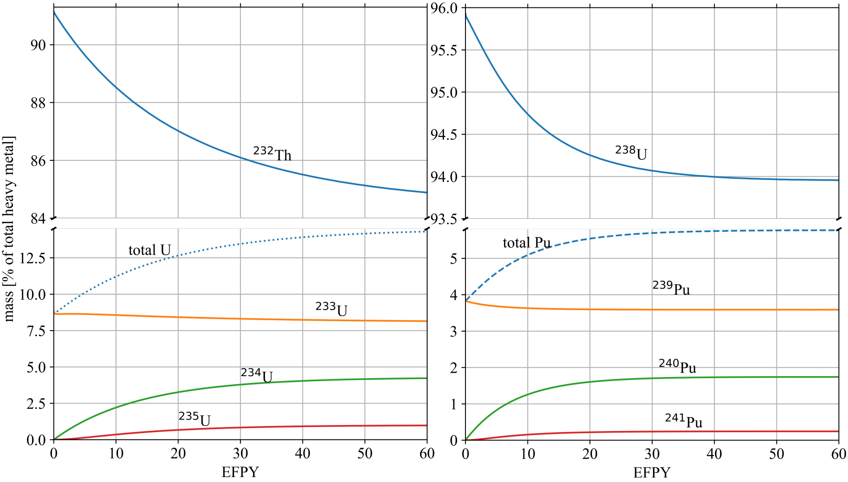


Figure 8: MSFR (left) and MCSFR (right) heavy metal isotopic salt content during operation calculated with the unit cell model (238-group transport).

Evolution of heavy metal inventory: MOSART and REBUS-3700

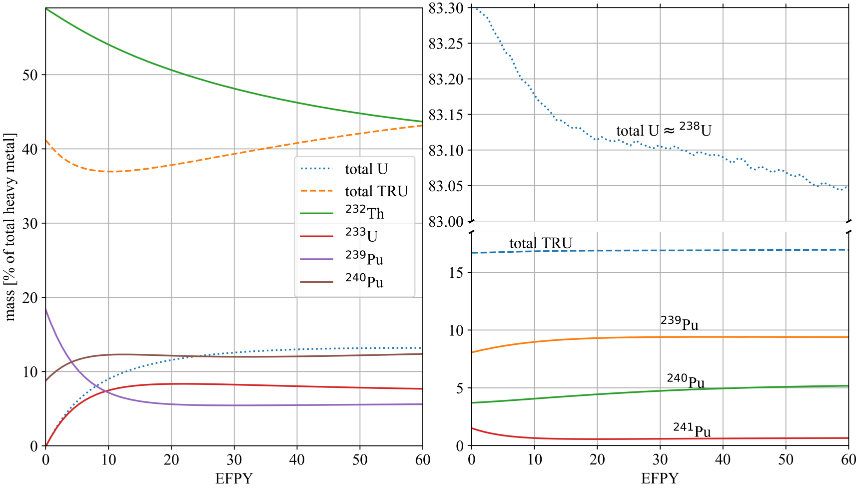


Figure 9: MOSART (left) and REBUS-3700 (right) heavy metal isotopic salt content.

Nuclear Fuel Cycle Evaluation and Screening Metrics

Table 2: The E&S evaluation metrics of selected fast spectrum MSR designs

Parameter	MSFR	MCSFR	REBUS	MOSART
Evaluation Group	EG28	EG23	EG24	EG28
Natural U or Th Utilization [t/GWe-yr]	0.663(Th)	0.973(U)	0.834(U)	0.402(Th)
Mass of SNF+HLW disposed [t/GWe-yr]	0.866	0.894	0.813	0.820
Mass of DU+RU+RTh disposed [t/GWe-yr]	0.0	0.0	0.0	0.0
Products from Reprocessing/Separation technology [t]:				
RU	8.7	83.2	92.6	3.9
RTh	41.9	0.0	0	12.9
Transuranic elements (TRU)	0.36	32.8	18.9	12.9
Fission products (FP)	69.51	140.3	79.6	54.1

Outline

Conclusions

FS-MSR design depletion with simplified unit cell vs full-core geometry

- Relative error in one-group neutron flux $< 3.15\%$
- Correlation coefficient > 0.9956
- Depleted mass relative error for major isotopes $< 1\%$ (for REBUS)
- $20\times$ speedup

Continuous reprocessing depletion simulations for four FS-MSR concepts

- All four selected designs are able to maintain criticality while the salt inventory is kept constant during lifetime
- Fuel utilization varies from 0.402 tTh/GWe-yr for MOSART to 0.973 MTU/GWe-yr for MCSFR (Metric Bin A, $<$ 3.8 t/GWe-yr)
- SNF+HLW generation for all four designs is consistent with fast spectrum fuel cycle technologies (Metric Bin A, $<$ 1.65 t/GWe-yr)
- No DU+RU+RTh disposed, assuming we recover all U/Th from the salt
- Fuel Cycle Performance of these fast MSRs is consistent with other fast reactor technologies

Future work

Future research effort

1. Code-to-code validation of SCALE/TRITON Alpha against another continuous reprocessing code (e.g., SERPENT2) and batch-wise Python package SaltProc [9]
2. MSFR simulation with additional protactinium isolation system which enhance ^{233}U breeding
3. MSFR simulation with another startup composition (transuranic (TRU)) to evaluate its performance as a waste burner
4. MCSFR might be optimized to operate with enriched uranium as startup composition instead of ^{239}Pu
5. Accident safety analysis using coupled neutronics/thermal-hydraulics code, such as Moltres [10]

Outline

Acknowledgement

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Selected Fast Spectrum MSR designs (extended table)

Table 3: Principal data of selected fast spectrum MSR designs.

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Thermal power, MW	3,000	6,000	3,700	2,400
Fuel salt volume, m^3	18	38	55.6	49.05
Fertile salt volume, m^3	7.3	75	—	—
Fuel and fertile salt initial composition, mol%	LiF-ThF_4-$^{233}UF_4$ (77.5-19.9-2.6) LiF-ThF_4 (77.5-22.5)	NaCl-UCl_3-$^{239}PuCl_3$ (60-36-4) NaCl-UCl_3 (60-40)	55mol%NaCl+ 45mol%(natU+ 16.7at.%TRU)Cl_3	LiF-BeF_2-ThF_4-$TRUF_3$ (69.7-27-1.3)
Fuel cycle	Th/^{233}U	U/Pu	U/TRU	Th/^{233}U
Initial fissile inventory, t	7.726	9.400	18.061	9.637
Fissile/fertile salt	973/973	1008/923	900	933