Fuel Cycle Performance of Fast Spectrum Molten Salt Reactor Designs

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Introduction

Fast spectrum molten salt reactor (MSR) designs with liquid fuel have following advantages:

- High coolant temperature (650–750℃) → potential high thermal efficiency, process heat for chemical industry
- Strong negative temperature feedback of liquid fuel
- Passive safety → fuel drains into tanks in emergency
- On-line (continuous) fuel reprocessing potential
- Practical closed nuclear fuel cycle implementation

Challenge: commonly available reactor physics codes *cannot simulate* continuous fuel reprocessing.

Objectives

1. Develop high-fidelity 3D models of 4 different fast MSRs using Monte Carlo code SERPENT2 [1]
2. Create and verify simplified 2D models for SCALE [2]
3. Perform depletion simulation with continuous fuel reprocessing to compare fuel cycle performance

Methods

Recently developed TRITON continuous reprocessing module performs depletion solve (Bateman equation) with continuous reprocessing capability.

Simplified geometry verified against full-core model by computing correlation factor for neutron energy spectra:

$$r = \frac{\sum_{i=1}^{n} ({}^{full}_{i}\Phi - \overline{{}^{full}\Phi})({}^{unit}_{i}\Phi - \overline{{}^{unit}\Phi})}{\sqrt{\sum_{i=1}^{n} ({}^{full}_{i}\Phi - \overline{{}^{full}\Phi})^2 ({}^{unit}_{i}\Phi - \overline{{}^{unit}\Phi})^2}}$$

Results

Table 1. Four fast spectrum MSRs are selected:

	Molten Salt Fast Reactor (MSFR) [3]	Molten Chloride Salt Fast Reactor (MCSFR) [4]	REBUS-3700 [5]	Molten Salt Actinide Recycler&Transmuter (MOSART) [6]
Thermal power, MW	3,000	6,000	3,700	2,400
Fuel salt volume (in/out of core), m^3	18 (9/9)	38 (16/22)	55.6 (36.9/18.7)	49.05 (32.7/16.35)
Fertile salt volume (in/out blanket), m^3	7.3/0	53/22	-	-
Salt initial composition (fuel/fertile), mol%	LiF-ThF_4-$^{233}UF_4$ (77.5-19.9-2.6) LiF-ThF_4 (77.5-22.5)	$Na^{37}Cl$-$U^{37}Cl_3$-$^{239}PuCl_3$ (60-36-4) $Na^{37}Cl$-$U^{37}Cl_3$ (60-40)	55 mol%NaCl + 45 mol%(natU+16.7at.% TRU)Cl_3	LiF-BeF_2-ThF_4-$TRUF_3$ (69.75-27-2-1.25)
Fuel cycle	Th/^{233}U	U/Pu	U/Pu	Th/^{233}U
Initial fissile inventory, kg	5 060	9 400	18 061	9 637

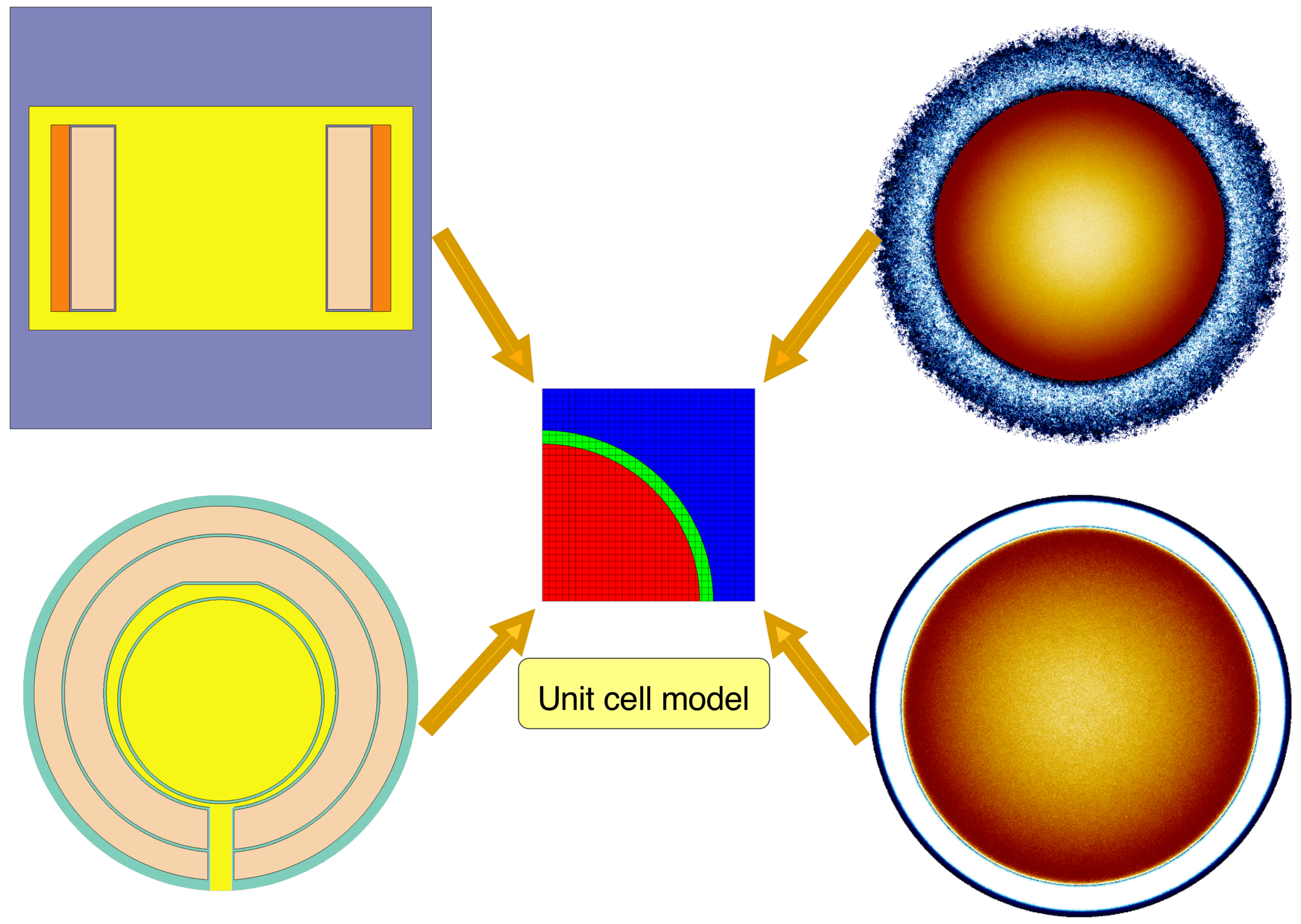

Figure 1. Full-core 3D models of MSFR (upper left), MCSFR (lower left), REBUS-3700 (upper right) and MOSART (lower right) simplified into 2D unit cell model. Simplification reduces computational time by factor of 20.

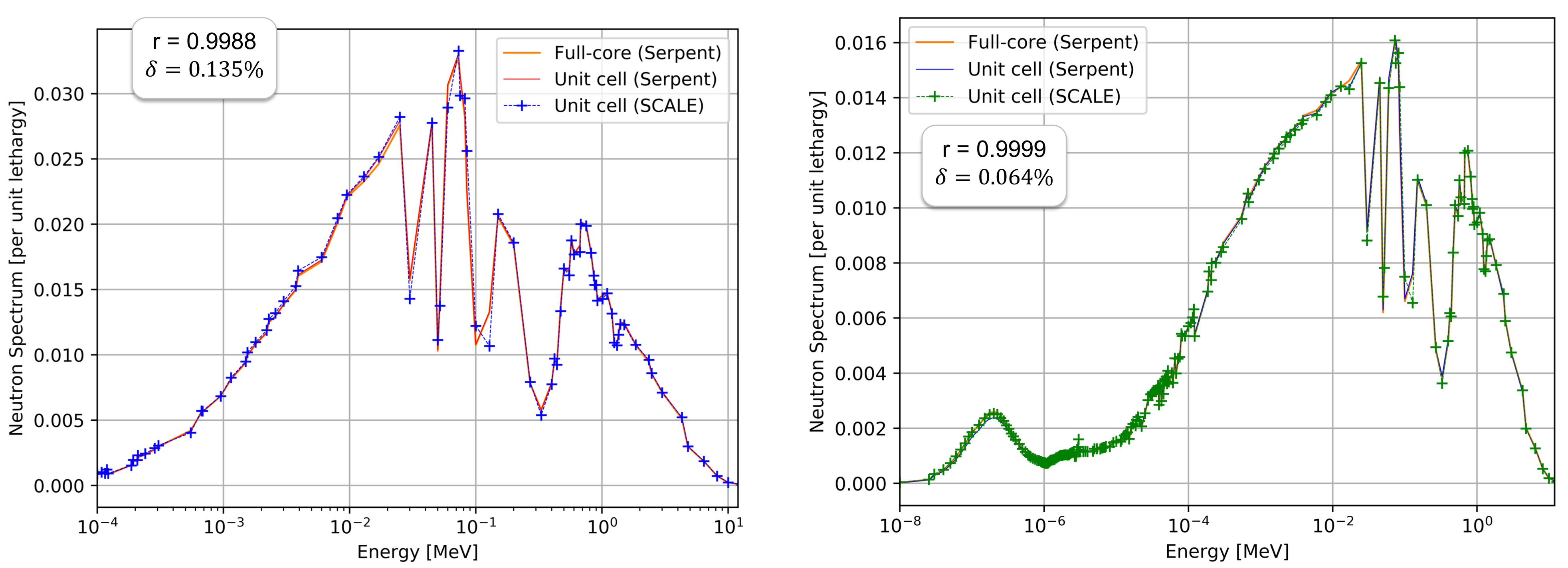

Figure 2. Neutron flux energy spectrum for full-core and simplified models for MSFR (left) and MOSART (right)

Continuous fuel reprocessing results

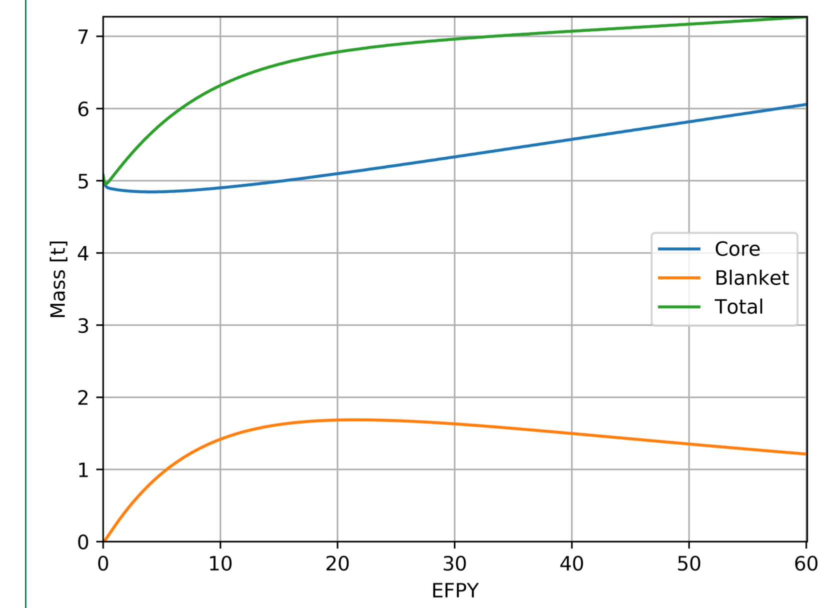

Figure 3. Fissile ^{233}U production from core and blanket of MSFR over 60 years' lifetime

MSFR fuel cycle performance

- ^{233}U production rate 36.6 kg/y
- Lifetime averaged breeding ratio 1.0072
- First 5 years averaged breeding ratio 1.0283
- Doubling time 139 yrs

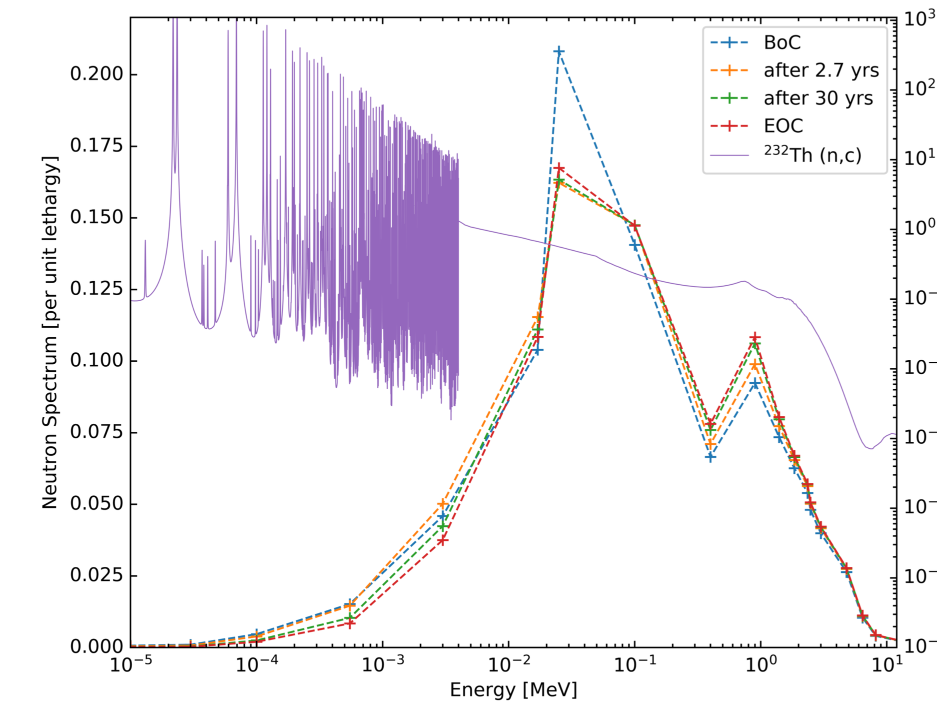

Figure 4. Neutron energy spectral shift during MSFR operation and ^{232}Th capture cross section

Conclusions

- Depletion simulations for fast spectrum MSRs can be performed with simplified model without losing accuracy.
- Th/^{233}U fuel cycle is not the best option for fast neutron spectrum in MSFR, ^{238}U/Pu fuel cycle might be studied.
- To achieve higher breeding ratio, fertile salt in blanket also might be reprocessed.
- Neutron energy spectrum softens during first 5 years of operation (which enhances ^{233}U breeding) and then hardens due to strong absorber accumulation.

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