Full-Core Analysis of Thorium-Fueled Molten Salt Breeder Reactor Using the SERPENT 2 Monte Carlo Code

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Outline

Reactor systems potentially meeting the Generation IV goals

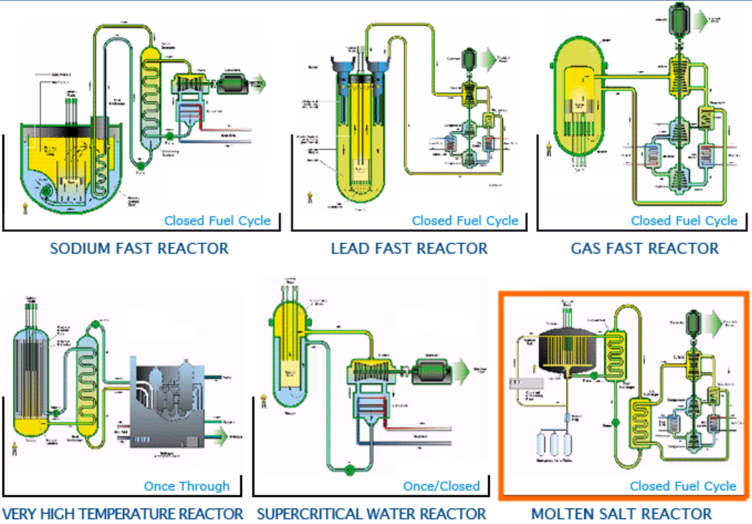


Figure 1: Potential Generation IV reactors [1].

Why Molten Salt Reactors?

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

1. High average coolant temperature (600-750°C) $\Rightarrow$ high thermal efficiency, hydrogen production, cheap heat for chemical industry.
2. May operate with epithermal or fast neutron spectrums.
3. Various fuels (^{235}U, ^{233}U, Thorium, U/Pu).
4. Inherent safety advantages: fuel already liquid and drains into tanks in emergency.
5. Large fuel utilization $\Rightarrow$ less nuclear waste generated.
6. Online reprocessing and refueling.

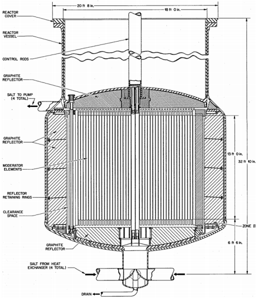
Main advantages of Molten Salt Breeder Reactor (MSBR)

1. Breed fissile ^{233}U from ^{232}Th with the breeding ratio 1.06 gives an annual fissile yield of 3.3%.
2. Fuel salt heats up to 705°C which makes thermal efficiency of over 44%.
3. ^{233}U, ^{235}U, or ^{239}Pu could be used for the initial fissile loading.
4. Outstanding neutron economy because of single-fluid two-region design.

Molten Salt Reactor Experiment vs Molten Salt Breeder Reactor

Molten Salt Reactor Experiment (MSRE)

1. Maximum power 8 MW_{th}
2. Fuel salt
   - $^{7}LiF\text{-}BeF_2\text{-}ZrF_4\text{-}UF_4$
   - $^{7}LiF\text{-}BeF_2\text{-}ZrF_4\text{-}UF_4\text{-}PuF_3$
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) [2]

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

Research objectives

Goals of current study

1. Create high-fidelity full-core 3-D model of MSBR, ideally, without any approximations.
2. Run steady-state criticality simulation using the SERPENT 2 Monte Carlo code [3] to determine effective multiplication factor and neutron spectrum.
3. Find temperature effect of reactivity varying fuel salt and graphite temperature from 900K to 1200K.
4. Compare obtained results with Park (MCNP6) model of MSBR [4] and Robertson *et al.* [2].

Why we need this model?

1. Depletion calculations, including online reprocessing simulation.
2. Nuclear data generation for multi-physics transient analysis (full-core model needed for asymmetric accidents).
3. Fuel cycle optimization.

Input data

Table 1: Summary of principal data for MSBR [2]

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	71.767-16-12-0.232 mole%

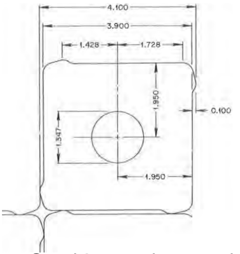
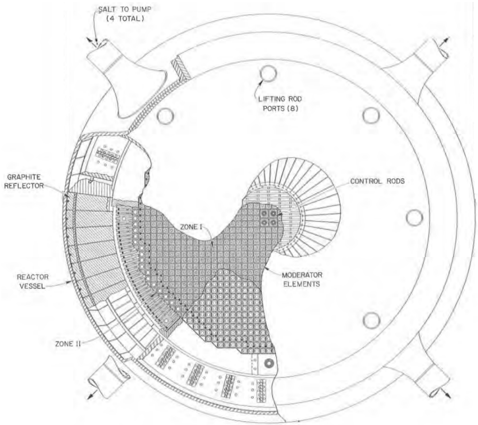


Figure 2: Graphite moderator element.



Outline

Geometry of MSBR model for SERPENT 2

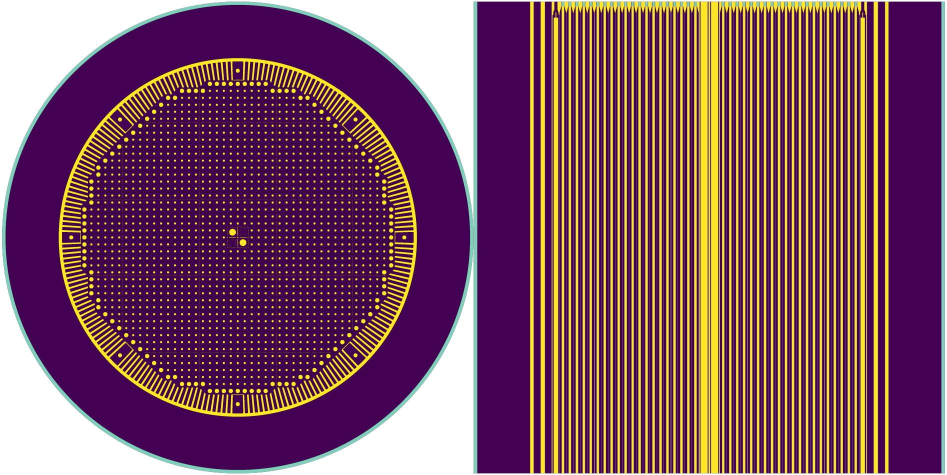


Figure 3: Plan (left) and elevation (right) view of MSBR model

Graphite elements geometry

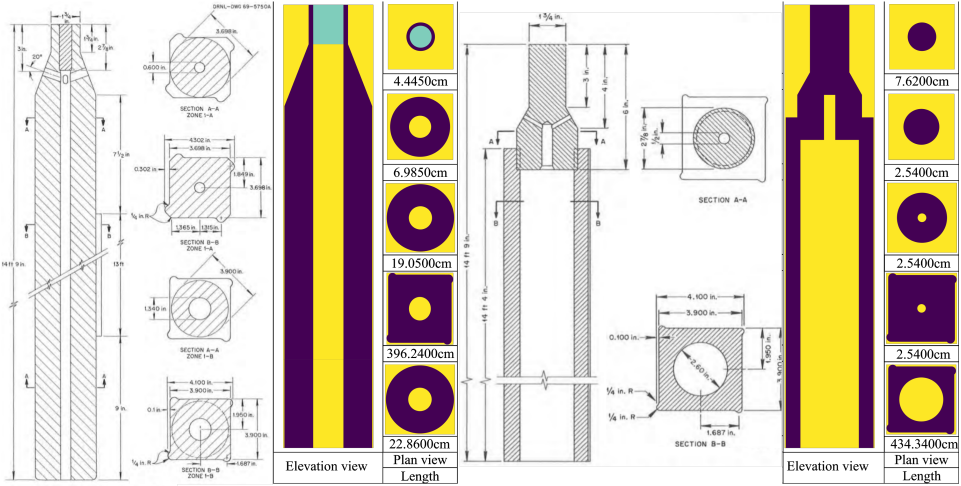


Figure 4: Zone I (left) and Zone II (right) reference design [2] and model.

Volume fraction of fuel salt in zones I and II was 0.132 and 0.37 respectively.

Core Zone II

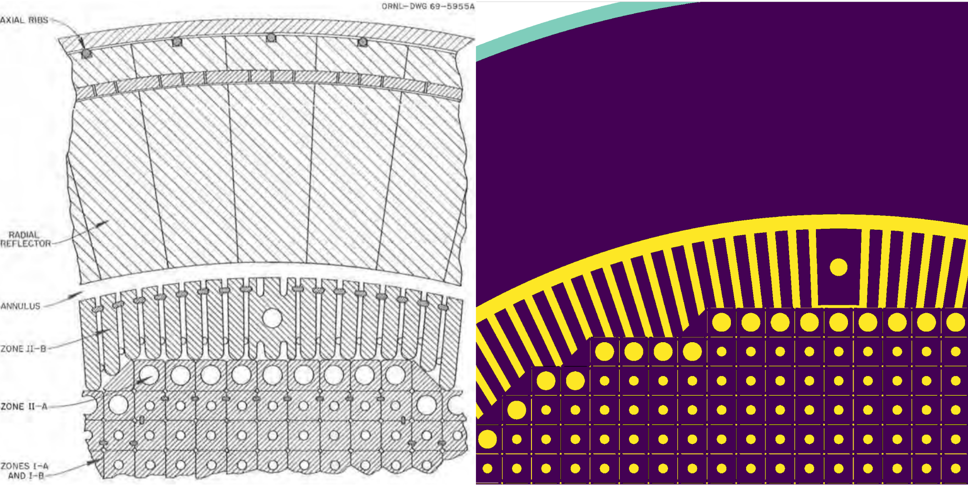


Figure 5: Detailed plan view of graphite reflector and moderator elements.

Approximations and assumptions

Geometry simplifications

1. Zone II-B elements simplified into right-circular cylindrical shapes with central channels.
2. Axial ribs in Zone I outer layer, Zone II-B and reflector was not described in the model.

Simulation conditions and nuclear data

1. Two graphite control rods are fully inserted.
2. Two safety rods are fully withdrawn.
3. Moderator and fuel temperature is 900K.
4. 10^5 neutrons per cycle for a total of 1000 cycles, the first 50 are inactive.
5. ENDF/B-VII cross sections were used.

Outline

Steady-state criticality simulation results

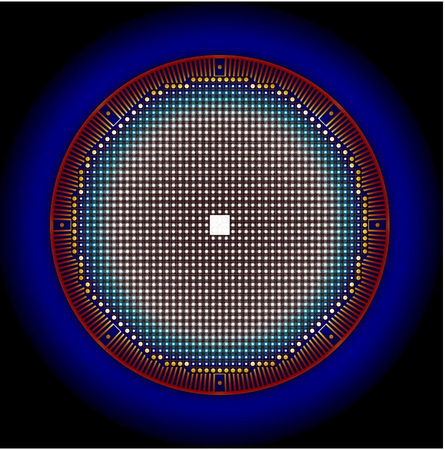


Table 2: Effective multiplication factor for full-core model

	SERPENT2	Park(MCNP6)[4]
K_{eff}	1.00397±0.00005	1.00736±0.00009

- SERPENT 2 factor is 300 pcm lower than that obtained by Park (MCNP6) [4]
- Standard deviation is 5 pcm versus 9 pcm for Park (MCNP6) model.

Effective multiplication factor for full-core model (cont.)

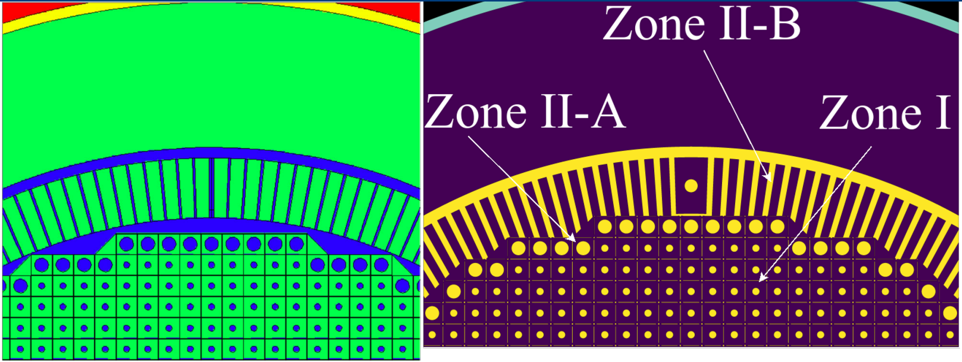


Figure 6: Detailed plan view of Park (MCNP6) (left) [4] and SERPENT 2 (right) model.

Possible reasons for the discrepancy

- Park (MCNP6) model has simplification in Zone I geometry.
- Zone II geometry in Park (MCNP6) has a gap between Zone II-A and Zone II-B.

Neutron spectrum

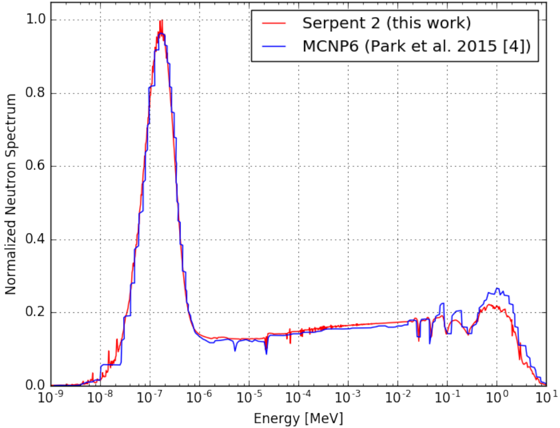


Figure 7: Normalized neutron spectrum for Park(MCNP6) and SERPENT 2 model.

- Thermal spectrum required to breed fissile ^{233}U from fertile ^{232}Th.
- Hardening the spectrum tends to increased resonance absorption in thorium and decreased absorption in fissile material.

Temperature effect of reactivity

The effect of temperature change on the reactivity can be expressed by temperature coefficient of reactivity:

$$\alpha_T = \frac{d\rho}{dT} \tag{1}$$

TABLE 3: Input data variation for temperature effect of reactivity analysis

α_T	**Nuclear data temperature**	**Density**	**Geometry**
Fuel salt	900-1200K	3.28-3.13 g/cm^3[2]	no changes[1]
Moderator	900-1200K	1.84 g/cm^3[2]	expanded[2,3]
Total	900-1200K	fuel: 3.28-3.13g/cm^3 graphite: 1.84 g/cm^3	only graphite expanded

[1] fuel salt is bounded by the graphite
[2] volumes of graphite were recalculated using linear thermal expansion coefficient 1.3×10^{-6} 1/K
[3] graphite density is assumed constant

Temperature effect of reactivity (cont.)

TABLE 4: Temperature coefficients of reactivity.

Reactivity coefficient [pcm/K]	SERPENT 2	MCNP6 [4]	Reference [2]
Fuel salt	-3.38 ± 0.015	-3.20 ± 0.05	-3.22
Moderator	$+2.33 \pm 0.027$	-0.11 ± 0.05	$+2.35$
Total	-1.57 ± 0.033	-3.21 ± 0.04	-0.87

- The fuel temperature coefficient (FTC) is negative due to thermal Doppler broadening of the resonance capture cross sections in the thorium and is in a good agreement with early research [2, 4].
- The moderator temperature coefficient (MTC) is positive due to thermal expansion and would increase during reactor operation because of spectrum hardening along with fuel depletion [4].
- To obtain MTC negative and closer to MCNP6 simulation more details about changes in Park *et al.* model needed (i.e. changes in graphite density, geometry recalculation).
- The isothermal temperature coefficient (ITC) is relatively large and negative and affords excellent reactor stability and controllability

Outline

Conclusions

This study outcomes

- Full-core MSBR 3-D analysis was performed using the SERPENT 2 Monte Carlo code.
- K_{eff} for initial fuel composition is slightly larger than 1 (1.00397) which allows reactor operation from startup to the first online reprocessing cycle.
- The neutron flux energy was calculated for the whole MSBR core.
- The total temperature coefficient is negative, but MTC is negative which has a negligible effect on safety because it is outweighed by the strong, negative FTC.
- Simulation results are in a good agreement with Park (MCNP6) model except moderator temperature coefficient.

Conclusions

Future research effort

This high-fidelity full-core model will be employed for:

1. Depletion simulations using SERPENT 2 capabilities to find the equliblium fuel composition of the MSBR.
2. Initial fuel salt composition and reprocessing parameters (i.e. rates of removing fission products, the rate of refilling thorium) optimization.
3. Problem-oriented nuclear data libraries generation for multi-physics models of MSBR in the MOOSE-based coupled neutronics/thermal-hydraulics code Moltres [5].

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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

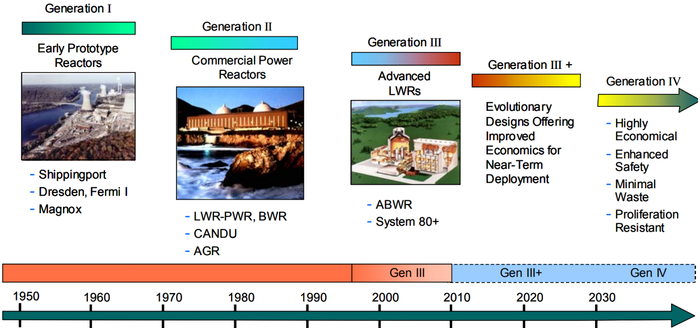

Figure 8: A Technology Roadmap for Gen IV Nuclear Energy Systems [1].