A New TRISO-Fueled Salt-Cooled Reactor Concept: Core Feasibility under Natural Circulation Cooling

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1. Introduction

This study proposes a new reactor design concept, the TRISO-Fueled Salt-Cooled Reactor (TFSCR). The design objective of this reactor is to enable safe and efficient operation in inland regions. The current stage of research focuses on verifying the feasibility of the core concept, assuming a thermal power of 100 MWth. Previous studies have already confirmed the feasibility of neutronic performance [1]; the present work conducts core temperature distribution calculations to further verify the feasibility of this design.

The TFSCR design adopts LiF-BeF_2 molten salt as the coolant, allowing the reactor to operate under low pressure conditions of 0.2–0.3 MPa while achieving a core outlet temperature of 750℃. This design enhances power generation efficiency while reducing the risk of large-scale coolant leakage in accident scenarios, thus retaining the inherent advantages of molten salt reactors (MSRs). Unlike conventional MSRs, this design uses TRISO fuel particles. The multi-layer coating structure of TRISO particles effectively isolates nuclear materials, providing resistance against neutron irradiation, corrosion, and high temperatures, thereby ensuring fuel integrity and operational safety. Graphite is used as the moderator, arranged in prismatic blocks. Each graphite block contains dedicated channels functioning either as fuel or coolant channels, with a fuel-to-coolant channel ratio of 1:2. The core is divided into 12 equal sectoral regions, where fuel channels are interconnected through U-shaped pipes to form continuous fuel flow paths. TRISO particles carried by LiF-BeF_2 molten salt are gradually introduced into the core through the fuel inlets, circulate within the system, and exit through the outlets, enabling continuous online refueling. This design prevents the fuel from entering the cooling circulation system, thereby reducing neutron irradiation effects on the cooling system.

In the calculations, core neutronics analysis and thermal-hydraulic analysis were performed using the MCS code and the GAMMA+ code, respectively. Core dimensions and power distributions satisfying design requirements were first obtained through neutronics analysis. Thermal-hydraulic analysis was then conducted to verify whether the resulting temperature distributions satisfied safety constraints. Based on the results, core structural dimensions were adjusted and neutronics analysis was repeated with the updated geometry. This iterative process continued until a core design satisfying both thermal safety limits and neutronic performance criteria was achieved.

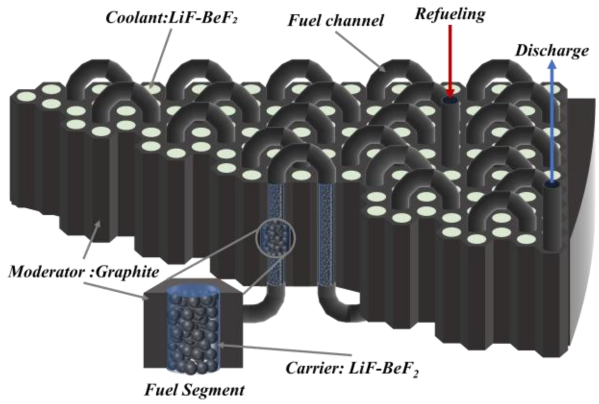

Figure 1. Geometric Layout of 1/12 Core Region

2. Calculation conditions and results

2.1 Temperature requirements

TRISO fuel can maintain structural integrity below 1600 ℃, preventing fuel failure. However, prolonged operation above 1250 ℃ may cause degradation of the SiC coating due to irradiation effects [2]. The salt LiF-BeF_2 has a melting point of 460 ℃ and a boiling point of 1400 ℃ at atmospheric pressure [3]. Therefore, in this design, the maximum core operating temperature is limited to 1250 ℃, and following reference MSR designs, the core outlet temperature is set to 750 ℃ [4].

2.2 Reactor system model

The reactor cooling system consists of a primary loop, intermediate loop, and secondary loop. Both the primary and intermediate loops use LiF-BeF_2 molten salt, while the secondary loop uses steam. The intermediate loop is introduced to prevent steam intrusion into the core in the event of pipe failure. The design objective is to achieve core cooling in the primary loop through natural circulation, thereby reducing system complexity and eliminating pump-related safety risks.

Since the overall reactor layout has not yet been finalized, this study focuses on verifying core feasibility. Two models were constructed for this purpose: the Loop-type and the Pool-type configurations (Figure 2). Only the primary and intermediate loops were modeled. Fuel and coolant channels in the core were axially divided into 10 segments, corresponding to the 10 axial divisions used in burnup calculations along the Z-axis [1].

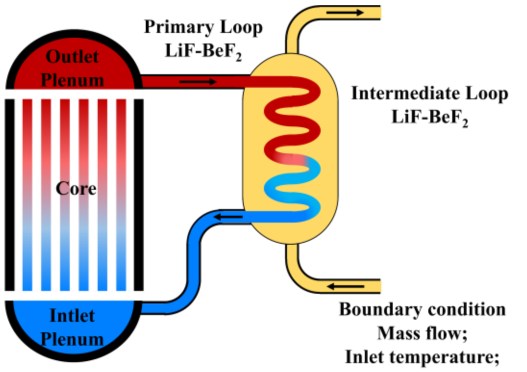

Fig.2. (a) Loop-Type Model,

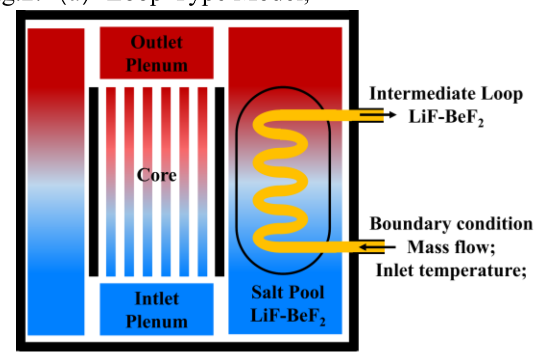

Fig.2. (b) Pool-Type Model,
Figure 2. Temperature simulation models

2.3 Core dimensions

Table I summarizes the calculation parameters, including geometric dimensions, fuel specifications, and power density. Graphite particles, of the same size as TRISO particles, were added to enhance thermal conductivity. The maximum random packing fraction of equal-sized spheres in a cylindrical channel is about 64%;[5] therefore, the assumed packing fraction of 50% is feasible within practical limits. Figure 3 illustrates the unit-cell model with the materials indicated.

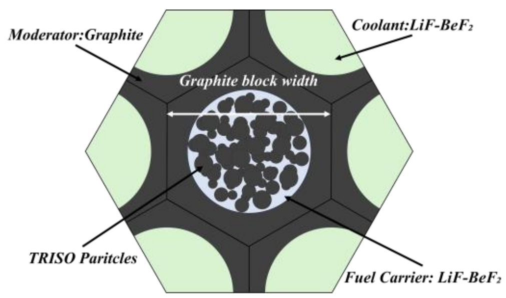

Figure 3. Unit-cell model

Table I: Core Design Parameters

Core parameters	Value	unit
Thermal power	100.00	MWth
Fresh fuel ^{235}U enrichment	10.00	wt%
TRISO packing fraction	30.00	%
Graphite packing fraction	20.00	%
Average power density	74.48	W/gU
Fuel effective thermal conductivity	4.50	W/g·K
Fuel channel radius	0.80	cm
Coolant channel radius	0.85	cm
Graphite block width	2.55	cm
Reflector thickness (Graphite)	85.00	cm
Active core height	400.00	cm
Core effective radius	137.00	cm
Total No. of fuel channels	2520	
Total No. of coolant channels	5041	

2.4 Core power distribution

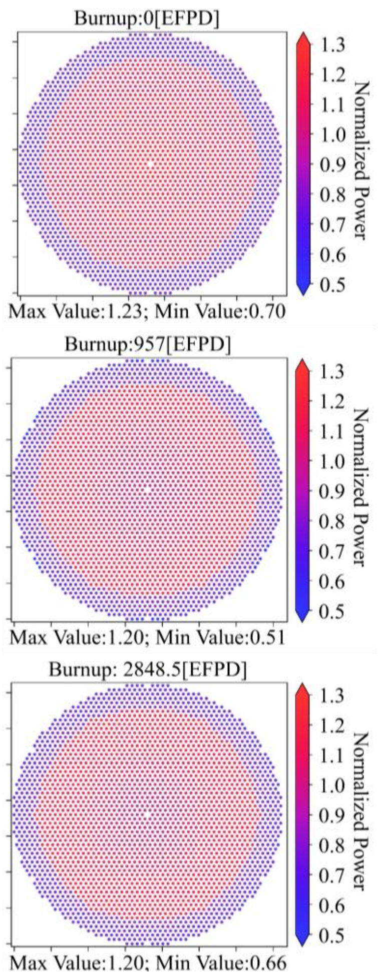

Figure 4. Core power distribution

Figure 4 presents the core power distributions at three burnup stages: the initial stage, the transition stage, and the equilibrium stage. Fuel gradually moves from the inlet into the core center, then to the periphery, and finally exits through the outlet. The power distribution pattern is consistent with the fuel flow direction: higher power density is observed in the central region of the core, while lower power density is exhibited in the peripheral regions.

2.5 Core temperature distribution and reactivity coefficients

Table II and Figure 5 present the temperature calculation results for the Loop-type and Pool-type models at three burnup stages. In the simulations, the intermediate loop inlet temperature was fixed at 578 °C, and its mass flow rate was adjusted to maintain the primary loop core outlet temperature at 750 °C, thereby evaluating the capability of natural circulation cooling in the primary loop.

Table II: Temperature calculation results

Parameters	Burnup: 0[EFPD]		Burnup: 957[EFPD]		Burnup: 2848.5[EFPD]	
	Loop	Pool	Loop	Pool	Loop	Pool
Boundary conditions: Secondary loop inlet temperature [°C]	578.0	578.0	578.0	578.0	578.0	578.0
Boundary conditions: Secondary loop mass flow[kg/s]	298.2	287.7	301.4	289.6	300.6	289.0
Secondary loop outlet temperature [°C]	718.2	723.4	716.7	722.4	717.1	722.7
Coolant temperature at core outlet [°C]	750.0	750.0	750.0	750.0	750.0	750.0
Coolant temperature at core inlet [°C]	607.2	616.1	606.1	615.1	606.4	615.4
Core coolant inlet and outlet temperature difference [°C]	142.8	133.9	143.9	134.9	143.6	134.6
Maximum fuel temperature, TRISO center [°C]	1074.6	1074.1	1071.4	1074.8	1073.4	1076.8
Average fuel temperature, TRISO meat [°C]	873.0	876.4	872.1	875.5	872.6	876.2
Primary loop core coolant velocity [m/s]	0.1313	0.1391	0.1303	0.1382	0.1305	0.1384

Table II shows that the maximum TRISO fuel center temperature is approximately 1075°C, below the design limit of 1250°C, while the average TRISO fuel temperature is about 875°C. The core coolant inlet temperature is around 600°C, above the melting point of LiF-BeF_2 (460°C), ensuring the coolant remains in liquid state.

Figure 5 illustrates the average core temperature distribution under different simulation conditions, ranging between 600–900 °C. The spatial temperature distribution corresponds well with the power distribution and remains consistent across the three burnup stages.

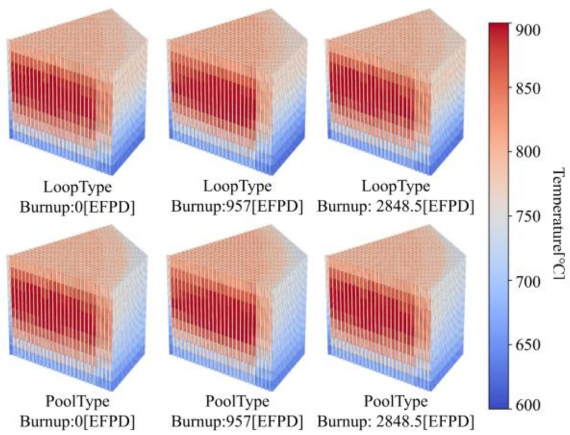

Figure 5. Core average temperature distribution

Table III: Reactivity coefficients

Parameters at equilibrium state	Value	Unit
Isothermal Temperature Coefficient	-4.87	pcm/K
Fuel Temperature Coefficient	-3.74	pcm/K
Moderator Temperature Coefficient	-0.92	pcm/K
Coolant Temperature Coefficient	-0.02	pcm/K
Coolant Void coefficient	-5.75	pcm/%Void

Table 3 provides the temperature coefficients and void coefficient at equilibrium. All coefficients are negative, consistent with the inherent negative feedback mechanism of the reactor core. The coolant temperature coefficient is −0.02 pcm/K, representing a relatively small negative feedback. The coolant temperature coefficient can be made more negative by adjusting the moderator-to-coolant ratio; however, it is sufficient at this stage that the coefficient remains negative to ensure the inherent safety margin, with further optimization left for future studies.

3. Summary

A thermal analysis model was established based on the calculated core power distribution and geometry, and temperature distribution simulations were performed. The results demonstrate that the TFSCR core operating at 100 MWth can meet the following design constraints:

a) The maximum fuel temperature remains below 1250 ℃；

b) The core outlet coolant temperature is maintained at 750 ℃；

c) The primary loop achieves effective cooling through natural circulation.

Therefore, it can be concluded that the TFSCR core under natural circulation cooling satisfies the safety design requirements and demonstrates feasibility. Future work will include introducing control rod models, recalculating burnup and temperature distributions, and performing accident scenario analyses.

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