A Feasibility Study of Advanced Molten Salt Fast Reactor (AMFR) Based on Stationary Fuel Salt

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Keywords : molten salt fast reactor, stationary salt, fission product removal, single channel TH analysis

1. Introduction

Molten salt reactors (MSRs) offer key advantages, including low-pressure operation, no danger of fuel melting, and inherent safety. However, conventional MSRs use a single molten salt as both the fuel and coolant, causing highly radioactive fuel to circulate through the entire primary loop. This design exposes components like the heat exchanger to significant radiation, necessitating extensive shielding and complicating maintenance. To address these challenges, Moltex Energy has developed the Stable Salt Reactor (SSR) design, which confines liquid salt fuel within standard fuel assemblies submerged in a separate, non-radioactive molten salt coolant [1]. This configuration reduces radiation exposure in the coolant loop but restricts the ability to drain fuel in emergency situations, limiting certain safety measures.

This study proposes an advanced molten salt fast reactor (AMFR) core design that separates fuel and coolant while preserving a functional fuel drain system. Unlike Moltex's approach, where fuel is encapsulated within tubes, our design channels coolant through dedicated passages, maintain the fuel in a distinct region. This arrangement significantly reduces radiation exposure at the heat exchanger and ensures safe fuel drain during emergencies, combining the benefits of MSRs and solid-fuel reactors. Designed for marine propulsion, the reactor features about 27-year core lifetime, aligning with typical ship operational lifespans. The reactor employs high-assay low-enriched uranium (HALEU) fuel and operates on a fast neutron spectrum. In fast reactors, fission products have a minimal impact on reactor reactivity, allowing for operation with minimal reprocessing. Although intended for continuous operation, the reactor undergoes scheduled maintenance every five years when the ship docks for approximately two months. During this period, replaceable structural components are fully replaced, ensuring long-term reliability without requiring fuel replacement. This paper presents the core design methodology and evaluates its neutronic and thermal-hydraulic performance, demonstrating its feasibility as a long-life, low-maintenance nuclear propulsion system. The neutronic performance analysis was performed with SERPENT 2 Monte Carlo code, and thermal-hydraulic results were obtained using COMSOL Multiphysics.

2. Core Design

AMFR employs a fuel and coolant separation strategy while maintaining the inherent advantages of molten salt reactors. The overall system layout is illustrated in Figure 1, showing the key components and flow paths of the reactor. The reactor is designed to operate at a thermal power of 100 MWth, ensuring sufficient energy generation for marine propulsion applications. In traditional MSRs, the fuel salt must fill not only the core but also the connecting piping and heat exchanger regions, leading to a significantly larger fuel salt inventory. Moreover, these designs suffer from delayed neutron losses, as some of delayed neutrons are emitted outside the core. In contrast, AMFR requires fuel salt only within the core region, significantly reducing the total fuel salt volume while eliminating delayed neutron losses outside the reactor. Given the high processing cost of fuel salt, reducing the required inventory provides a substantial economic advantage.

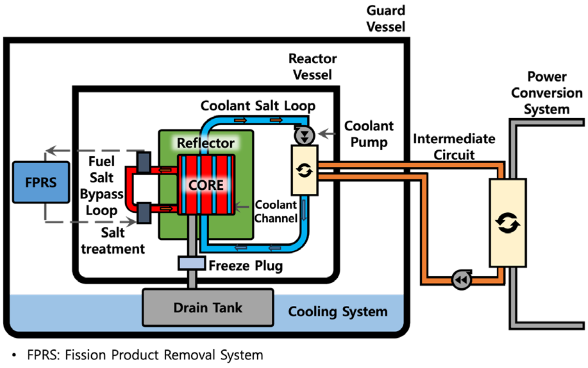

Figure 1. System layout of AMFR

However, a stationary MSR concept is not feasible for thermal spectrum reactors due to fundamental design constraints. Thermal spectrum MSRs require a high fuel salt circulation rate to effectively remove fission products, ensuring long-term reactivity control and reactor performance. Without sufficient circulation, neutron-absorbing fission products accumulate, severely impacting reactor operation. Additionally, implementing coolant channels within the active core of a thermal MSR is nearly impossible due to material limitations. Low neutron absorption materials such as zirconium must be used to minimize neutron loss, but these materials lack the structural integrity to withstand high-temperature reactor conditions.

In contrast, AMFR operates with a fast neutron spectrum, which mitigates these issues. In fast reactors, fission products have a minimal impact on reactivity, reducing the need for continuous fission product removal and enabling a stationary fuel configuration. Furthermore, the fast spectrum allows the use of stainless steel for coolant channels, as neutron absorption by stainless steel is not a significant concern in this environment.

The reactor utilizes a hybrid fuel salt composed of $KCl-UCl_3-UF_4$ with a molar composition of 28-36-36, where uranium-235 is enriched to 19.75 w/o. To reduce neutron absorption, chlorine-37 is enriched to 99 a/o, as chlorine-35 has a high neutron capture cross-section. The selection of this hybrid salt is driven by its high uranium density, which enhances neutron economy and contributes to long-term core sustainability. For coolant, the reactor employs $KF-ZrF_4-NaF$ (48%-42%-10%), a molten salt mixture originally proposed by Moltex Energy. The coolant channels are 0.5 cm in radius, with a hexagonal pitch of 1.95 cm between adjacent fuel and coolant channels, optimizing heat transfer efficiency. The geometric arrangement of the fuel and coolant channels is depicted in Figure 2, which provides both a top view and a side view of the core structure. The coolant flows through stainless steel 316 (SS316) tubes with a wall thickness of 0.06 cm, selected for its corrosion resistance and structural integrity in high-temperature molten salt environments.

The core is designed with a fuel region diameter and height of 2.1 m and surrounded by multiple layers of shielding and structural components to ensure neutron reflection and thermal stability. A 0.04 cm thick Ni shield and a 0.8 cm thick SS316 shield enclose the core, providing initial neutron and gamma attenuation. Beyond these shields, a 60 cm thick MgO reflector enhances neutron economy by reducing neutron leakage. The entire assembly is contained within a 3 cm thick SS316 vessel, which provides structural integrity and ensures long-term durability under high-temperature molten salt conditions.

Given that AMFR is designed for marine propulsion, periodic maintenance is expected as part of standard ship operation. Ships typically undergo scheduled maintenance every five years, during which replaceable components such as coolant tubes can be swapped. As a result, these structural materials are designed for a service life of approximately five years, ensuring reliable performance while allowing for routine replacements during maintenance cycles.

A key safety advantage of this design is the drain system, which enables fuel removal from the core in the event of an emergency. Unlike tube-based fuel designs, where solid or liquid fuel is confined within fixed assemblies, AMFR's fuel salt is not enclosed within tubes, allowing for passive drainage when required. As illustrated in Figure 1, the reactor is equipped with a drain system that can effectively evacuate the fuel salt from the core, significantly reducing the risk of severe accidents. This feature enhances safety by ensuring that, in the case of abnormal conditions such as loss of power or overheating, the fuel can be rapidly drained into a subcritical, passively cooled storage system. Furthermore, since AMFR separates the fuel and coolant, the heat exchanger is exposed only to low-activity coolant rather than highly radioactive fuel salt. This substantially reduces shielding requirements and simplifies maintenance compared to traditional MSRs, where the heat exchanger must handle high-radiation fuel salt.

To enhance long-term performance, the reactor design includes a fuel salt bypass loop, allowing a small fraction of the fuel salt to be diverted for fission product removal. This process helps maintain salt quality and reactor stability by continuously extracting neutron-absorbing fission products. The detailed design for this bypass loop shall be determined in future works. The placement and routing of this bypass loop can be seen in Figure 1, which highlights the integration of the fuel treatment system within the reactor layout. The impact of fission product removal rates on reactor reactivity will be further analyzed in the numerical results section.

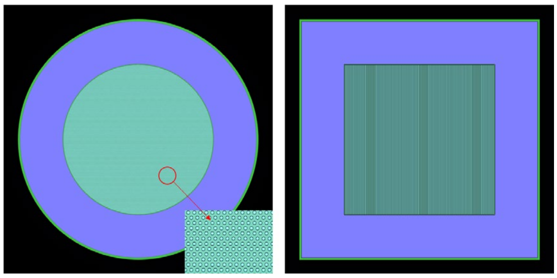

Figure 2. Top view (left) and side view (right) of AMFR design

Table 1. Key parameters of AMFR

Input Parameter	Value
Thermal power	100 MWth
Active core diameter and height	2.1 m
Initial Fissile mass	14,912 kg
Burnup at EOC	66.1 GWD/tU
Fuel temperature	900 K
Coolant inlet temperature	773.15 K
Average Coolant outlet temperature	823.15 K
Coolant channel radius	0.5 cm
Fuel-coolant channel pitch	1.95 cm
Coolant volume fraction	25%

3. Numerical Results

3.1 Neutronics Analysis

To evaluate the impact of fission product removal on reactor sustainability, reactor burnup calculations were performed. First, a reactor neutronics calculation was conducted for the given core geometry to establish baseline characteristics. Subsequently, multiple burnup calculations were performed to assess whether the core could achieve an appropriate operational lifetime through fission product treatment. Figure 3 presents the reactor eigenvalue evolution under different fission product removal scenarios. The simulations consider the following cases:

1. Removal of hydrogen alone at 90% per year.
2. Removal of hydrogen and noble gases at 90% per year.
3. Removal of hydrogen and noble gases at 90% per year, with noble metals removed at 60% per year.

The results indicate that without fission product removal, the core achieves a lifetime of approximately 23 years. However, by implementing appropriate salt treatment, the reactor lifetime can be extended to 26–27 years, depending on the specific removal strategy. The calculations were performed using the Monte Carlo code Serpent 2, with 10,000 histories, 300 active cycles, and 100 inactive cycles. The eigenvalue uncertainty in these simulations was 65 pcm.

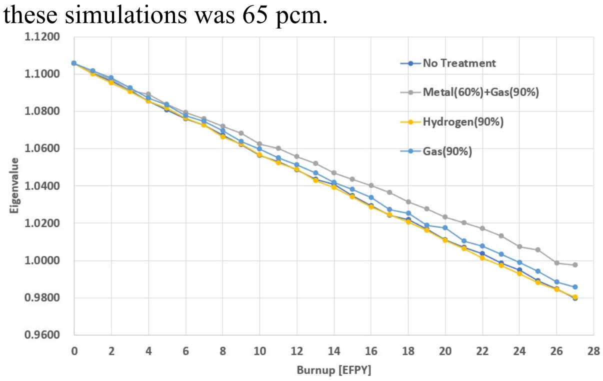

Figure 3. Multiplication factor change through cycle with different fission product removal scenarios

To further analyze the neutronic characteristics of the reactor, the neutron spectrum was evaluated in Figure 4. The neutron spectrum was plotted for both the entire core region and the active core region. In the active core region, the neutron spectrum exhibits the characteristics of a typical fast spectrum reactor, with a dominant population of high-energy neutrons. However, when plotted for the entire core, a small peak appears in the thermal energy region. This is attributed to neutron moderation occurring in the reflector region, where neutrons undergo energy loss before re-entering the active core as thermal neutrons. The presence of thermalized neutrons re-entering the active core region contributes to fission reactions, influencing overall reactor behavior. As a result, in reactors of this type, it is essential to consider the reflector temperature coefficient (RTC) when evaluating temperature feedback effects.

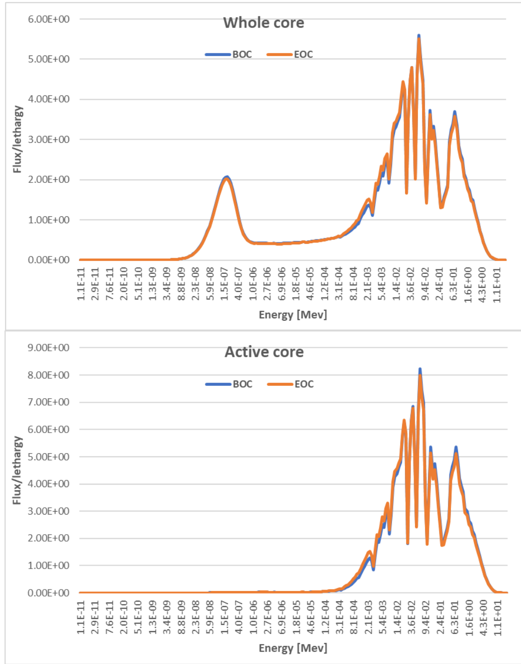

Figure 4. Neutron spectrum of AMFR

To assess the reactor's response to temperature variations, temperature coefficients were evaluated for the fuel, coolant, and reflector regions. The temperature effects were analyzed by perturbing the temperature of each region independently and observing the resulting changes in reactivity. The fuel temperature was varied by ±200 K, while the coolant temperature was perturbed by ±20 K. The reflector temperature was adjusted by ±150 K, and the corresponding changes in reactivity were calculated. The results of these calculations, including the fuel temperature coefficient (FTC), coolant temperature coefficient (CTC), and reflector temperature coefficient (RTC), are summarized in Table 2.

Table 2. Temperature coefficient at BOC and EOC

	FTC [pcm/K]	CTC [pcm/K]	RTC [pcm/K]
BOC	-6.71±0.02	0.700±0.177	1.05±0.09
EOC	-6.76±0.02	0.970±0.177	1.03±0.10

The Monte Carlo calculations were performed using Serpent 2, with 1,000,000 histories, 300 active cycles, and 100 inactive cycles for RTC and 3,000,000 histories were used for FTC and CTC calculations. One of the critical safety criteria for reactor operation is ensuring that the integral temperature coefficient (ITC) is negative. The sum of FTC, CTC, and RTC confirms that the reactor meets this requirement, demonstrating negative temperature feedback.

3.2 Thermal-Hydraulic Analysis

A 2D-axisymmetric model was developed in COMSOL Multiphysics to conduct a single-channel thermal-hydraulic analysis of the AMFR core. The model was designed to represent the coolant channel arrangement in the core while maintaining thermal and flow equivalence with the full-core configuration. The geometry of the computational domain used for this analysis is shown in Figure 5, where red-line is the origin of the axis-symmetry.

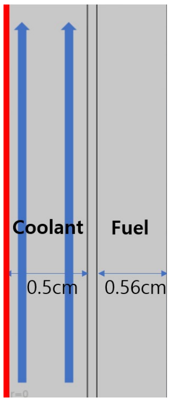

Figure 5. COMSOL computational domain

In this model, the fuel region was treated as laminar flow, while the coolant channel was modeled with a turbulent flow regime to account for expected flow conditions. The appropriate density, heat capacity, and thermal conductivity values were calculated with ideal liquid model using each salt's value [2-6]. The reactor's axial power profile was assumed to follow a cosine distribution, reflecting the typical power shape in nuclear reactors. The boundary conditions and key input parameters are summarized in Table 3.

Table 3. Input parameters of COMSOL analysis

Input Parameter	Value
Inlet coolant mass flow rate per channel	0.207 kg/s
Coolant inlet temperature	773.15 K
Turbulent model	k-ε
Fuel region boundary condition	Adiabatic

The simulation results provide key insights into the temperature and velocity distributions within the representative channel. The radial temperature distribution at two different axial positions, corresponding to H = 150 cm and H = 210 cm, is presented in Figure 6. At both heights, a clear temperature gradient is observed, with the highest temperature in the fuel region and a decreasing trend toward the coolant. The highest fusel salt temperature is observed at H = 150 cm. Although the power density is highest at the center of the core, natural circulation of the fuel salt leads to this temperature distribution. Notably, the fuel salt temperature near the coolant tube remains below 1000 K, suggesting that severe corrosion risks are not expected in this region.

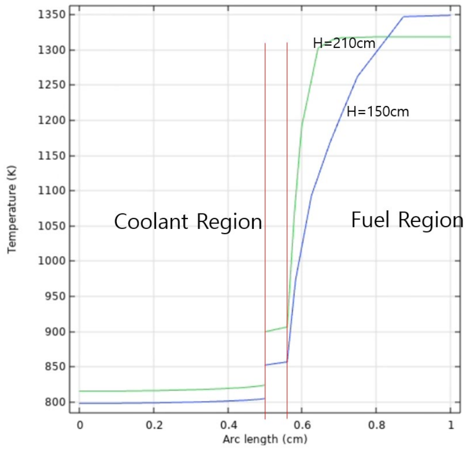

Figure 6. Radial temperature distribution at H = 210 cm, H = 150 cm

However, the average fuel temperature exceeds the 900 K value used in Monte Carlo simulations, indicating that a more detailed burnup calculation incorporating thermal-hydraulic coupling is necessary to refine the core's long-term performance.

The axial velocity distribution at H = 150 cm as a function of radial position is shown in Figure 7, illustrating the flow characteristics of both the fuel salt and coolant. Within the coolant region, coolant exhibits a higher velocity than fuel salt due to inlet mass flow rate. The fuel salt velocity profile exhibits downward motion near coolant tube surface and upward motion at boundary region driven by buoyancy effects, demonstrating natural circulation patterns.

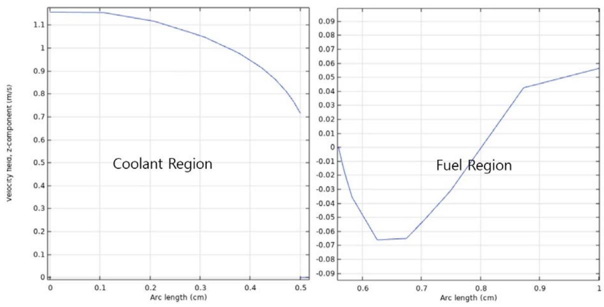

Figure 7. Axial velocity profile at H = 150 cm

4. Conclusions

This study explores the feasibility of the Advanced Molten Salt Fast Reactor (AMFR), which separates fuel and coolant while maintaining the benefits of conventional molten salt reactors. Neutronic analysis showed that fission product removal can extend the core lifetime from 23 years to 26–27 years. Temperature coefficient evaluations confirmed that AMFR maintains a negative integral temperature coefficient (ITC), ensuring inherent safety. Thermal-hydraulic analysis demonstrated that natural circulation significantly influences temperature distribution, with the highest fuel salt temperature observed at H = 150 cm. Future work will focus on burnable absorber implementation for reactivity control, control drum implementation, and thermal-hydraulic (TH) coupling to refine core optimization.

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ACKNOWLEDGEMTNS

This research was supported by Korea Energy Technology Evaluation and Planning (KETEP) grant funded by the Korean Government (MTIE) (RS-2024-00439210).