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The Effect of Different Shipping Routes on the Performance of Molten Salt Reactor (MSR) Systems for Marine Propulsion

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1. Introduction

Climate change has become a critical global issue, and the International Maritime Organization (IMO) is promoting stringent regulations and policies aimed at achieving net-zero carbon emissions in the shipping industry by 2050 [1]. In response, the shipping and shipbuilding industries have intensified research into low- or zero-carbon energy sources to replace conventional fossil fuel-based propulsion. Although nuclear propulsion at sea has thus far been limited mostly to certain military vessels (aircraft carriers, submarines) and Russian icebreakers, the rapid advancement of fourth-generation nuclear technologies, including Small Modular Reactors (SMRs), has heightened interest in nuclear propulsion within the commercial maritime sector.

Among these technologies, Molten Salt Reactors (MSRs) stand out as a next-generation marine propulsion system due to their ability to operate at high temperatures and achieve high thermal efficiency, while also offering greater safety and more efficient fuel utilization compared to conventional Pressurized Water Reactors (PWRs) [2, 3, 4]. MSR-based systems use natural or pump circulation of molten salts as both fuel and coolant, allowing for more flexible load-following capabilities during long voyages. This flexibility is a significant advantage in responding to diverse operating profiles, such as changes in cruising speed or port calls.

When combined with a power conversion cycle, MSRs are can be paired with a supercritical carbon dioxide (sCO_2) cycle. In particular, the recompression cycle offers higher thermal efficiency, and a markedly reduced system volume compared to traditional steam cycles, making it well-suited for marine applications [5, 6]. Since the working fluid remains in a supercritical state, the sCO_2 cycle can operate at elevated temperatures with high efficiency while reducing the size of turbines and heat exchangers, an important benefit in the confined spaces of ships. Moreover, this high-efficiency nuclear propulsion system can be designed for extended fuel replacement intervals and can respond sensitively to load fluctuations, maintaining stable power for long-distance, high-speed travel.

The purpose of this study is to compare and analyze the operational suitability of MSR-powered vessels on major long-distance routes such as Busan–Los Angeles, Belgium–Shanghai, and Portugal–New York. Specifically, by considering each route's distance and speed, the study will evaluate uranium consumption and energy efficiency in MSR-based propulsion systems. Through this comparison, it aims to identify the most efficient route while also examining the advantages and disadvantages of MSR propulsion under different voyage conditions. These insights are expected to inform the potential adoption of MSRs as a next-generation eco-friendly marine power source and serve as foundational data for the future design and operational guidelines of nuclear-powered ships.

2. Methodology and Results

2.1 Analyzing Load Following Performance of MSR with Quasi-steady-state Cycle Design (QCD)

In this study, the KAIST-CCD is first employed to determine the design point for an sCO_2 Brayton cycle, thereby identifying the optimal operating conditions at a target output (40 MWe). From this process, baseline data is obtained – such as design flow rates for turbines and compressors, heat exchanger performance parameters, and recirculation line configurations–that define the "design point" of the system. Since actual maritime operations often entail fluctuating loads, the KAIST-QCD (Quasi-steady-state Cycle Design) method is then applied to analyze the system's performance under off-design (partial-load) conditions, building on the information obtained at the design point.

Table 1. Fuel Salt and Cooling Salt Information [7]

Category	Fuel Salt	Coolant Salt
Type	NaCl - KCl - UCl_3	NaCl - KCl - $MgCl_2$
Composition Ratio	42.9 - 20.3 - 36.8 mol%	15.11 - 38.91 - 45.98 mol%
Temperature Range	655℃ ~ 565℃	645℃ ~ 500℃

Table 2. Initial Conditions for cycle design [8, 9, 10, 11]

Parameter	Design Specification
Thermal Power	100 MWth
Maximum Operating Pressure	20~25 MPa
Maximum Temperature	635℃
Minimum Temperature	50 ℃

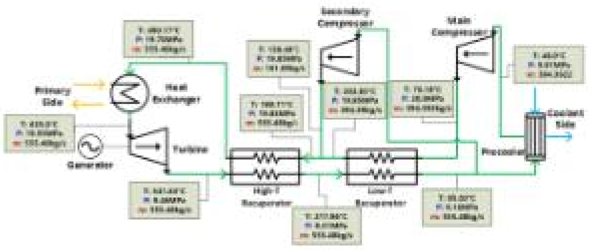

Fig. 1 sCO_2 Cycle Design Results

KAIST-QCD iteratively solves the mass and energy balances, along with pressure-balance equations, to reflect changes in each system component (turbines, compressors, heat exchangers, piping, etc.) as the target power level shifts. Specifically, it (1) adjusts turbine and compressor flow rates and pressure ratios to match the new power setting, (2) recalculates heat transfer in the heat exchangers and pressure drops in the piping, and (3) repeats these steps until the inlet and outlet values of each device converge. As a result, it records the efficiency, turbine output, compressor work, and heat exchanger performance at various load points, ultimately constructing a performance map for the entire power range.

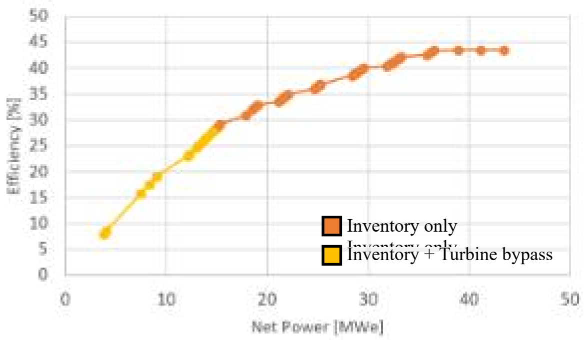

Fig. 2 Efficiency variations according to power output

This performance map enables a systematic assessment of operating limits under different control strategies, including Inventory Control and Turbine Bypass. Inventory Control–adjusting the sCO_2 inventory in the system reservoir–provides a gradual response with minimal efficiency degradation over time, which is advantageous for extended voyages. Conversely, Turbine Bypass, which diverts part of the flow around the turbine, is applied only in low-load regions due to its low efficiency. Moreover, further reductions in power output were constrained by the onset of salt solidification, preventing operation at even lower loads.

Furthermore, how total heat output changes as net power decreases was investigated, and the corresponding temperature, pressure, and flow conditions were also analyzed for the secondary side (heat exchangers and turbomachinery). This offers deeper insights into component interactions and efficiency trends under partial-load conditions. For example, if turbine flow drops significantly, the temperature approach in the heat exchanger changes, resulting in a decrease in heat transfer, which may require adjustments to the compressor inlet pressure and the recirculation flow. Such findings are crucial for establishing operational guidelines to handle frequent low-load or transient scenarios in actual shipboard applications.

2.2 Comparison of Major Shipping Route

The Europe (EU) - East Asia (EA) route, spanning about 14,600 NM over 35.57 days at an average speed of 16.32 knots, often requires detours around the Cape of Good Hope for vessels exceeding 15,000 TEU, as they cannot pass through the Suez Canal. In addition, ships typically transit the busy Malacca Strait route, necessitating frequent speed adjustments to navigate congested waters and varied climate zones. In contrast, the East Asia (EA) - North America (NA) Pacific route–approximately 6,335 NM and taking around 14 days at 18.02 knots–presents more predictable conditions with fewer speed changes. Finally, the Europe (EU) - North America (NA) transatlantic route is shorter than both, generally consuming less fuel and requiring fewer speed adjustments.

Table 3. Compare distance, duration, and speed by route

Route	EU-EA	EA-NA	EU-NA
Distance [NM]	14,600	6,335	3,704
Period [Days]	35.57	14	8.64
Speed[kts]	16.32	18.02	16.52

Fig. 3 Map of routes (EU-EA, EA-NA, EU-NA) [12]

2.3 Refueling Cycle Calculation

In this study, the mole fractions of the fuel salt were calculated based on the uranium enrichment level in the initial active core (approximately 20%; meaning that the total uranium mass is five times the mass of pure U-235). Using this enrichment level, the moles of UCl_3 in the fuel salt were determined. Based on the given mole fractions of NaCl (0.429) and KCl (0.203), the mole fractions of NaCl, KCl, and UCl_3 were calculated. From these mole fractions, the moles and masses of each compound were determined, resulting in an estimated total fuel salt mass of approximately 9.53 kg per 1 kg of pure U-235.

The total mass of the initial active-core fuel salt was first calculated by multiplying the core volume by the density of the fuel salt, yielding approximately 16,268.1 kg. Using this total mass and the previously calculated ratio of 9.53 kg of fuel salt per 1 kg of U-235, the initial mass of U-235 in the active core was derived.

$$\text{Initial } U_{235} \text{ mass [kg]} = \frac{\text{Total fuel salt mass [kg]}}{\text{Fuel salt mass per 1kg of } U_{235} \text{ [kg]}}$$
$$= \frac{16{,}268.1}{9.53} = 1{,}707.041 \text{ kg}$$

This study also calculated the amount of U-235 consumed for each scenario based on the required thermal energy and the energy released by U-235 fission (approximately 0.95 GWD/kg and 22,800 MWh/kg). The molten salt reactor (MSR) used in this study has a uranium enrichment level of 20%, which is four times higher than that used in MSRE, resulting in a higher rate of U-235 consumption. As fissile material is consumed during operation, changes in chemical composition necessitate a refueling criterion. In this study, a refueling criterion was established based on reducing the initial mole fraction of UCl_3 from 36.8 mol% to 3.68 mol% whereas MSRE used a reduction criterion of approximately 0.5 mol% [14]. Applying this refueling criterion, the maximum amount of U-235 consumable per refueling cycle was determined to be approximately 170.704 kg, which corresponds to about 10% of the initial U-235 loading.

2.4 Thermal power calculations

To determine the propulsion power required for each route, the correlation developed by PK Korlak for estimating the preliminary power requirements of large cargo ships was used [13].

$$y = 5.333x^3 \quad (1)$$

where y represents the propulsion power in kW and x is the sailing speed in knots. This allowed the estimation of the propulsion power needed based on the specific sailing speed for each route. Once the propulsion power was calculated, it was converted to net power (MWe) using the system's efficiency. Next, the hotel load, which accounts for the energy required by the ship's non-propulsion systems, was added. The hotel load was determined based on the ship's specifications and was calculated to be 15 MWe. This total value, including both propulsion and hotel load, was used in the subsequent calculations.

Finally, the total power, including both propulsion and hotel load, was used to calculate the thermal energy (Q) using QCD. The QCD model was employed to convert the total power into thermal energy (MWth), considering the reactor's thermal efficiency and the overall system performance. This allowed for the accurate determination of the thermal energy required for the complete operational scenario.

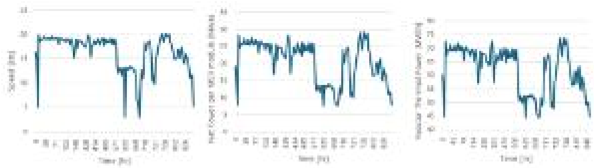

Fig. 4 Europe - East Asia Profiles (Speed, Net power, Reactor Thermal Power) [12]

Fig. 5 East Asia – North America Profiles (Speed, Net power, Reactor Thermal Power) [12]

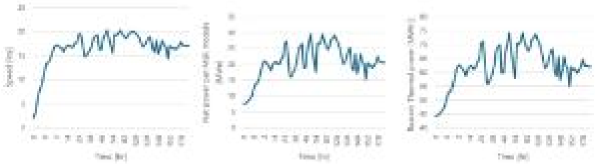

Fig. 6 Europe – North America Profiles (Speed, Net power, Reactor Thermal Power) [12]

Table 4. Refueling Cycle Calculation results each route

Route	EU-EA	EA-NA	EU-NA

Total Thermal Energy [MWhr]	53,992	23,103	13,629
Initial Active-Core Fuel Salt [kg]	16,268.1		
Initial Active-Core U-235 [kg]	1,707.04		
Initial UCl_3 [mol%]	36.8		
UCl_3 Consumption [mol%]	3.68 (Refueling Criteria)		
U235 Consumption[kg]	170.7		
U-235 consumption per voyage [kg]	**2.67**	**1.14**	**0.67**
Number of possible voyages	63.85	149.59	253.03
Refueling Cycle [years]	**6.22**	**5.7**	**5.99**

The results presented in Table 4 summarize the reactor design conditions and U-235 consumption for each route, considering a 100% operational scenario without factoring in time spent in port or waiting. The refueling cycle values, which indicate the number of years before refueling is required, are based on continuous operation without interruptions. According to the data, all three routes–EU-EA, EA-NA, and EU-NA–have refueling cycles exceeding 5 years, with the EU-EA route having a refueling cycle of 6.22 years, the EA-NA route at 5.7 years, and the EU-NA route at 5.99 years. These values are calculated assuming the reactor is running at full capacity for the entire period.

However, in real-world operations, the refueling cycle would likely be longer, as factors such as port calls, waiting times, and reduced speeds during certain segments would reduce the actual number of operating days per year. As a result, the actual refueling cycle could extend beyond the calculated values, allowing for longer periods of operation between refueling in practice. Therefore, these results indicate that, even with operational delays and non-constant speeds, the MSR systems for all routes can operate efficiently for several years before requiring refueling.

3. Summary and Conclusions

This study analyzed the operational suitability of Molten Salt Reactors (MSRs) for marine propulsion on long-distance routes, including Europe-East Asia, East Asia-North America, and Europe-North America. The results demonstrated that MSRs, with their high thermal efficiency and advanced fuel utilization, offer extended operational periods before refueling. Specifically, the refueling cycles for all three routes exceeded six years, with the Europe-East Asia route requiring 6.22 years, the East Asia-North America route 5.7 years, and the Europe-North America route 5.99 years. These results assume 100% operational conditions without factoring in time spent in port or waiting. In real-world operations, delays such as port calls and reduced speeds would extend the refueling cycles, making the MSR systems viable for several years of operation before requiring refueling.

As a result, they can operate efficiently on routes where maintaining a steady cruising speed is crucial. However, on routes such as Europe-East Asia, where frequent speed adjustments are required, MSRs may struggle with immediate load control. Furthermore, low-load operation segments along this route can increase the risk of salt precipitation within the molten salt, potentially affecting reactor performance and reliability. Therefore, special operational strategies are necessary to manage these challenges effectively.

Fig. 7 Europe - East Asia net power Profiles (low load) [12]

However, when compared to conventional diesel-powered vessels, which typically require an Overhaul (OVHL) cycle of approximately 5 years, MSR-powered ships offer a significant advantage in terms of operational longevity. The extended refueling cycle of MSRs, often exceeding 6 years, makes them viable for long-distance routes without the need for frequent maintenance or fuel replacement, thus providing a clear advantage over traditional diesel-powered vessels in terms of both operational efficiency and sustainability [15].

In conclusion, while MSR propulsion systems offer significant potential for long-distance shipping by reducing greenhouse gas emissions, careful consideration is required for routes with frequent speed fluctuations, like the Europe-East Asia route. Despite this, MSRs can still offer a practical and efficient solution across all major shipping routes, making them a promising candidate for the future of eco-friendly maritime propulsion.

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REFERENCES

[1] International Maritime Organization (IMO), "Addressing climate change over a decade of regulatory action to cut GHG emissions for shipping", 2023

[2] The Maritime Executive, "Korean shipbuilder joins maritime SMR project", 2021

[3] Riviera, "China reveals molten-salt nuclear reactor-driven 24,000-TEU box ship design", 2023

[4] World Nuclear News, "Samsung to Explore MSR Nuclear Power for Zero Emission Shipping", 2024

[5] 이정익; 안윤한; 차재은. 초임계 CO_2 발전시스템 소개 및 개발동향. 한국유체기계학회 논문집, 2014, 17.6: 95-103.

[6] DOSTAL, V.; DRISCOLL, M.; HEJZLAR, P. A supercritical carbon dioxide cycle for next generation nuclear reactors. Massachusetts Institute of Technology, MA, 2004.

[7] YEO, Dongyeol; LEE, Chan; KOO, Gyeong-Hoi. Parametric study of the fuel salt drain system design of K-MSR. 2024

[8] BRUN, Klaus; FRIEDMAN, Peter; DENNIS, Richard (ed.). Fundamentals and applications of supercritical carbon dioxide (sCO2) based power cycles. Woodhead publishing, 2017.

[9] YOO, Sunghyun; LEE, Wonkoo; LEE, Kwon-Yeong. A Conceptual Design of Supercritical CO_2 Brayton Cycle for a Small Modular Molten Salt Reactor. In: Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, 2022.

[10] SON, In Woo, et al. Thermal-sizing of the molten salt reactor system with gas Brayton cycle. System, 2021, 12: 14.

[11] SON, In Woo, et al. Design study of heat transport and power conversion systems for micro molten salt reactor. International Journal of Energy Research, 2022, 46.11: 15441-15462.

[12] https://www.marinetraffic.com/

[13] KORLAK, Piotr Kamil. Prediction of the Ultra-Large Container Ships' Propulsion Power at the Initial Design Stage. Komunikácie-vedecké listy Žilinskej univerzity v Žiline, 2022, 24.3: 228-238.

[14] HOLCOMB, D. E., et al. Fast spectrum molten salt reactor options. ORNL/TM-2011/105, 2011.

[15] MAN Diesel & Turbo. (2017, August). *Service Letter SL2017-650/SRJ: Guiding overhaul intervals* (Overhaul intervals and expected service life of engine components on two-stroke low speed engines). Copenhagen, Denmark: MAN Diesel & Turbo.