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Conceptual Design of a Seawater Passive Decay Heat Removal System for the GPT-Marine Reactor

Yeongchan Kim [a], Jeong Ik Lee [a*]
[a]Dept. Nuclear & Quantum Eng., KAIST, Daehak-ro 291, Daejeon, Republic of Korea, 34140
[*]Corresponding author: jeongiklee@kaist.ac.kr

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1. Introduction

With the International Maritime Organization (IMO) enforcing strict strategies to achieve net-zero greenhouse gas emissions by 2050, the shipping industry is urgently seeking carbon-free propulsion alternatives. For large commercial vessels, such as a 15,000 TEU container ship, alternative fuels like hydrogen or ammonia present significant energy density challenges, directly competing with payload space and degrading economic performance on long-haul routes. Nuclear propulsion offers extremely high energy density and multi-year operation without refueling, making it a highly viable commercial option.

However, transitioning nuclear reactors to commercial maritime environments requires highly compact systems with rapid, self-regulating load-following capabilities to accommodate ship maneuvering [1]. Furthermore, the limited machinery space demands innovative approaches to safety and decay heat removal. This study introduces the conceptual design of the Gas-cooled Pressure-tube reactor for Marine propulsion (GPT-Marine) and highlights its ultimate safety mechanism: the Seawater Passive Decay Heat Removal System (SPDHRS).

2. GPT-Marine Concept Overview

2.1 Direct sCO_2 Recompression Brayton cycle

The KAIST-developed GPT-Marine couples a gas-cooled reactor directly to an sCO_2 recompression Brayton cycle, in which the primary coolant is also the working fluid driving the turbine [2]. High CO_2 density near the critical point reduces volumetric flow rates and enables compact turbomachinery, while printed circuit heat exchangers (PCHEs) support high effectiveness within minimal volume [3, 4]. In the reference concept, two identical 100 MWth reactor modules provide an overall electrical output exceeding 80 MWe for a 15,000 TEU-class container vessel [2].

Fig. 1 illustrates the direct recompression cycle configuration and representative state points. The cycle is designed around a high turbine inlet temperature of 640 °C and a maximum pressure of 20 MPa, with the compressor inlet maintained above the CO_2 critical pressure to improve operational robustness during load transients.

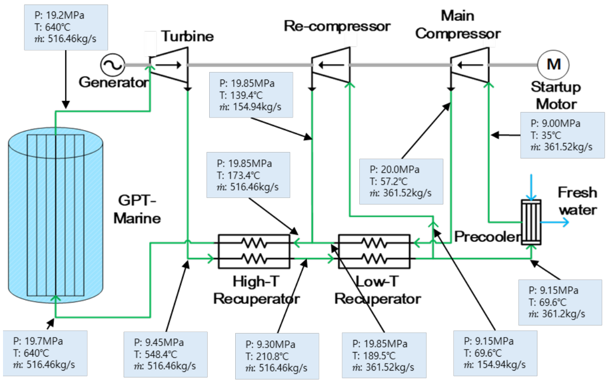

Fig. 1. Cycle configuration and thermodynamic state points of the GPT-Marine.

2.2 Pressure-Tube Core with Moderator Tank

The GPT-Marine adopts a pressure-tube architecture rather than a large integrated pressure vessel. sCO_2 at high temperature and pressure flows inside each fuel channel, while a low-pressure H_2O moderator in a moderator tank surrounds the fuel channels as shown in Fig. 2. This separated pressure boundary approach provides: (1) localization of a tube failure to a single channel, (2) modular access for refueling, and (3) shielding benefits from the moderator. A distinctive design intent is to exploit the moderating contribution of sCO_2 and a tightened lattice displacement strategy to strengthen neutronic coupling between coolant density and reactivity, supporting inherent load-following features [2]. Since this paper focuses on the safety system, only key architectural features are summarized. Table I lists key concept specifications of the GPT-Marine.

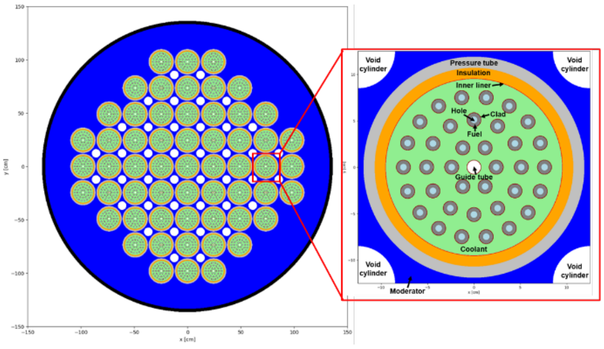

Fig. 2. The whole core (left) and single channel cross-section (right) of the GPT-Marine.

Table I: Key design parameter and performance characteristics of the GPT-Marine [2].

Parameter	Value
Target vessel	15,000 TEU container vessel
Thermal power	100 MWth (×2 modules)
Net electric output	41.4 MWe per module (82.8 MWe total)
Power conversion	Direct sCO_2 recompression Brayton
Max pressure and temperature	20 MPa / 640 °C
Compressor inlet condition	9 MPa / 35 °C
Fuel / Enrichment	UO2 (hollow) / 9 wt%
Dimension	2.8 m (D) × 3.7 m (H)
Feedback coefficient	FTC: -0.62 pcm/K CTC: -0.51 pcm/K CVR: -374.2 ±7.9 pcm
Interval target	5 years

3. Seawater Passive Decay Heat Removal System

3.1 Motivation

For marine and offshore nuclear plants, passive decay heat removal systems are recognized as a key safety feature to ensure long-term core cooling during extended station blackout or loss of ultimate heat sink events, when external assistance may be unavailable or delayed [5]. A ship provides a unique environmental advantage relative to land installations: the reactor is continuously surrounded by seawater, which can be treated as a practically unlimited heat sink over accident-relevant time scales. Therefore, rather than relying solely on finite onboard water inventories, the GPT-Marine proposes a seawater-coupled passive decay heat removal architecture designed for long-term cooling.

3.2 Concept

The SPDHRS is designed to remove decay heat by establishing single-phase natural circulation between the reactor moderator tank and a seawater-cooled heat exchanger installed in the ship's high sea chest. The concept uses density differences between hot and cold legs to drive natural circulation without pumps or external power. Following shutdown/accident conditions, decay heat is transferred from fuel channels and surrounding structures to the moderator water inventory. Heated moderator water (lower density) rises through the SPDHRS hot leg to the sea-chest heat exchanger. Heat is rejected to seawater; the cooled water increases in density and returns to the moderator tank through the cold leg, sustaining circulation.

Figure 3 illustrates the SPDHRS concept. The key to this integration is locating the sea chest heat exchanger at a higher elevation relative to the moderator tank to secure adequate static head. Positioning the high sea chest near the upper portion of the draft can provide several meters of effective driving head. This elevation difference is a key enabler for robust thermosyphon behavior while keeping the heat exchanger submerged and continuously supplied by seawater.

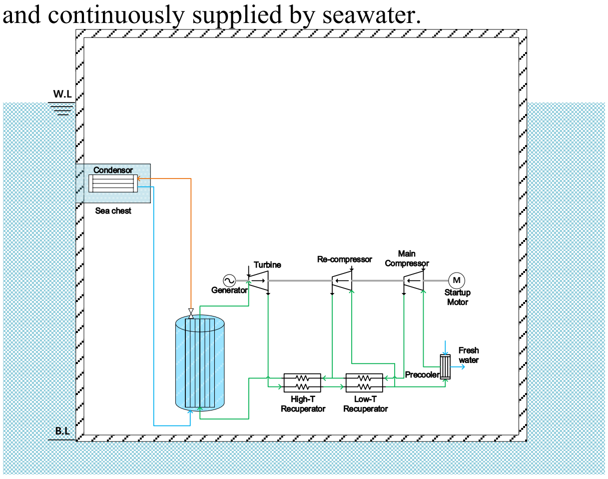

Fig. 3. SPDHRS schematic integrated with the ship high sea chest.

As summarized in Table II, the fundamental design of the SPDHRS relies on the robust and predictable physics of natural circulation. The system utilizes the moderator water as the working fluid, transferring decay heat to the ultimate heat sink—the infinite ocean, assumed at a global average temperature of near 20°C. The primary driving mechanism is the thermosyphon effect, which is proportional to the density difference, gravity, and height. Therefore, maintaining a significant elevation difference between the moderator tank and the submerged heat exchanger is the critical enabler of this system. This configuration guarantees continuous, passive long-term decay heat removal under emergency conditions, completely independent of external power sources.

Table II: Conceptual design parameters of the SPDHRS.

Parameter	**Concept**
Ultimate heat sink	Seawater (global average near 20 °C)
Working fluid	Moderator water loop (single phase natural circulation)
Heat exchanger location	Submerged in high sea chest
Driving mechanism	Thermosyphon ($\Delta\rho \cdot g \cdot H$)
Key geometric enabler	Elevation difference between moderator tank and sea chest HX
Purpose	Passive long-term decay heat removal

3.3 Parametric analysis of natural circulation elevation

To verify the physical feasibility of the SPDHRS, an analytical sizing check was performed to determine the required elevation difference necessary to remove the target decay heat of 1 MW_{th}, which corresponds to approximately 1% of the full core power. This value is used as a practical long-term passive heat-removal sizing point, while higher early-time decay heat is assumed to be managed by short-term active/backup measures [6].

The system reaches a steady-state natural circulation flow when the buoyancy-induced driving head (ΔP_{drive}) equals the total system pressure loss (ΔP_{loss}):

$$\Delta P_{drive} = \Delta\rho \cdot g \cdot H \quad \text{(Eq. 1)}$$

Where,

$\Delta\rho$ = density difference (kg/m^3)
g = gravitational acceleration (m/s^2)
H = elevation difference (m)

$$\Delta P_{loss} = K_{tot} \cdot \frac{\dot{m}^2}{2 \cdot \rho_{avg} \cdot A^2} \quad \text{(Eq. 2)}$$

Where,

K_{tot} = total effective loss coefficient
$\dot{m}$ = mass flow rate (kg/s)
ρ_{avg} = average fluid density (kg/m^3)
A = cross-sectional flow area (m^2)

The heat removal rate ($\dot{Q}$) is governed by the energy balance equation:

$$\dot{Q} = \dot{m} \cdot C_p \cdot \Delta T \quad \text{(Eq. 3)}$$

Where,

C_p = specific heat capacity (J/kg-K)
ΔT = temperature difference (K)

As the GPT-Marine reactor is currently in the conceptual design phase, a detailed piping layout has not yet been finalized. Therefore, representative engineering assumptions were made to evaluate the macroscopic physical feasibility of the SPDHRS. A pipe diameter of 0.15 m and a conservative total loss coefficient (K_{tot}) of 7.5 were assumed to represent an approximately 20 m loop with bends and the sea-chest HX flow path.

Since the moderator tank is designed to operate at 80 °C and its residual heat is removed through the moderator cooling loop, this temperature was adopted as the representative hot-leg condition (T_{hot}) for the present steady-state SPDHRS assessment. To account for varying seawater conditions and heat exchanger effectiveness, three different cold leg return temperatures (T_{cold}) were evaluated: 30°C, 40°C, and 50°C. Table III summarizes the calculation results required to achieve the 1 MW_{th} heat removal target.

Table III: Required natural circulation parameters for 1MW_{th} decay heat removal.

Parameter	Case 1	Case 2	Case 3
T_{hot} (°C)	80	80	80
T_{cold} (°C)	30	40	50
ΔT (°C)	50	40	30
$\Delta\rho$ (kg/m³)	23.9	20.4	16.2
$\dot{m}$ (kg/s)	4.77	5.97	7.95
ΔP_{loss} (Pa)	283	445	791
Required H (m)	1.2	2.2	5.0

Furthermore, Figure 5 illustrates the heat removal capacity as a function of the available elevation difference for the three temperature cases.

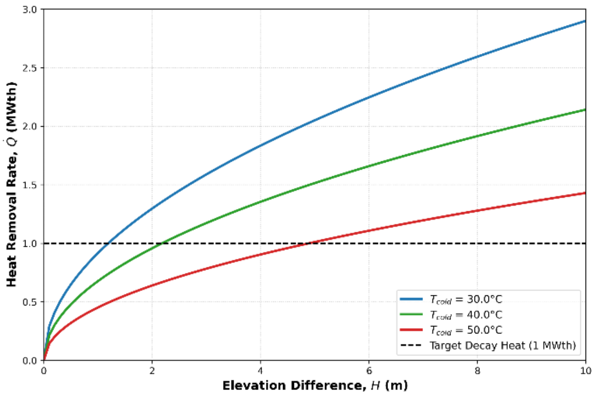

Fig. 5. Heat removal capacity as a function of elevation difference under varying cold leg temperatures.

As shown in the analytical results, a higher cold leg temperature reduces the ΔT, necessitating a larger mass flow rate to extract the same 1 MWth of heat. This increase in flow rate exponentially amplifies the frictional pressure drop while simultaneously diminishing the available density difference ($\Delta\rho$) for buoyancy. Consequently, for the most conservative scenario where the return temperature is 50°C, the system requires an elevation difference of approximately 5.0 meters to sustain the necessary natural circulation flow.

Given that modern 15,000 TEU container ships typically have design drafts on the order of 16 m [7], securing an elevation difference of about 5 m between the moderator tank and the high sea-chest heat exchanger is well within the available vertical envelope. Positioning the SPDHRS heat exchanger near the upper portion of the draft is therefore a practically viable arrangement for GPT-Marine and similar large commercial vessels.

It should be noted that the calculated H in Table III represents the minimum elevation difference required to balance the system pressure loss at the target 1 MW_{th} heat removal rate. If the actual elevation provided by the ship exceeds this minimum requirement, the excess buoyancy-induced driving head will naturally accelerate the circulation flow. This increased mass flow rate will ultimately extract heat more rapidly, forcing the reactor to stabilize at a lower, safer steady-state temperature. Therefore, securing a larger elevation difference directly translates into a substantial thermal design margin for the passive safety system.

4. Summary and conclusions

This paper summarized a seawater-based passive decay heat removal concept for the GPT-Marine, a direct sCO_2 cycle pressure tube reactor concept intended for large merchant-ship propulsion. The SPDHRS leverages a marine platform advantage to provide a conceptually indefinite ultimate heat sink (seawater) via a single-phase natural circulation loop.

Through parametric analytical sizing, this study demonstrated that a minimum elevation difference of approximately 5.0 meters is required to remove 1 MW_{th} of long-term decay heat under conservative conditions. Crucially, the 16 m design draft of 15,000 TEU container ships provides enough vertical space to exceed this requirement, even when accounting for the reactor's baseline installation height and the high sea chest's location. This guarantees a driving head that safely surpasses the minimum threshold, providing a robust thermal design margin and fundamentally strengthening resilience under extended loss-of-power scenarios. Beyond this specific application, the proposed SPDHRS concept demonstrates broad feasibility for any marine or floating nuclear reactor utilizing a light or heavy water moderator tank.

Future work will focus on system-level dynamic validation and safety analysis to confirm the effectiveness of the SPDHRS under severe casualty conditions. Using thermal-hydraulic system codes, time-domain transient analyses will be performed to simulate representative marine accident scenarios, such as a blackout or a Loss of Coolant Accident (LOCA). These simulations will quantitatively evaluate the coupled response of the reactor core and the passive heat removal path, verifying the system's capacity to maintain adequate cooling margins and fuel integrity during extended emergencies. The potential impact of ship motions (roll and pitch) on the stability and robustness of the natural circulation loop will also be investigated in future work. In addition, long-term performance degradation mechanisms on the seawater-side heat exchanger, such as bio-fouling and corrosion, will be considered in future assessments.

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