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Lattice Pitch Optimization for a Gas-Cooled Pressure-Tube Reactor (GPT-Marine) for Maritime Propulsion

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1. Introduction

Driven by the International Maritime Organization (IMO)'s net-zero strategy for around 2050, a rapid transition to zero-carbon ship propulsion has become crucial. Although hydrogen and ammonia are under active study, the long-range, high-power demands of oceangoing vessels make nuclear propulsion a practical candidate. Indeed, nuclear propulsion has accumulated substantial operating experience in naval fleets and Russian icebreakers, with several historical merchant ship demonstrations. Meanwhile, among Generation-IV options, molten-salt reactors (MSRs) offer high-temperature, low-pressure merits but still face challenges in corrosion management, limited operational experience, and licensing [1].

To address these challenges and enable viable zero-carbon nuclear propulsion, this work introduces a gas-cooled, pressure-tube marine reactor (GPT-Marine), a preliminary concept under active development at KAIST. GPT-Marine maximally integrates proven commercial technologies: (i) a Canada Deuterium Uranium (CANDU)-derived pressure-tube architecture that avoids a large pressure vessel; (ii) an Advanced Gas-cooled Reactor (AGR) -derived high-temperature CO_2-cooled fuel bundle to raise thermal efficiency; and (iii) elimination of a large steam generator by using printed-circuit heat exchangers (PCHEs) to couple the primary CO_2 loop to an indirect supercritical carbon dioxide (sCO_2) Brayton cycle.

The paper presents an initial neutronic design for 100 MW_{th} GPT-Marine sized to supply 40 MW_e for Post Panamax class container ship propulsion. Using OpenMC, the study (i) characterizes the moderation regime across the full-core lattice, (ii) evaluates coolant-void reactivity (CVR) in a single-channel model, and (iii) performs lattice-pitch optimization with depletion to maintain slight under-moderation over the fuel cycle.

2. Methodology

2.1 Design criteria

The target vessel is a post-Panamax container ship in the 5,000–10,000 Twenty-foot Equivalent Unit (TEU) range. Figure 1 shows Specified Maximum Continuous Rating (SMCR) as a function of TEU. For this class an electrical supply of about 40 MW_e is sufficient for propulsion and hotel loads under the intended service profile. The plant is therefore sized at 100 MW_{th} and 40 MW_e using an indirect sCO_2 Brayton cycle, which provides at least 40% thermal efficiency and a more compact machinery than a steam Rankine system.

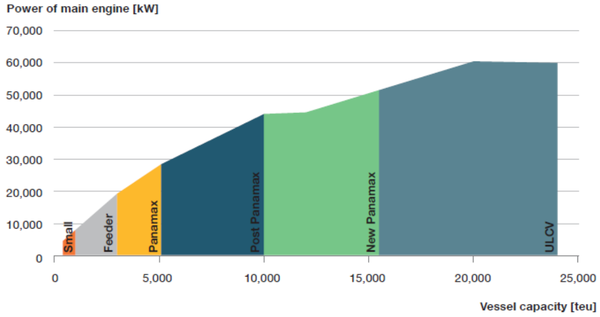

Fig. 1. SMCR power with respect to TEU [2].

Modern container services spend about 15–20% of a full rotation in port and the remainder at sea [3]. For sizing, 80% at sea and 20% in port are adopted. According to IMO survey regulations, a renewal survey is required every five years and bottom or docking inspections must be carried out at least twice within this period with a maximum interval of 36 months [4]. These requirements set the overhaul and refueling schedule.

The three-year operating period is based on historical experience. The first core of NS Savannah was designed for about 69 MW and about 52,200 MWd, corresponding to roughly three years without refueling [5]. Operational records indicate that a single fuel shuffle was conducted rather than a full refuel in the subsequent period [6]. In this study, the operating period is set to three years. With 80% at sea the design core-life target is at least 870 EFPD, which corresponds to 0.80 times three years.

Figure 2 provides a schematic layout of an 11,400 TEU container ship. The engine-room bay, approximately 20 m in length, 45 m in breadth, and 29 m in depth, is indicated as the space that would accommodate the reactor, the power-conversion system, auxiliary equipment, and shielding when nuclear propulsion is applied to container ships [7].

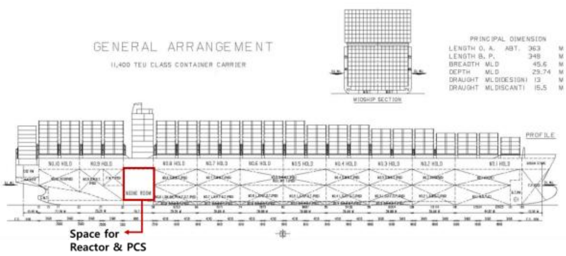

Fig. 2. Schematic layout of 11,400 TEU container ship [7].

2.2 GPT-Marine reactor

Figure 3 outlines the overall GPT-Marine configuration. The reactor adopts heavy-water moderation and a pressure-tube geometry following the CANDU. The coolant and fuel-bundle are derived from the UK AGR as shown in Figure 4. The same geometry of fuel bundle was used in this study except for graphite sleeve. The AGR's graphite sleeve is re-engineered as a pressure tube with an integrated thermal-insulation layer. The power-conversion system applies an indirect recompression sCO_2 Brayton cycle, enabling a compact plant footprint.

Given the compact size core, high thermal-neutron utilization (neutron economy) is essential. Heavy water offers an excellent moderation ratio and very low neutron-absorption cross section, yielding superior neutron economy relative to light water or graphite. In addition, housing the core within a heavy-water calandria tank and operating in a thermal spectrum provides favorable neutron shielding characteristics, potentially reducing required biological-shield thickness compared with typical fast-spectrum systems such as molten salt fast reactor.

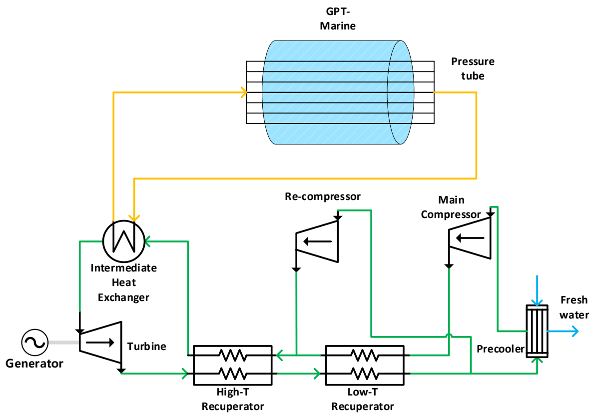

Fig. 3. GPT-Marine reactor and power conversion system layout.

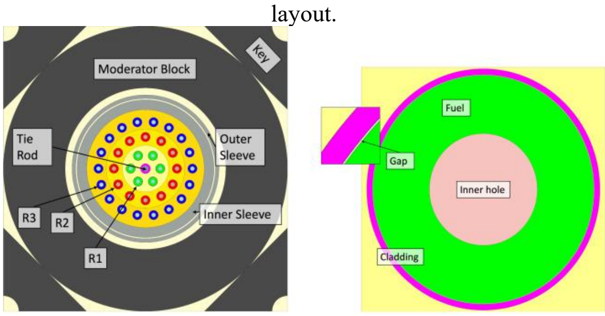

Fig. 4. A cross-sectional view of U.K. AGR fuel bundle [8].

2.3 Reactor core design

Fuel-bundle design follows Margulis and Shwageraus [9]. Figure 5 shows the GPT-Marine fuel-bundle cross-section modeled in OpenMC: a CANDU-type pressure-tube lattice with heavy-water moderation and CO_2 coolant at 4.1 MPa, with AGR-reference operating temperatures of 330–660 °C [10]. The 1m long AGR-derived concentric bundle uses 3 wt%-enriched UO_2 clad in 20/25/Nb stainless steel [4]. The AGR graphite sleeve is replaced by a 1 mm alumina inner sleeve and a thermal-insulation layer, while the pressure boundary is provided by a Zr-2.5Nb pressure tube. Pressure-tube wall thickness is sized per ASME B31.1. Detailed specifications are summarized in Table 1.

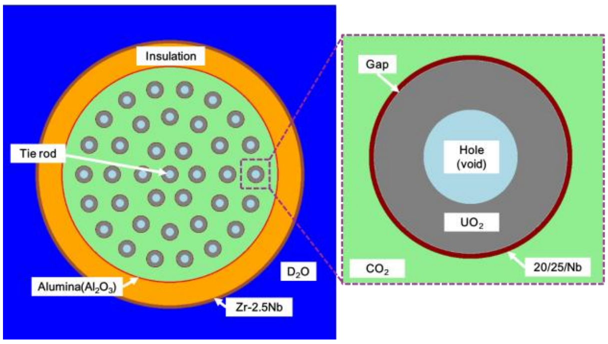

Fig. 5. A cross-sectional view of single fuel bundle and fuel pin built in OpenMC.

Table 1. Major design data of fuel bundle in GPT-Marine.

Fuel pin		Inner tube	
Material	UO_2	Material	Al_2O_3
Inner radius	0.354 cm	Inner radius	9.5 cm
Outer radius	0.724 cm	Outer radius	9.6 cm
Cladding		Pressure tube (outer tube)	
material	20/25/Nb	Material	Zr-2.5Nb
Inner radius	0.727 cm	Inner radius	11.6 cm
Outer radius	0.765 cm	Outer radius	11.9 cm

Table 2. Hot full power temperatures assumed in the neutronic model.

Component	Material	Temp. [K]	Ref. reactor
Fuel	Hollow UO_2	1200	AGR
Cladding	20/25/Nb SS	900	AGR
Coolant	CO_2	873.15	AGR
Moderator	D_2O	343.6	CANDU
End-caps / inner sleeve	Al_2O_3	900	AGR
Insulation	CO_2	600	CANDU
Pressure tube	Zr-2.5Nb	343.6	CANDU
Calandria / vessel steel	SS316	343.6	CANDU

2.4 lattice pitch optimization

To identify the optimal lattice pitch for the fuel-bundle array in the heavy-water tank, the open-source Monte Carlo code OpenMC was used [11]. The full-core model comprises three axially stacked 1-m fuel bundles per channel on a 7×7 rectangular lattice with 37 fuel channels (111 bundles total). Using the ENDF/B-VIII.0 library, depletion was performed to determine the cycle-wise optimum, targeting slight under-moderation throughout the cycle to preserve neutron economy. The CE/LI predictor–corrector integrator, which solves the burnup ODEs with linear interpolation of flux/cross sections between predictor and corrector sub-steps, was employed. Each depletion step used 20,000 particles per batch, 150 total batches with 50 inactive, and a fixed reactor thermal power of 100 MW_{th}.

The burn schedule used short initial steps (0.3, 0.3, 0.4, 1, 3, 25 days) to resolve early fission-product poison transients (e.g., ^{135}Xe, ^{149}Sm) and stabilize the effective multiplication factor (k_{eff}) evolution; thereafter, monthly steps continued through 36 months. At each burnup snapshot, the updated fuel compositions were mapped to a pitch-sweep model, and k_{eff} was computed for pitches from 30 to 70 cm to locate the global optimum.

To assess coolant-void reactivity (CVR), a known safety concern in CANDU [12], a single-channel model with radial and axial reflective boundary conditions was analyzed. CVR was defined from the reactivity change due to coolant voiding, and contributions were interpreted via the four-factor formula (ε,p,f,η) for fast-fission factor, resonance-escape probability, thermal-utilization factor, and reproduction factor.

3. Results and discussion

3.1 Fresh fuel eigenvalue sweep

To identify the optimum lattice pitch at beginning-of-cycle (fresh fuel), k_{eff} was calculated over a pitch sweep. The 7×7 rectangular core model contains 37 fuel channels. As pitch increases, the core radius grows, so the radius is defined from the lattice center to the outer edge of the outermost lattice. Outside this boundary, heavy-water reflectors of 20 cm (radial) and 30 cm (axial, top/bottom) were applied while CANDU designs typically employ 65 cm heavy-water reflectors [13]. As shown in Figure 6, k_{eff} exhibits a broad plateau for lattice pitches of 45–50 cm and declines at larger pitches due to over-moderation, which means a reduction in thermal utilization as moderator fraction grows. The sweep's maximum occurs at a pitch of 48.0 cm with k_{eff} = 1.38108.

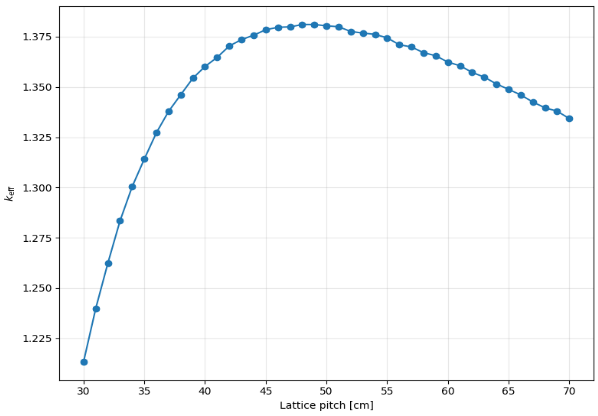

Fig. 6. Fresh fuel k_{eff} as a function of lattice pitch.

3.2 CVR four- factor analysis

To reduce reactivity uncertainty, OpenMC used 500,000 particles, 300 batches, and 50 inactive. CVR is the change in reactivity between the voided-coolant case and the nominal CO_2 case at hot full power. The CVR study used a single channel with reflective boundaries by design to enable a clean four-factor breakdown; results emphasize local spectral/absorption effects rather than core-level leakage. As shown in Figure 7, CVR remains positive across 30–50 cm lattice pitch, with an average of about +18 ± 4 pcm.

Figure 8 breaks the change into four-factor contributions: the fast-fission factor (ε) is largest in tight lattices and declines with increasing pitch; the reproduction factor (η) is slightly negative at all pitches; both resonance-escape (p) and thermal utilization (f) are positive but modest, consistent with mild spectrum hardening and reduced coolant absorption when CO_2 is removed. Relative to the 15 mk (1,500 pcm) typical of CANDU-6 heavy-water cores [13], the CVR magnitude is much smaller because low-density CO_2 provides far less moderation and absorption; voiding it induces only a minor spectral shift. Figure 9 shows the 100%-CO_2 and 0%-CO_2 (void) neutron spectra nearly overlapping, resulting in a small positive CVR.

Given the small, positive CVR, overall feedback is expected to remain negative because UO_2 fuel typically has a negative fuel-temperature coefficient under thermal neutron conditions. In other words, modest voiding–induced hardening adds only a few tens of pcm, which the Doppler feedback can plausibly offset.

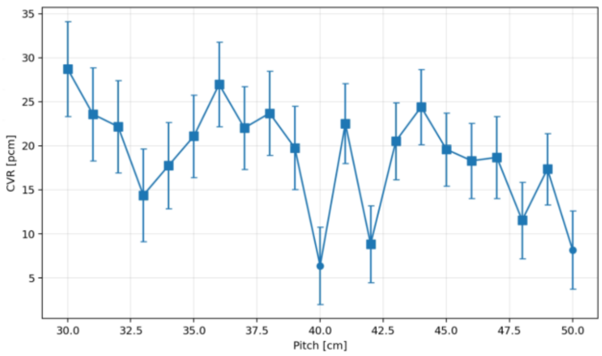

Fig. 7. CVR with respect to lattice pitch with error bars.

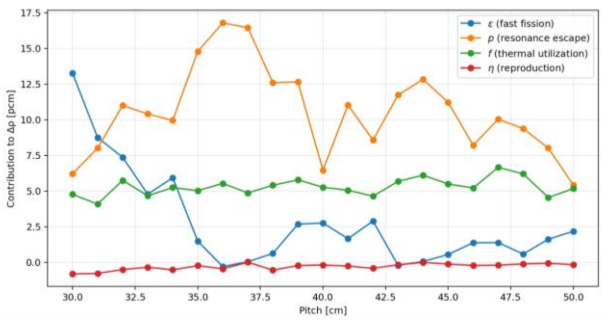

Fig. 8. Four-factor contributions to CVR as a function of pitch.

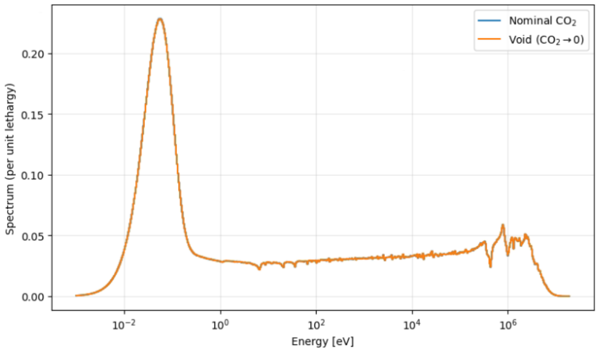

Fig. 9. Neutron energy spectra of GPT-Marine at 100% coolant and 0% coolant (void).

3.3 Cycle-wide optimal lattice pitch (depletion-coupled)

A global optimum over the fuel cycle was obtained by coupling a lattice-pitch sweep with depletion. A reference depletion at a 45 cm pitch was run for three years. Figure 10 shows that k_{eff} remains above 1.01 until ~880 effective full-power days. Consequently, the subsequent analysis is limited to that window (870 EFPD in this study). At each burnup snapshot, the updated fuel compositions were mapped into a pitch-sweep model and k_{eff} was evaluated for pitches of 30–70 cm using 50,000 particles per batch, 300 total batches, and 100 inactive batches. The resulting burnup-dependent optimal pitch is shown in Figure 9.

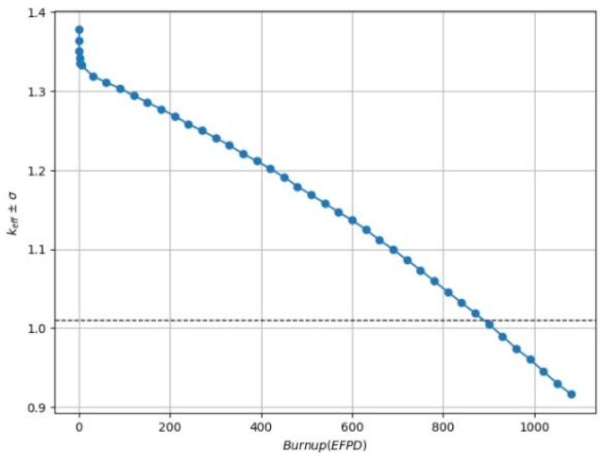

Fig. 10. K_{eff} versus effective full power days at a 45cm pitch

As Figure 11 indicates, the optimal pitch varies with time step. The shortest optimal pitch observed across the cycle was 47 cm; adopting a slight under-moderation margin, a final design pitch of 45 cm was selected for GPT-Marine.

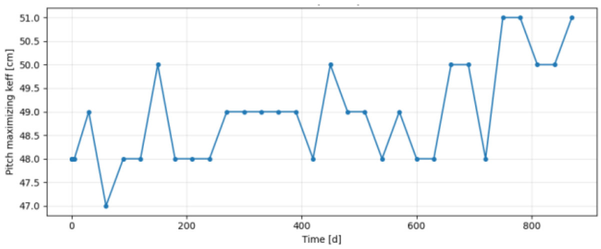

Fig. 11. Burnup-dependent optimal lattice pitch from the depletion-coupled sweep.

3.4 design results

Table 3 summarizes the key design criteria and the initial results of the GPT-Marine reactor. The thermal power of the reactor was set to 100 MW_{th}, which is achieved in the current design. The electrical output and thermal efficiency are left as TBD, as the power conversion system design is beyond the scope of this work. However, future work will focus on PCS design to achieve more than 40 MWe electrical output with a thermal efficiency of approximately 40%. The core design satisfies the targeted 870 EFPD and a three-year operating cycle, achieving 880 EFPD and 3.01 years of continuous operation, thereby meeting the design criteria proposed in this study.

Table 3. GPT-Marine reactor design criteria and results.

Parameter	Criteria	Design result
Thermal power	100MWth	100MWth
Electrical power	40MWe	TBD
Thermal efficiency	40%	TBD
EFPD	870	880
Operating period	3 years	3.01 years

4. Conclusions and Further Works

Under the proposed design criteria, this study introduces a 100 MW_{th} gas-cooled, pressure-tube marine reactor (GPT-Marine) concept that couples CANDU-style moderation with AGR-motived CO_2 coolant. Monte Carlo analysis shows a broad fresh-fuel optimum at 45–50 cm lattice pitch, peaking at 48 cm. Coolant-void reactivity in CO_2 is small and positive, consistent with the low density and weak absorptivity of CO_2. Depletion-coupled sweeps identify a burnup-dependent optimum varying mainly between 47 and 51 cm; adopting slight under-moderation, a 45 cm design pitch is selected.

Planned work couples the GPT-Marine core with the indirect recompression sCO_2 Brayton cycle in MARS-KS to evaluate load-following operation under representative ship profiles. Reactor kinetics will be represented by effective delayed neutron fraction (β_{eff}) and prompt-neutron lifetime (Λ). Also, reactivity feedback will be calculated such as fuel Doppler, coolant density/temperature, and control-rod worth. The parameters calculated at BOC/MOC/EOC will be integrated into the MARS-KS control system for step and ramp tests.

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