

Pollution Prevention by Design for Wing-in-Ground Craft: A Technical Design Review Based on IMO Environmental Requirements

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Abstract— The increasing development of Wing-in-Ground (WIG) craft as an energy-efficient maritime transportation system has highlighted the importance of integrating environmental protection into the early stages of vessel design. Although WIG craft offer advantages in fuel efficiency and reduced operational resistance through the ground effect phenomenon, their unique operational characteristics introduce environmental risks associated with fuel leakage, solid waste, sewage discharge, and atmospheric emissions. Existing WIG craft designs primarily emphasize aerodynamic and hydrodynamic performance, while environmental protection systems are often considered secondary, potentially compromising regulatory compliance and operational sustainability. This study aims to evaluate the implementation of the Pollution Prevention by Design (PPbD) concept in WIG craft through a Technical Design Review (TDR) based on the environmental requirements established by the International Maritime Organization (IMO). A qualitative design assessment was conducted by reviewing four principal environmental protection systems: fuel and lubrication systems, solid waste management, sewage treatment, and air emission control. The evaluation was performed using compliance criteria derived from relevant IMO instruments, including MARPOL Annexes I, IV, V, and VI, together with the IMO Guidelines for Wing-in-Ground Craft. The technical review identified deficiencies in four environmental subsystems, namely fuel containment, sewage management, waste handling, and emission control. The proposed design modifications improved the compliance level from Low–Moderate to Moderate–High according to the developed IMO-based assessment framework. Several design improvements are proposed, including double-wall fuel tanks, leak detection systems, modular waste storage, compact sewage treatment units, and low-emission propulsion technologies. The findings demonstrate that integrating pollution prevention measures during the conceptual design stage significantly enhances environmental performance without compromising operational efficiency. This study contributes a structured technical review framework that supports environmentally sustainable WIG craft development while facilitating compliance with international maritime environmental regulations.

Keywords— Wing-in-Ground Craft; Pollution Prevention by Design; Technical Design Review; IMO Environmental Requirements; MARPOL; Environmental Protection.

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I. INTRODUCTION

Wing-in-Ground (WIG) craft have attracted increasing attention as an alternative high-speed maritime transportation system due to their ability to exploit the aerodynamic ground effect, which significantly enhances lift while reducing induced drag during operation close to the water surface. Compared with conventional ships, WIG craft provide higher cruising speeds with lower hydrodynamic resistance, whereas compared with conventional aircraft, they require substantially lower propulsion power for equivalent payload capacities. These characteristics make WIG craft a promising solution for coastal transportation, island connectivity, maritime surveillance, search and rescue operations, and rapid

logistics while offering improved fuel efficiency and reduced greenhouse gas emissions.

Despite these operational advantages, WIG craft present unique environmental challenges resulting from their hybrid characteristics as both marine and aeronautical vehicles. Their operation in coastal waters, estuaries, and environmentally sensitive marine ecosystems increases the potential consequences of accidental fuel leakage, improper waste disposal, sewage discharge, and atmospheric emissions. Furthermore, the compact structural configuration and strict limitations on weight and available installation space complicate the integration of environmental protection systems that are commonly applied to conventional ships. Consequently, environmental considerations should be incorporated during the conceptual design stage rather than being introduced as supplementary systems after the primary vessel design has been completed [1].

International environmental regulations established by the International Maritime Organization (IMO), particularly the International Convention for the Prevention of Pollution from Ships (MARPOL), provide comprehensive requirements for controlling marine pollution originating from oil (Annex I), sewage (Annex IV), garbage (Annex V), and atmospheric emissions (Annex VI). Although these regulations were primarily developed for conventional ships, their underlying environmental protection principles remain applicable to

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WIG craft. In addition, the IMO Guidelines for Wing-in-Ground Craft emphasize that environmental protection should be considered alongside safety and operational performance throughout the design process. However, the absence of detailed technical guidance specifically addressing pollution prevention systems for WIG craft creates uncertainty for designers in implementing environmentally compliant configurations [2].

The concept of Pollution Prevention by Design (PPbD) has emerged as an effective engineering strategy that integrates environmental protection into the earliest phases of system development. Rather than relying solely on operational control measures or post-release mitigation, PPbD seeks to eliminate or minimize pollution sources through appropriate engineering decisions involving system configuration, material selection, component arrangement, containment strategies, and environmental risk reduction. Previous studies have demonstrated the effectiveness of PPbD in ship engineering, offshore facilities, and industrial process systems. Nevertheless, its application to WIG craft remains limited because most existing studies primarily focus on aerodynamic optimization, hydrodynamic performance, structural design, stability, propulsion efficiency, and operational safety, while environmental protection systems receive comparatively little attention [3].

A review of the existing literature reveals several important research gaps. First, previous investigations generally evaluate individual environmental systems, such as fuel containment or emission reduction, without considering their integration into the overall WIG craft design. Second, only limited studies assess WIG craft compliance with internationally recognized environmental regulations, particularly the requirements specified in MARPOL Annexes I, IV, V, and VI. Third, no comprehensive technical assessment framework has been established to evaluate pollution prevention measures systematically throughout the WIG craft design process. These limitations hinder the development of environmentally sustainable WIG craft capable of meeting future international regulatory expectations.

To address these research gaps, this study conducts a comprehensive Technical Design Review (TDR) of pollution prevention systems implemented in a representative WIG craft design using the principles of Pollution Prevention by Design and the environmental requirements established by the IMO. Four major environmental protection systems are evaluated, including the fuel and lubrication system, solid waste

management system, sewage management system, and air emission control system. Each subsystem is examined to identify potential environmental risks, assess its level of compliance with applicable IMO environmental requirements, and formulate engineering recommendations for improving environmental performance while maintaining operational efficiency.

The primary contribution of this research is the development of a structured environmental design review framework specifically tailored for WIG craft. Unlike previous studies that concentrate mainly on aerodynamic or propulsion performance, this work integrates environmental engineering principles with maritime regulatory compliance into the conceptual design evaluation process. The proposed framework provides practical guidance for designers, researchers, classification societies, and maritime authorities in developing environmentally sustainable WIG craft that simultaneously satisfy operational performance, safety requirements, and international environmental standards. The novelty of this study lies in the development of an integrated Technical Design Review framework that combines Pollution Prevention by Design principles with IMO environmental requirements specifically for Wing-in-Ground craft during conceptual design [4].

II. Method

A. Research Framework

This study employed a qualitative engineering evaluation using a Technical Design Review (TDR) framework to assess the implementation of Pollution Prevention by Design (PPbD) in Wing-in-Ground (WIG) craft. The review focused on the integration of environmental protection measures into the conceptual design stage rather than evaluating operational performance after construction. The assessment was performed by comparing the existing WIG craft design with internationally recognized environmental protection requirements established by the International Maritime Organization (IMO) [5].

The research framework consisted of five sequential stages: (1) literature review and regulatory identification, (2) identification of potential pollution sources within the WIG craft design, (3) technical design evaluation of environmental protection systems, (4) compliance assessment with IMO environmental requirements, and (5) formulation of engineering design recommendations.



Figure. 1 WIG Craft Type A

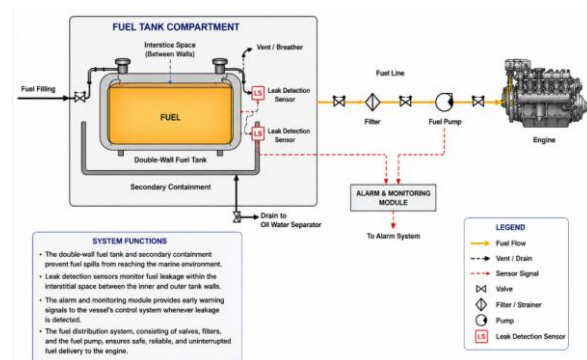


Figure. 2 Proposed Fuel System Incorporating Double-Wall Tank, Leak Detection, and Secondary Containment Based on Pollution Prevention by Design Principles

B. System Object

The object of this research was a conceptual Type-A Wing-in-Ground (WIG) craft designed for coastal transportation. The technical review focused exclusively on environmental protection systems integrated into the vessel design. Four major engineering subsystems were evaluated:

- Fuel storage and fuel distribution system;
- Solid waste (garbage) management system;
- Sewage collection and treatment system;
- Air emission control and propulsion system.

Structural strength, hydrodynamic performance, stability, and aerodynamic characteristics were considered only insofar as they influenced the implementation of environmental protection measures [6].

C. Data Collection

The study utilized both primary and secondary data.

Primary data consisted of engineering design documents, general arrangement drawings, fuel system layouts, machinery arrangements, technical specifications, and environmental system configurations

of the WIG craft [7].

Secondary data were obtained from scientific publications, technical standards, and international regulations relevant to marine environmental protection. The principal references included:

- IMO Guidelines for Wing-in-Ground Craft;
- MARPOL Annex I (Oil Pollution);
- MARPOL Annex IV (Sewage Pollution);
- MARPOL Annex V (Garbage Management);
- MARPOL Annex VI (Air Pollution Prevention);
- ISO 14001 Environmental Management Systems;
- Published journal articles addressing pollution prevention and environmentally sustainable marine vehicle design

D. Technical Design Review Procedure

The Technical Design Review (TDR) was conducted systematically by evaluating each environmental subsystem against engineering best practices and applicable IMO environmental requirements [8].

The review consisted of the following steps:

1. Identification of pollution sources within each

subsystem.

2. Analysis of the existing engineering design.
3. Identification of potential environmental risks.
4. Comparison with applicable IMO environmental requirements.
5. Identification of design deficiencies.
6. Development of engineering improvement recommendations [21].

Each subsystem was independently evaluated before integrating the overall findings into a comprehensive environmental assessment of the WIG craft [9].

E. Environmental Compliance Assessment

Compliance with international environmental regulations was evaluated using a structured assessment matrix developed for this study. The matrix compared the existing WIG craft design against the principal environmental requirements contained in MARPOL and the IMO WIG Craft Guidelines [10].

Five evaluation criteria were adopted:

- Oil pollution prevention;
- Sewage management;
- Garbage management;
- Air emission control;
- Integration of Pollution Prevention by Design principles.

Each criterion was assessed qualitatively according to four compliance levels as shown in table 1. The assessment enabled systematic identification of environmental risks and engineering priorities for design improvement [11].

F. Pollution Prevention Assessment Criteria

The evaluation of each subsystem considered both engineering performance and environmental sustainability. The principal assessment criteria included:

- Fuel leakage prevention capability;

while maintaining operational reliability and safety [12].

G. Data Analysis

The collected data were analysed using descriptive engineering analysis supported by regulatory compliance assessment [29]. Existing design characteristics were compared with Pollution Prevention by Design principles and applicable IMO environmental requirements to identify design gaps and opportunities for improvement. The final analysis generated:

1. Identification of environmental risks associated with each subsystem;
2. Evaluation of compliance with international maritime environmental regulations;
3. Engineering recommendations to improve environmental performance; and
4. A comprehensive Technical Design Review framework for environmentally sustainable WIG craft development [13].

III. RESULTS AND DISCUSSION

A. Technical Design Review of Environmental Protection Systems

The Technical Design Review (TDR) was conducted to evaluate the environmental performance of the proposed Wing-in-Ground (WIG) craft based on the Pollution Prevention by Design (PPbD) concept and the environmental requirements specified by the International Maritime Organization (IMO) [22]. The evaluation focused on four critical environmental protection systems, namely the fuel system, solid waste management, sewage management, and atmospheric emission control. The review revealed that although the conceptual WIG craft design adequately satisfies operational and structural requirements, several environmental protection components require significant

TABLE 1.
FOUR COMPLIANCE LEVELS

Compliance Level	Description
High	Fully complies with IMO environmental requirements.
Moderate	Most requirements are satisfied, with minor improvements required.
Low	Several important requirements remain unmet.
Non-compliant	Major deficiencies requiring complete redesign.

- Secondary containment effectiveness;
- Leak detection capability;
- Waste storage efficiency;
- Sewage containment and treatment performance;
- Air emission reduction capability;
- Ease of inspection and maintenance;
- Space and weight efficiency;
- Integration with the overall WIG craft design. These criteria were selected because they directly influence environmental protection

improvement to achieve compliance with international maritime environmental standards. Unlike conventional vessels, WIG craft operate very close to the water surface while maintaining relatively high cruising speeds. Consequently, accidental release of fuel, lubricants, sewage, or solid waste may directly affect environmentally sensitive coastal ecosystems. Therefore, environmental protection systems must be incorporated during the conceptual design stage instead of being installed as additional equipment after the vessel configuration has been finalized [14].

B. Fuel System Evaluation

The fuel storage and distribution system represents the subsystem with the highest environmental risk. The existing conceptual design employs a conventional single-wall fuel tank connected to the propulsion engine through multiple pipe joints. Although this configuration simplifies construction and reduces structural weight, it considerably increases the probability of fuel leakage caused by structural vibration, fatigue loading, corrosion, or accidental impact [23]. The TDR identified several deficiencies, including the absence of secondary containment, leak detection sensors, and emergency fuel isolation devices[24]. These shortcomings increase the likelihood that leaked fuel would be discharged directly into the surrounding marine environment [15]. To mitigate these risks, several engineering modifications are proposed:

- installation of double-wall fuel tanks;
- incorporation of continuous leak detection sensors;
- implementation of secondary containment beneath machinery spaces;
- utilization of corrosion-resistant piping materials;
- simplification of fuel pipe routing to minimize leakage points.

These improvements are consistent with the preventive philosophy of MARPOL Annex I by emphasizing containment and early leak detection rather than relying solely on operational responses after pollution has occurred [16].

C. Solid Waste Management Assessment

The assessment of the garbage management system indicates that environmental considerations have not yet been fully integrated into the conceptual design. Existing arrangements assume that domestic waste generated by passengers and crew will remain onboard until the craft

D. Sewage Management Evaluation

The existing sewage management system consists primarily of a holding tank without any onboard treatment capability. Although this arrangement temporarily prevents direct discharge, prolonged operation or unexpected storage overflow may still create environmental hazards, particularly in coastal waters and shallow marine environments [28]. The Technical Design Review recommends integrating compact biological treatment or membrane filtration technologies into the sewage management system. Recent advances in compact marine wastewater treatment units make such installations technically feasible even under the severe spatial limitations of WIG craft. The incorporation of a closed holding tank together with small-scale treatment technology substantially improves compliance with MARPOL Annex IV while reducing environmental risks during extended operations [18].

E. Air Emission Control Assessment

Atmospheric emission remains another important environmental issue because the baseline WIG craft utilizes conventional fossil-fuel propulsion. Although WIG craft generally consume less fuel than conventional ships operating at similar speeds, exhaust gases still contain nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), particulate matter, and greenhouse gases [25]. The current conceptual design primarily emphasizes propulsion performance while providing limited consideration of emission reduction technologies. No exhaust after-treatment devices or alternative propulsion concepts have been incorporated. Several engineering improvements are therefore proposed: adoption of low-sulphur marine fuel; installation of catalytic converters; integration of exhaust gas after-treatment systems; optimization of engine combustion efficiency; gradual transition toward hybrid-

TABLE 2.
PREVIOUS RESEARCH

Author	Topic and Limitation
Wang (2022)	Ship emission and not WIG
Luo (2024)	Pollution design and not IMO review
Perera (2024)	Sustainable ship and no PPbD

reaches port facilities. However, no dedicated waste storage compartment or waste segregation system has been incorporated. Considering the limited installation space available in WIG craft, compact modular waste containers are recommended. Modular storage improves space utilization while allowing separation of recyclable, organic, and hazardous waste. Such an approach is fully consistent with the waste minimization principles promoted in MARPOL Annex V. The proposed system also improves operational efficiency because waste handling procedures become simpler during port operations without significantly increasing structural weight. Therefore, no previous study has integrated PPbD, Technical Design Review, and IMO environmental requirements specifically for WIG craft as shown in table 2 [17].

electric propulsion. These modifications support the objectives of MARPOL Annex VI by reducing atmospheric pollutants while simultaneously improving fuel efficiency [19].

F. IMO Environmental Compliance Assessment

A compliance assessment was conducted by comparing the existing WIG craft design with the principal environmental protection requirements established by IMO. The assessment demonstrates that environmental performance can be substantially improved through relatively modest engineering modifications. The results indicate that the largest improvements occur in fuel containment and emission control [26]. These systems initially exhibit relatively low compliance because environmental protection had

not been explicitly considered during conceptual design. Following implementation of the proposed recommendations, the overall environmental compliance level increases substantially without fundamentally altering the vessel configuration [20].

G. Discussion

The findings demonstrate that Pollution Prevention by Design constitutes an effective engineering strategy for improving the environmental sustainability of WIG craft. Unlike conventional environmental protection approaches that depend largely on operational procedures and pollution response, PPbD minimizes pollution risks through engineering decisions implemented during the earliest phases of vessel development [27]. The Technical Design Review further reveals that environmental protection systems should not be treated as independent auxiliary components. Instead, they must be integrated with structural design, machinery arrangement, fuel system architecture, and propulsion selection. Such integration minimizes future design modifications while reducing both operational risk and lifecycle costs. The study also highlights the applicability of IMO environmental regulations to emerging marine transportation technologies. Although no dedicated environmental regulations currently exist for WIG craft, the principles contained in MARPOL Annexes I, IV, V, and VI provide an effective regulatory framework for evaluating environmental performance during conceptual design. Consequently, the proposed review methodology offers practical guidance for designers, shipbuilders, classification societies, and maritime authorities engaged in the development of environmentally sustainable WIG craft. Compared with previous studies that primarily emphasize aerodynamic efficiency, hydrodynamic performance, structural optimization, or propulsion systems, this research introduces an integrated environmental assessment framework based on international maritime environmental regulations. The proposed framework enables environmental risks to be identified systematically before prototype construction, thereby reducing future redesign requirements and facilitating regulatory compliance. This contribution supports the advancement of environmentally responsible WIG craft and provides a foundation for future quantitative investigations involving risk assessment, lifecycle environmental analysis, and optimization of integrated pollution prevention systems. Unlike previous studies that primarily evaluated propulsion efficiency, this study integrates environmental protection systems into the conceptual design stage using the Pollution Prevention by Design framework. Consequently, environmental compliance can be considered before prototype construction, reducing redesign efforts and improving lifecycle sustainability [30].

CONCLUSION

This study presented a Technical Design Review (TDR) of a conceptual Wing-in-Ground (WIG) craft based on the principles of Pollution Prevention by Design (PPbD) and the environmental protection

requirements established by the International Maritime Organization (IMO). The assessment demonstrated that environmental protection should be integrated into the conceptual design stage rather than introduced as an auxiliary system during later phases of vessel development. The review identified several environmental deficiencies in the baseline WIG craft design, particularly in fuel containment, sewage management, solid waste handling, and atmospheric emission control. The absence of secondary fuel containment, leak detection systems, dedicated waste storage, onboard sewage treatment, and emission reduction technologies resulted in relatively low compliance with the environmental principles embodied in MARPOL Annexes I, IV, V, and VI. The proposed engineering improvements—including double-wall fuel tanks, leak detection sensors, secondary containment, modular waste storage, compact sewage treatment units, and low-emission propulsion technologies—substantially enhance the environmental performance of the WIG craft while preserving its operational efficiency and design feasibility. These improvements demonstrate that environmental protection can be effectively integrated into WIG craft without imposing significant technical constraints. The principal contribution of this study is the development of a structured environmental evaluation framework that combines the Technical Design Review methodology with IMO environmental requirements for assessing pollution prevention systems in WIG craft. This framework provides a practical engineering tool for designers, researchers, shipbuilders, classification societies, and maritime authorities to systematically evaluate environmental compliance during the early stages of WIG craft development.

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