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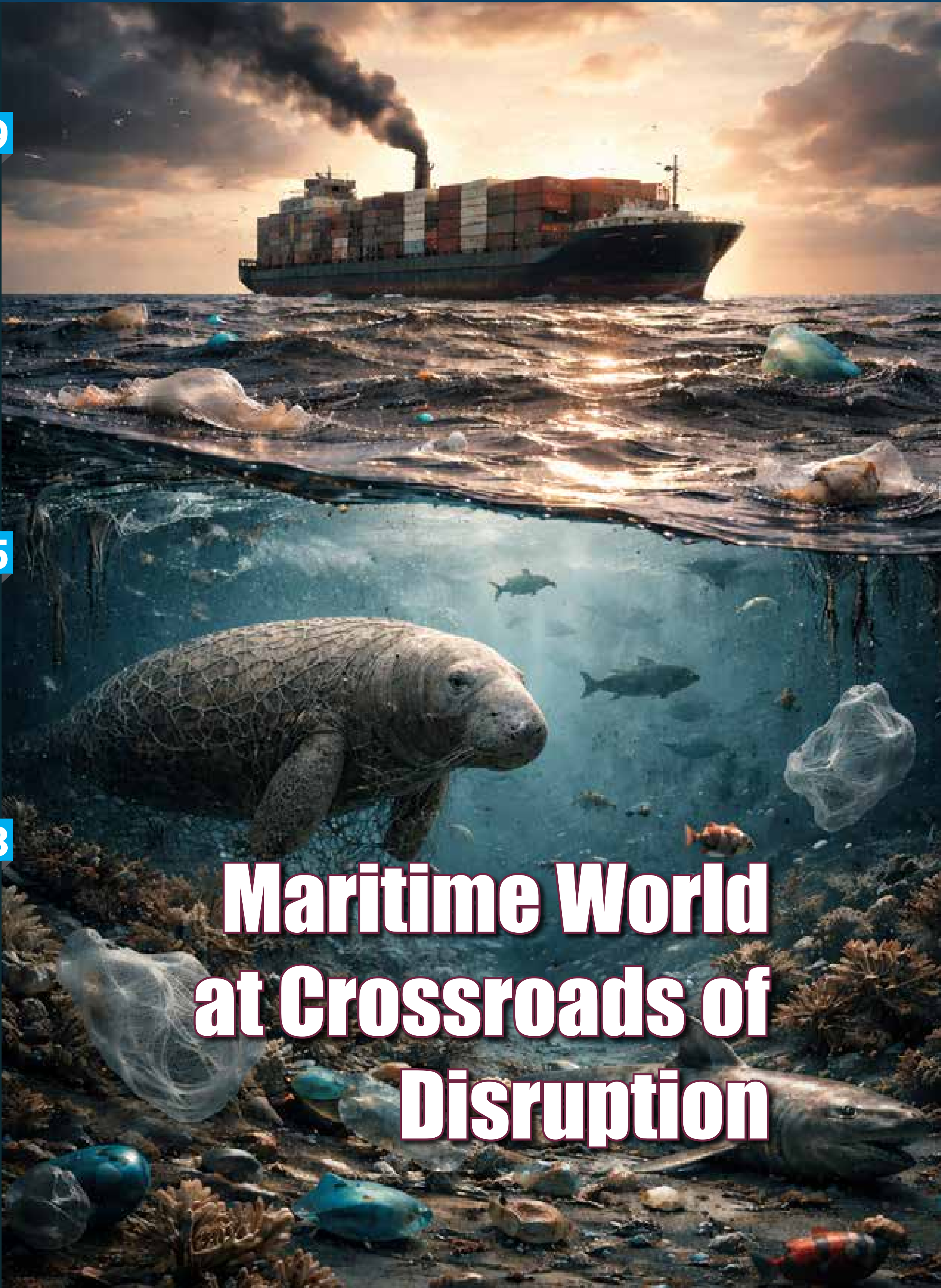

Maritime World at Crossroads of Disruption

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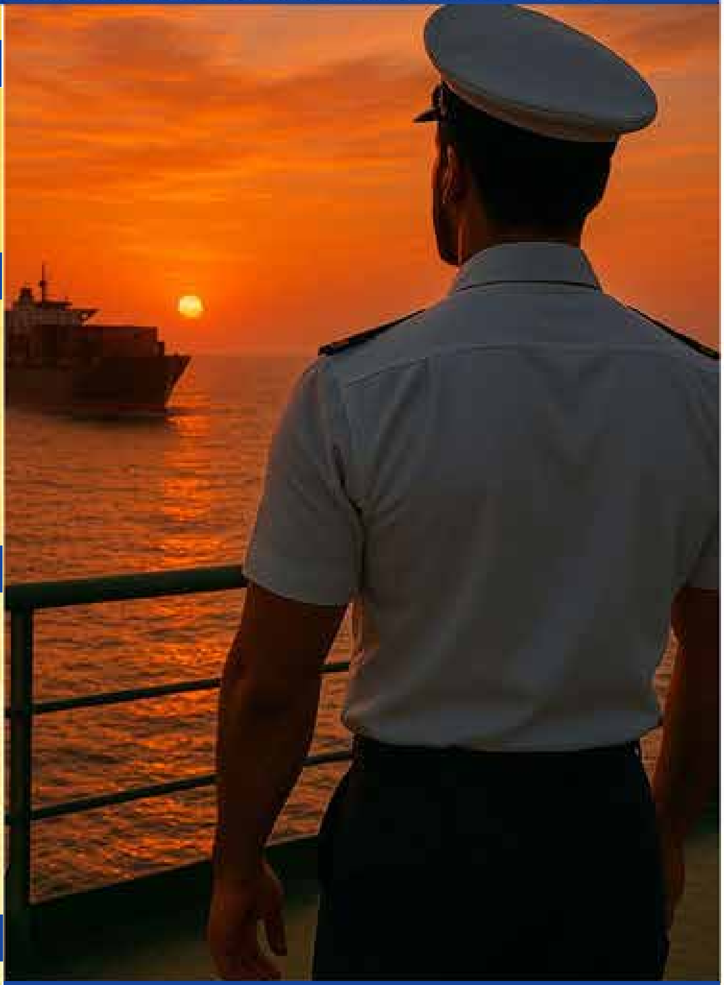

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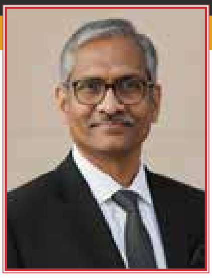

"In the midst of chaos, there is also opportunity." — *Sun Tzu*

"Chokepoints, Conflict and a World Recalibrating"

The world today feels increasingly like a system operating beyond its design envelope. From regional conflicts to shifting alliances, the geopolitical landscape is no longer defined by predictable blocs but by fluid tensions that ripple across economies and industries. Nowhere is this more evident than in the maritime domain, where global trade—carrying nearly ninety percent of the world's goods—has become both a barometer and a transmission channel of instability.

Recent conflicts in critical corridors such as the Strait of Hormuz and the Bab el-Mandeb Strait highlight how strategic choke points are now being influenced, if not effectively controlled, by regional power dynamics and non-state actors. These narrow passages, once routine arteries of commerce, have become zones of heightened risk. Vessel rerouting around the Cape of Good Hope, rising war-risk premiums and naval escorts are no longer exceptions but emerging norms. What begins as a regional disruption quickly cascades into global consequences.

For perhaps the first time in decades, the world's attention has turned sharply toward the shipping industry—particularly tankers and gas carriers transporting crude oil and LNG across volatile corridors. Once operating quietly in the background, these vessels are now at the very eye of the storm. Their vulnerability has exposed the fragility of global energy supply chains. Insurance markets, traditionally resilient, are showing visible strain, with underwriters increasingly reluctant or selective in covering ships and cargoes in high-risk zones. The implications are immediate: rising freight rates, constrained cargo movement and uncertainty in global energy pricing.

The impact is not merely economic. It is deeply human. Lives are lost, ships are damaged, seafarers operate under constant threat and coastal communities bear the consequences of instability. Ports slow down, cargoes are delayed and essential supplies face disruption. The cost of conflict is measured not only in strategy, but in human vulnerability.

At the same time, the global decarbonisation agenda faces growing uncertainty. While regulatory ambition remains firm, execution pathways are increasingly blurred by geopolitical tensions.

We are witnessing not collapse, but recalibration under pressure—where resilience, adaptability and foresight will define leadership.

This month, the first article take a life-cycle lens for analysis for putting markers on emerging maritime technologies in the near horizon that introduce new human health risks beyond regulatory compliance, emphasising proactive risk management, occupational exposure awareness and integrating safety into design, operations, maintenance and ship recycling stages.

* * *

The second article explains how varying definitions across IMO conventions reflect distinct regulatory philosophies, aligning terminology with safety, environmental protection and liability objectives, ensuring effective application of principles like polluter pays, strict liability and risk-based maritime governance.

* * *

The third article examines seafarer mental health challenges, highlighting stigma, operational stressors and organisational responsibility, advocating leadership-driven cultural change, proactive support systems and integration of psychological well-being into safety, performance and sustainable maritime operations.

* * *

Part of an accident investigation learning series, this article examines hidden fuel system defects causing propulsion loss, covering contamination, valve failures, vapour lock and pump issues, highlighting fault-tree analysis, regulatory implications and serious safety, legal consequences.

* * *

The fifth article presents AI-driven cognitive digital twin "Chaitanya" supporting Matsya6000 submersible, integrating system engineering, reliability modelling and real-time scenario prediction to enhance crew safety, manage life-critical risks and optimise deep-ocean mission performance under extreme conditions.

* * *

The sixth article in the fourth in a five articles series and looks at a comprehensive analysis of dual-fuel marine engines covering technology, performance, emissions, economics, retrofit feasibility and future fuels, highlighting operational reliability, regulatory compliance, methane slip challenges and their central role in maritime decarbonisation pathways.

* * *

Here is the May 2026 issue for your reading pleasure and intellectual rumination.

Mani Ganapathi Ramachandran
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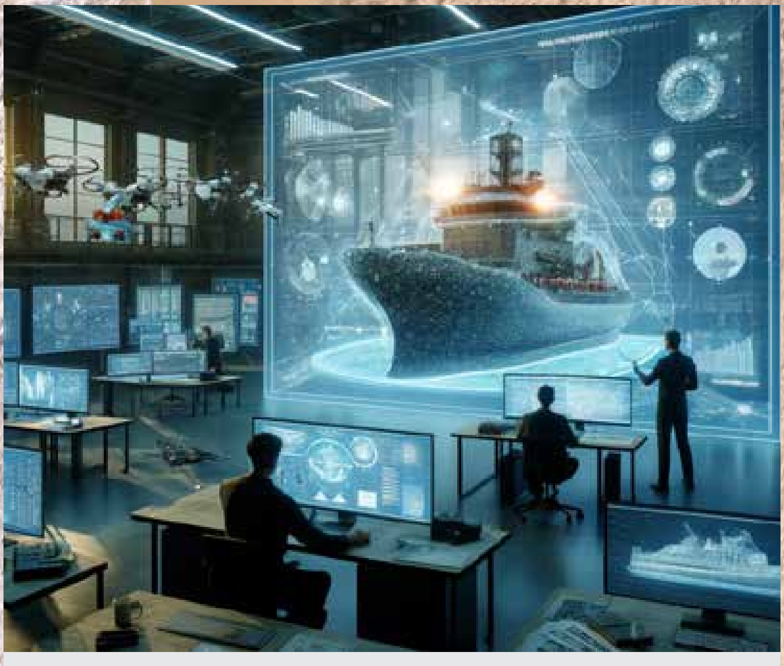

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Beyond Compliance: Human Health Across the Ship Life Cycle in an Era of New Technologies

Tapan Kumar Sahu

Abstract

Rapid technological change in the maritime sector is transforming the nature of occupational health risks faced by seafarers, shipyard workers and maritime stakeholders. While modern ships increasingly comply with stringent environmental and safety regulations, new systems such as chemical ballast water treatment, alternative fuels, large marine batteries, advanced exhaust treatment technologies and complex retrofits introduce new types of human exposure.

This paper examines how these emerging technologies influence human health across the **entire ship life cycle**, from design and construction through operation, maintenance, repair and recycling. Using a life-cycle perspective, the study highlights risks associated with chemical exposure, toxic gases, confined spaces, hot work, cargo emissions, chronic noise and psychosocial stress.

The paper argues that existing regulatory frameworks provide essential minimum standards but often lag behind technological innovation. Many maritime regulations historically evolved through **reactive learning following incidents or scientific evidence of harm**.

By examining past regulatory responses to hazards such as asbestos, PFOS firefighting foams, benzene exposure and ozone-depleting substances, the study demonstrates the need for a **more anticipatory approach to emerging technologies**.

The paper concludes that sustainable maritime innovation requires integrating **human health considerations into ship design, operational management and technology adoption**. A proactive, collaborative approach involving designers, ship operators, regulators and researchers is essential to ensure that environmentally advanced vessels are also safe and healthy workplaces.

Keywords : Human health; maritime safety; shipping; ship life-cycle; alternative fuels; lithium-ion batteries; ballast water management; toxic exposure; maritime regulation; decarbonisation.

1. Introduction

The maritime industry is undergoing one of the most significant technological transformations in its history. Decarbonisation initiatives, environmental regulations, digitalisation and operational efficiency requirements are driving the rapid adoption of new technologies.

These include:

- Ballast Water Management Systems (BWMS) using chemical treatment
- Alternative fuel systems such as LNG, methanol, hydrogen and ammonia
- Large-scale marine battery installations
- Exhaust gas cleaning and carbon-capture technologies
- High-voltage electrical systems
- Extensive retrofit programmes for energy efficiency

> *Compliance alone cannot address emerging maritime health risks*

These innovations offer clear benefits in reducing emissions and improving environmental performance. However, their implications for **human health and occupational exposure** are less frequently discussed.

Maritime regulations such as **SOLAS, MARPOL, the Maritime Labour Convention and the Ballast Water Management Convention** provide robust frameworks governing ship safety, environmental protection and crew welfare. Yet these frameworks are typically developed around known hazards and established technologies.

When new technologies are introduced, **health risks may appear in unexpected ways or shift between stakeholders**, including designers, shipyard workers, seafarers, contractors, port personnel and ship recyclers.

This paper examines these evolving risks through a **ship life-cycle perspective**, exploring how new technologies influence human health during:

- design and construction
- ship operations
- maintenance and retrofit
- ship repair
- ship recycling.

Rather than criticising existing regulatory systems, the objective is to encourage maritime stakeholders to think **"beyond compliance"** and incorporate proactive health considerations into innovation.

2. Regulation, Minimum Standards and Reactive Learning

The maritime sector operates within one of the most comprehensive regulatory systems of any global industry. International frameworks administered by the **International Maritime Organization (IMO)** establish baseline safety and environmental standards.

These include:

- **SOLAS** – ship safety
- **MARPOL** – pollution prevention
- **ISM Code** – safety management systems
- **MLC** – crew welfare and working conditions
- **Ballast Water Management Convention**

Classification societies, flag administrations and insurers reinforce these rules through technical standards and guidance.

While these regulations establish minimum safety thresholds, they **cannot anticipate every technological development or operational scenario**. Many regulatory changes historically occurred after evidence of harm accumulated.

This pattern of **reactive learning** is common across high-risk industries.

New technologies may therefore be **fully compliant yet still introduce unanticipated human-health challenges**.

For example:

- regulations may assume ideal maintenance conditions
- environmental compliance standards may overlook occupational exposure
- complex system interactions may not be fully addressed.

This gap highlights the need for **professional judgement, operational vigilance and anticipatory risk management**.

3. Lessons from Reactive Regulation

Several historical cases illustrate how materials widely adopted in shipping were later found to pose serious health risks.

Asbestos in Ship Construction

For decades asbestos was used extensively for fire protection and insulation. Its thermal resistance and low cost made it highly attractive for ship construction.

However, asbestos exposure later proved to cause:

- lung cancer
- asbestosis
- mesothelioma.

International regulations eventually prohibited asbestos installation on ships, yet many vessels still contain legacy materials, creating long-term risks for repair and recycling workers.

PFOS Firefighting Foams

Perfluorooctane sulfonate (PFOS) was widely used in firefighting foams due to its ability to suppress hydrocarbon fires.

Research later showed PFOS compounds to be **persistent environmental pollutants linked to cancer, immune disruption and developmental effects**.

International conventions now require the **phase-out of PFOS-based foams**, demonstrating how environmental and health concerns may only become evident years after adoption.

Benzene Exposure in Tankers

Tanker crews historically experienced benzene exposure during cargo loading, sampling and tank cleaning. Benzene is now recognised as a carcinogen associated with blood disorders.

Stricter vapour control measures and operational procedures were introduced only after occupational health studies revealed these risks.

Ozone-Depleting Substances

Chlorofluorocarbons (CFCs) and halons were widely used in refrigeration and firefighting systems. These substances were later linked to **ozone layer depletion**, leading to international restrictions under the **Montreal Protocol**.

Hazardous Materials in Ship Recycling

Ship recycling practices historically exposed workers to hazardous materials including:

- asbestos
- PCBs
- heavy metals
- toxic residues.

The **Hong Kong Convention on Ship Recycling** and related regulations were introduced only after widespread documentation of dangerous conditions in recycling yards.

These examples demonstrate a common regulatory pattern:

1. Technology adoption based on operational advantages
2. Scientific evidence of health impacts emerges
3. Regulations are strengthened or substances phased out
4. Legacy materials continue to pose long-term risks.

This history highlights why emerging maritime technologies must be assessed **not only for immediate safety but also for long-term human health implications**.

4. A Life-Cycle Perspective on Human Health

Human exposure risks may arise at different stages of a ship's life.

Design Phase

Technology selection affects exposure for decades. Decisions involving fuel systems, ventilation arrangements, battery chemistries or chemical treatment systems influence occupational risk profiles.

Construction and Retrofit

Shipyards implementing new systems face concentrated exposure risks including:

- confined spaces
- chemical handling
- welding fumes
- simultaneous operations.

Retrofit projects often combine modern systems with legacy materials.

Ship Operation

Operational conditions may introduce new exposure scenarios through:

- equipment malfunction
- cargo interaction

> *New technologies introduce risks beyond traditional safety frameworks*

- maintenance activities
- unexpected system behaviour.

Repair and Recycling

Ship dismantling concentrates hazardous materials accumulated throughout a vessel's life.

Workers may encounter multiple generations of hazardous substances in the same environment.

5. Health Risks from Emerging Technologies

5.1 Ballast Water Treatment Systems

Chemical ballast water treatment systems use oxidising substances such as:

- ozone
- chlorine
- peracetic acid.

These chemicals effectively control invasive species but may create occupational exposure risks through leaks, maintenance activities or disinfection by-products.

Residual gases may accumulate in ballast tanks or poorly ventilated spaces.

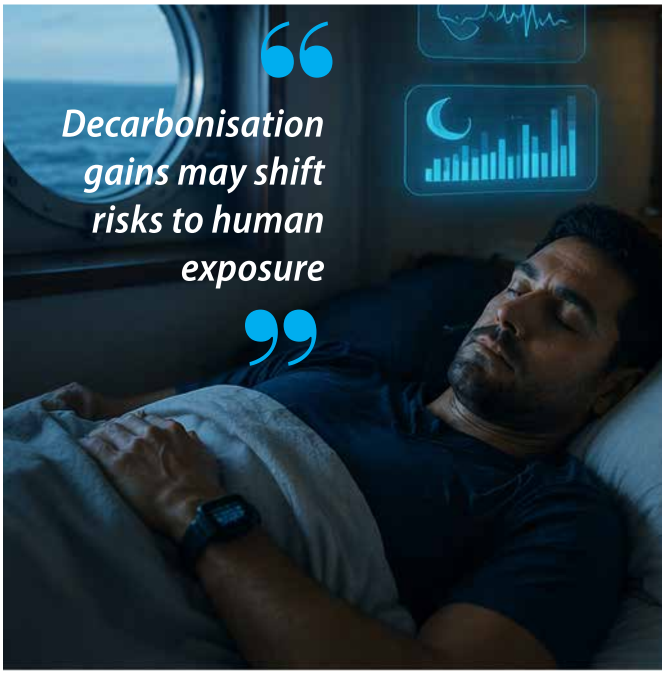
5.2 Exhaust Gas Cleaning and Carbon Capture

Scrubbers and emerging carbon capture systems introduce additional chemical handling risks.

Workers may encounter:

- acidic wash water
- chemical solvents
- sludge residues.

Maintenance and sampling activities can expose personnel to corrosive or toxic substances.



Decarbonisation gains may shift risks to human exposure

5.3 Alternative Marine Fuels

Decarbonisation initiatives are accelerating adoption of fuels such as:

- ammonia
- hydrogen
- methanol.

Each introduces distinct safety considerations.

Ammonia is toxic and corrosive. Hydrogen is highly flammable with wide explosive limits. Methanol is toxic and burns with nearly invisible flames.

Bunkering operations therefore require enhanced safety procedures and training.

5.4 Marine Battery Systems

Large lithium-ion battery installations are increasingly used for hybrid propulsion.

Battery failures can release toxic gases including:

- hydrogen fluoride
- carbon monoxide
- volatile organic compounds.

Confined battery rooms can accumulate hazardous concentrations during thermal runaway events.

6. Cargo and Operational Hazards

Certain cargoes generate toxic gases during transport.

Examples include:

- hydrogen sulphide from decomposing organic cargo
- fumigant gases in grain shipments
- vapours from chemical cargoes.

Confined cargo spaces may therefore present unexpected hazards during inspection or maintenance.

Hot Work in Retrofit Projects

Retrofitting ships for new technologies often requires extensive welding and cutting operations.

Hot work can generate hazardous fumes containing:

- metal oxides
- combustion products
- toxic coating residues.

Simultaneous operations may expose workers to cumulative hazards from multiple sources.

7. Chronic Exposure and Psychosocial Factors

Not all health risks arise from acute incidents.

Long-term exposures include:

- noise and vibration
- air pollution
- fatigue

- psychological stress.

Digitalisation and automation are changing shipboard work patterns. Increased monitoring responsibilities and alarm systems can create **cognitive overload and fatigue**.

Mental health challenges among seafarers are increasingly recognised as significant occupational risks.

8. Cross-Cutting Challenges

Several themes emerge across these technologies.

Environmental vs Occupational Trade-offs

Technologies introduced to reduce emissions may introduce new occupational exposures.

Weak Signals

Minor symptoms or unusual odours may indicate emerging risks but are often overlooked.

Real-World Variability

Operational conditions rarely match design assumptions.

Life-Cycle Risk Transfer

Hazards may shift from one phase to another, particularly from operation to recycling.

9. Future Research Needs

Many questions require interdisciplinary research involving engineers, toxicologists, occupational hygienists and human-factors specialists.

Key areas include:

- exposure assessment for new fuels
- battery off-gas behaviour in shipboard environments
- ballast water treatment by-products
- mental health impacts of automated operations.

10. Conclusions

Shipping is entering an era of rapid technological change driven by environmental and operational pressures.

While regulatory frameworks remain essential, compliance alone cannot fully address evolving human-health risks associated with new technologies.

Adopting a **life-cycle perspective** helps identify where exposures may arise and how risks shift across design, construction, operation and recycling stages.

Future maritime innovation must therefore integrate **human health considerations alongside environmental performance and economic efficiency**.

> *Life-Cycle thinking essential to manage hidden maritime hazards*

By proactively addressing these issues, the maritime industry can ensure that the ships of the future are not only cleaner and smarter but also healthier workplaces for the people who build, operate and recycle them.

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Contextual Aspects of IMO Conventions (An Understanding of Concepts)

Vikrant Rai

Abstract

Anyone who follows IMO Conventions would have noted that there are many technical and non-technical words like Oil, ship, owner etc., which have different definitions in different IMO Conventions and sometimes within different chapters of same convention.

This paper is an attempt to understand the philosophies of various conventions while at the same time justifying the need to have different definitions, due the differences in philosophies leading to design of a convention and drafting of regulations.

This paper is part of a book the author intends to write and include following topics:

1. Functioning of International Maritime Organization
2. Philosophies behind Regulations in some key conventions.
3. Definition of Oil and some other key words in various conventions and reasons for the same based on the philosophy of the design of a Convention.

Keywords: IMO Conventions; SOLAS; MARPOL; CLC Convention; Bunker Convention; Definitions in Maritime Law; Polluter Pays Principle; Strict Liability; Marine Pollution; Regulatory Philosophy; Risk-Based Design; Maritime Safety; Environmental Protection; Liability Framework; International Maritime Law

Introduction

International Maritime Organization (IMO) Conventions form the backbone of the global maritime regulatory framework, addressing safety, environmental protection and liability. At first glance, these conventions appear to share a common vocabulary, employing terms such as *oil*, *ship* and *owner* across multiple instruments. However, a closer examination reveals that these terms are often defined differently—not only across different conventions but sometimes even within different chapters of the same convention.

This apparent inconsistency is not accidental; rather, it reflects the underlying philosophies and objectives that shape each convention. IMO instruments are designed with specific regulatory intents—whether it is safety (SOLAS), pollution prevention (MARPOL), or compensation and liability (CLC, Bunker Convention). Consequently, definitions are carefully tailored to align with these intents, ensuring that legal, technical and economic outcomes are both effective and enforceable.

Understanding these contextual definitions is essential for marine professionals, regulators and legal practitioners. It enables correct interpretation of compliance requirements, supports better decision-making and prevents misapplication of regulatory provisions. This paper explores how the design philosophy

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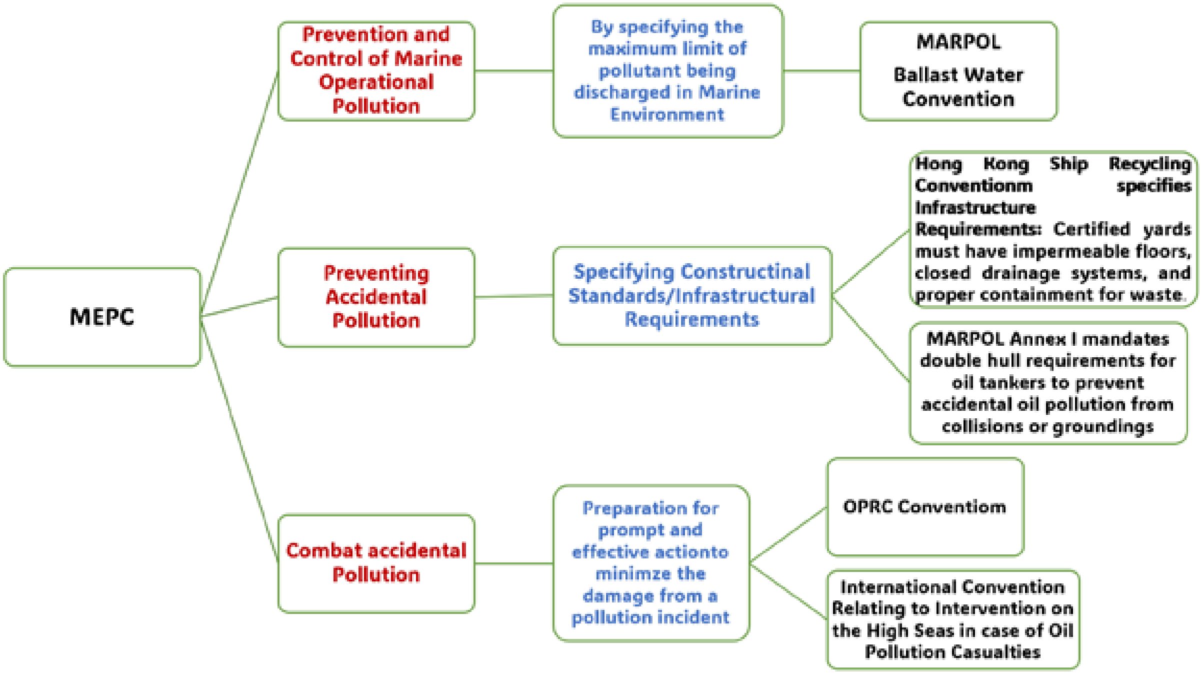
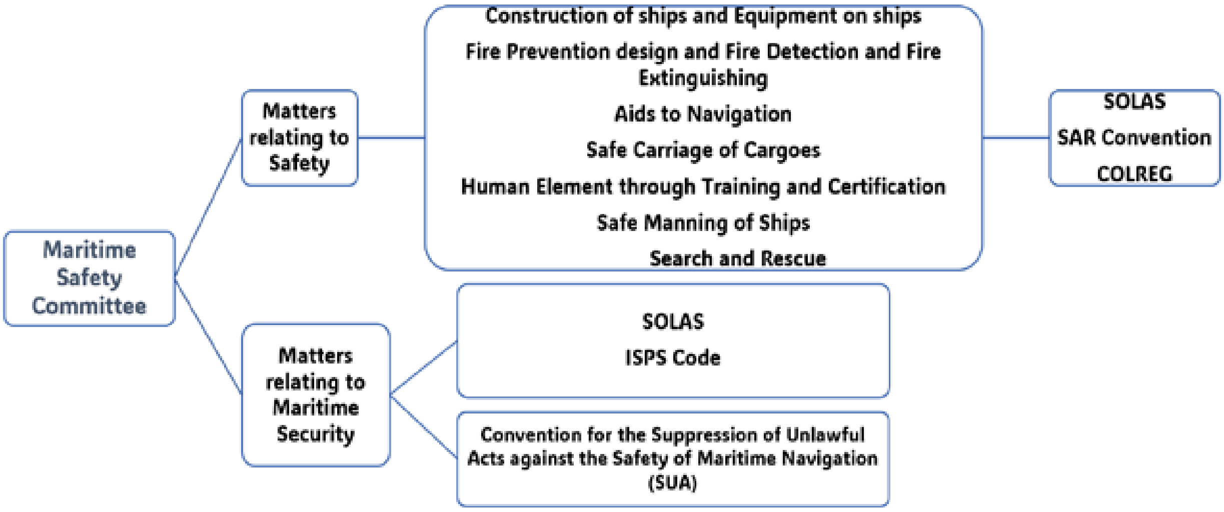
Paper 1: Differently Defined Technical/Non-Technical Words in Different IMO Conventions: **An understanding of the Design of a Convention**

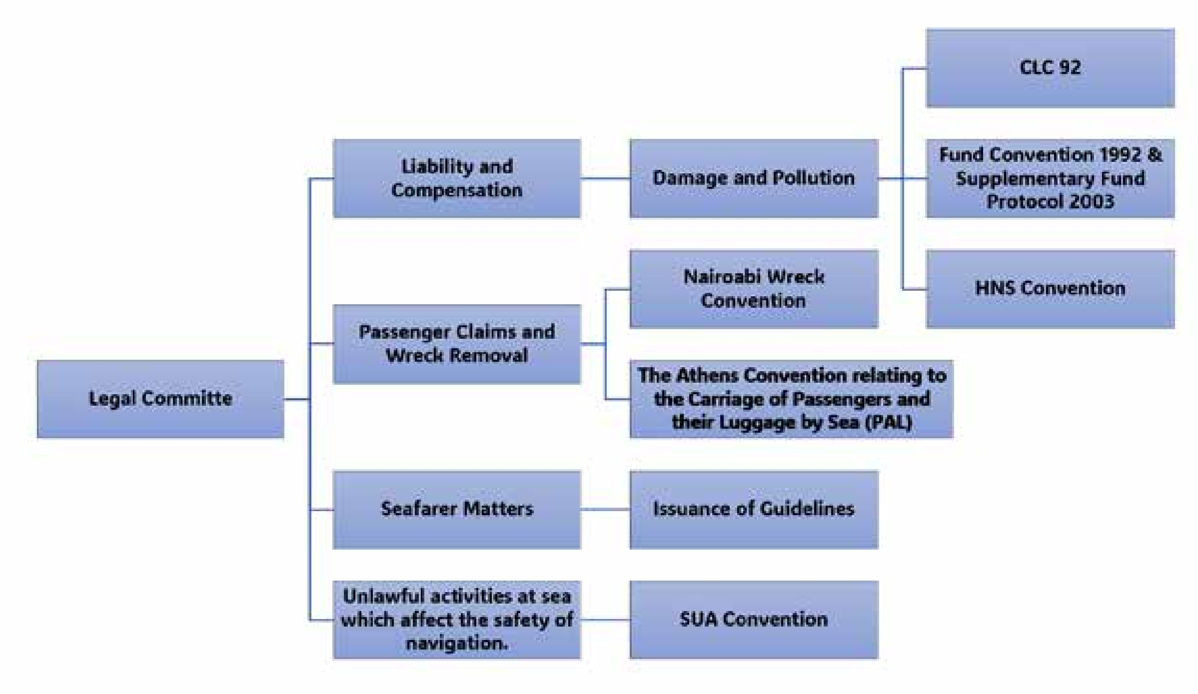
of IMO conventions influences the definition of key terms, demonstrating that variation in terminology is a deliberate and necessary feature of an effective international regulatory system.

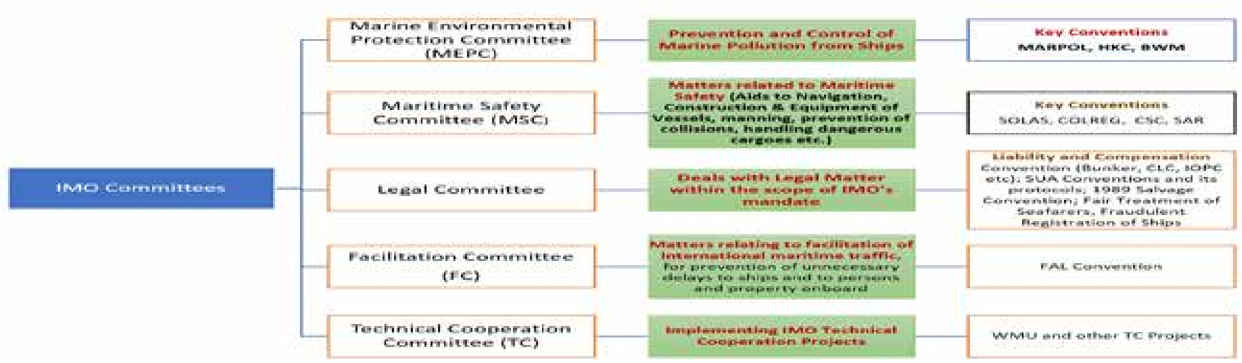
Functioning of International Maritime Organization

The International Maritime Organizations have five main committees dealing with five separate topics as detailed below:









Philosophies behind Regulations in some key conventions

Safety of Life at Sea or SOLAS: The SOLAS presents a safety framework for ships and deals with construction and design of ship from safety perspective. It deals with design of ship to prevent fires and also fight fires effectively in any part of the ship, if necessary, that is when preventive measures and fails and as a last resort to abandon ship speedily and safely and effect rescue if necessary.

Over a period, the SOLAS regulatory approach has shifted from a prescriptive approach to a risk-based, "single-failure" design philosophy, that is, it ensures that the failure of any essential system (machinery, power, or steering) does not result in the loss of the ship.

International Convention on Prevention for Marine Pollution from Ships (MARPOL):

1. MARPOL deals with Marine Pollution through following methodology:

a) It specifies maximum allowed operational pollutants to be released in Marine Environment and thus specifies design standards for equipment (Example NO_x for Diesel engines) and fitment of specialised equipment (Example Oily Water Separator or Sewage Treatment Plant).

b) It also specifies constructional standards to prevent accidental pollution, as an example, all oil tankers delivered from July 6, 1996, are required to have double hulls. Older tankers were phased in to comply with double hull requirements or **Chemical Tankers:** Must comply with the International Bulk Chemical Code (IBC Code) for ships built after July 1, 1986, which dictates tank design, construction and equipment to reduce residual discharge.

> *Same words different meanings across imo conventions explained*

2. **Basically, in accordance with** General Assembly resolution 47/191 **and** Resolution MEPC.67(37) {Guidelines on incorporation of the Precautionary Approach in the Context of Specific IMO Activities}, IMO incorporates a precautionary approach in its decision making. The underlying philosophy of the precautionary approach as set out in Principle 15 of the Rio Declaration and particularly the section on "lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation" could usefully be applied

Liability Conventions {Civil Liability Convention (CLC) 1992: Ensures prompt compensation for victims of oil pollution damage from tankers carrying over 2,000 tons of persistent oil. It imposes strict liability on shipowners, requiring compulsory insurance; **Fund Convention (1992/2003):** Supplements the CLC by providing additional compensation when CLC coverage is inadequate or unavailable. It is funded by contributors (entities receiving over 150,000 tons of crude oil annually); **Bunker Convention (2001):** Covers pollution damage caused by spills of fuel oil (bunkers) from any ship, including non-tankers, over 1,000 gross tonnage (GT). It requires mandatory insurance for owners, mirroring the strict liability regime of the CLC; **Nairobi Wreck Removal Convention (2007):** Provides a legal basis for coastal states to remove hazardous shipwrecks in their exclusive economic zone (EEZ). It mandates shipowners to have insurance for costs associated with locating, marking and removing such wrecks.

The above liability conventions are based on following 4-tier principles:

1) **Polluter Pays Principle:** The polluter pays principle is entrenched in the IMO Liability Conventions. The Polluter pays not only for the accidental damages but also pays for the preventive measures taken to contain the pollution. This principle will be discussed in detail in subsequent paragraphs.
2) **Strict Liability:** The polluter is liable to bear the cost of damages and preventive measures except under certain specific exemptions and which the polluter has to prove in each case that any of such exceptions should in fact operate.

> *Definitions change because regulatory purpose drives convention design*

3) **Limitation of Liability:** The polluter is entitled to limit his liability under these conventions in respect of any one incident to an aggregate amount calculated based on tonnage.
4) **Compulsory Insurance: These conventions often require mandatory insurance via P&I Clubs above a certain threshold limit of prospective pollutant carried by ship; as an example under CLC 92,** ship registered in a Contracting State and carrying more than 2,000 tons of oil in bulk as cargo is required to maintain insurance or other financial security, such as the guarantee of a bank or a certificate delivered by an international compensation fund, in the sums fixed by applying the limits of liability as detailed in Convention to cover his liability for pollution damage under this Convention.

The principle behind various Conventions and Definitions of same terms in Different Conventions

Definition of Oil

SOLAS: Oil fuel is defined in regulation 1 of Annex 1 of the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto. Under MARPOL Annex I, "Oil fuel" is defined as any oil used in connection with the propulsion and auxiliary machinery of the ship, including distillate (gas oil) and residual fuel oils.

Solas details following specific requirements related to oil-fuels to ensure safety:

a) SOLAS regulation II-2/4.2.1 requires that fuel oil used in ships (excluding emergency generators) must have a minimum flash point of 60^0 C to minimise fire and explosion risks in machinery spaces. It requires bunker suppliers to provide a signed declaration ensuring the fuel complies with this minimum 60^0 C requirement.
b) To ensure safety, SOLAS Chapter II-2, details specific requirements with respect to location of fuel oil systems, oil fuel tanks, prevention of over pressure in part of oil fuel system or oil tank and requirements relating to oil fuel piping.
c) Solas defines oil fuel **only in relation to safety due to fuel burned to extract energy/power and it has no other function.**

However, **MARPOL** apart from defining oil in MARPOL Annex I, {"Oil fuel" is defined as any oil used in connection with the propulsion and auxiliary machinery of the ship, including distillate (gas oil) and residual fuel oils, the MARPOL Annex VI defines **oil as** Fuel oil as any fuel delivered to and intended for use on board a ship. **Note here term fuel oil is used for oil**. It provides specific requirement relating to fuel oil supplied to ships and only to prevent pollution from oil burned on ships to get energy/power. These requirements are related to maximum Sulphur content in fuel oil or cause an engine to exceed NO_x emission limits, free from inorganic acid etc. Note that definition is linked to pollution prevention.

The definition of Oil in Liability Conventions:

The **International Convention on Civil Liability for Oil Pollution**

Damage, 1969, renewed in 1992 and often referred to as the **CLC Convention defines oil as**: “Oil” means any persistent hydrocarbon mineral oil such as crude oil, fuel oil, heavy diesel oil and lubricating oil, whether carried on board a ship as cargo or in the bunkers of such a ship.

The International Convention on Civil Liability for Bunker Oil Pollution Damage (2001) defines not oil but Bunker Oil as “Bunker oil” means any hydrocarbon mineral oil, including lubricating oil, used or intended to be used for the operation or propulsion of the ship and any residues of such oil.

The polluter pays principle is entrenched in the IMO Liability Conventions. The Polluter pays not only for the accidental damages but also pays for the preventive measures taken to contain the pollution.

The polluter pay principle is an economic principle and is designed not to punish polluters but to set appropriate signals in place in the economic system so that environmental costs are incorporated in the decision-making process that is internalisation of cost. This use of the Polluter-Pays Principle is to secure economic efficiency and reduce distortions in international trade and investment to a minimum. As a rule, the polluter pays, that is, he is simply the first to pay and he may often pass the cost of pollution on in his prices or share his costs with other potential polluters under insurance schemes or even pass such costs to the person liable for the pollution. In the end, the person who really pays will usually be the consumer or user.

But the question is, who is the polluter?

Various OECD text states that:

- At Community level, the polluter was defined in OECD text 1975(8) as the person who directly or indirectly causes deterioration of the environment or establishes conditions leading to its deterioration. For pollution from an industrial plant, the polluter is the owner of the plant.
- On grounds of economic efficiency and administrative convenience, it is occasionally appropriate to identify the polluter as the economic agent playing a decisive role in the pollution, rather than the agent originating it. Hence a vehicle manufacturer could be deemed the polluter, although pollution results from the vehicle’s use by its owner.
- Doubts as to the identity of the polluter have been clarified in specific cases. With waste, the waste generator can be deemed the polluter even when he has transferred its waste to a third party. In the case of accidental pollution from hazardous installations, OECD has designated the operator.
- It leads to the polluter being identified as the economic agent in the pollution chain with whom it is most efficient to deal in both economic and administrative terms. But difficulties could arise if that agent is not the same for all the various costs to be allocated.

> *IMO conventions designed around intent not uniform terminology*

The fundamental is that no unnecessary cost should be passed on to any person who is not a consumer or end user.

Therefore, the definition of oil, ship and polluter are interlinked in any IMO Liability Conventions.

Let us study each of the conventions one by one:

a) **Civil Liability Convention (CLC)**

“Ship” means any sea-going vessel and seaborne craft of any type whatsoever constructed or adapted for the carriage of oil in bulk as cargo, provided that a ship capable of carrying oil and other cargoes shall be regarded as a ship only when it is actually carrying oil in bulk as cargo and during any voyage following such carriage unless it is proved that it has no residues of such carriage of oil in bulk aboard.

“Owner” means the person or persons registered as the owner of the ship or, in the absence of registration, the person or persons owning the ship. However, in the case of a ship owned by a State and operated by a company which in that State is registered as the ship’s operator, “owner” shall mean such company.

“Oil” means any persistent hydrocarbon mineral oil such as crude oil, fuel oil, heavy diesel oil and lubricating oil, whether carried on board a ship as cargo or in the bunkers of such a ship.

The Convention deals with only persistent oil because non-persistent oil and light products evaporate quickly without any trace when spilled at sea. If non-persistent oils are taken into consideration, the economic angle to polluter pays principle is not justified as carriers of non-persistent oils will have to share the cost of accidental pollution by way of insurance.

The definition of oil is inextricably linked to the ship definition. If two terms are taken together the resulting definition is: Persistent oil, whether carried as cargo or in the fuel tanks of a ship which is any sea going vessel or seaborne craft of any type whatsoever actually carrying oil in bulk as cargo. Logically, in case of damage or pollution, the first point to establish is whether the ship has a cargo of oil. If the answer is no, the oil released from the fuel tanks does not come within the terms of the Convention (Economic justification of polluter pays principle). If the answer is yes, the convention does not distinguish between oil as cargo or oil as fuel to avoid difficulty in distinguishing source of an oil spill.

The third justification of economic efficiency principle is the definition of owner as economic agent. In this case the

> Polluter pays principle, shapes definitions across liability

owner is the ship registered owner as he must internalise the cost while fixing up a charter.

Similarly in the Bunker Liability Convention, the definition of Oil, Ship and Owners is also interlinked to ensure passing of liability to polluter only as can be seen from below:

b) **Bunker Liability Convention 2001**: Similarly in the Bunker Liability Convention, the definition of Oil, Ship and Owners is also interlinked to ensure passing of liability to polluter only.

“Ship” means any seagoing vessel and seaborne craft, of any type whatsoever while “Shipowner” means the owner, including the registered owner, bareboat charterer, manager and operator of the ship. “Bunker oil” means any hydrocarbon mineral oil, including lubricating oil, used or intended to be used for the operation or propulsion of the ship and any residues of such oil.

The strict liability under this convention is on the shipowner and is stated that the ship owner at the time of an incident shall be liable for pollution damage caused by any bunker oil on board or originating from the ship.

It may be noted here that the definition of ship owner in Bunker Convention unlike the registered owner (person or persons owning the ship) in CLC Convention, includes the bareboat charterer, manager and operator of the ship (who may be ISM Manager).This is to ensure correct identification of the polluter at the time of the incident, that is the person responsible for operation of ship at the time of incident.

The International Convention on oil pollution preparedness, response and cooperation, 1990 defines Oil as petroleum in any form including crude oil, fuel oil, sludge, oil refuse and refined products and “Ship” as a vessel of any type whatsoever operating in the marine environment and includes hydrofoil boats, air-cushion vehicles, submersibles and floating craft of any type. The Convention acknowledges that in the event of an oil pollution incident, prompt and effective action is essential to minimise the damage which may result from such an incident and thus emphasises the importance of effective preparation for combating oil pollution incidents. It acknowledges polluter pays principle and requires Ships, offshore units and seaports are to have established emergency plans.

Thus, the definitions should be such that the essence of Conventions is reflected and thus different conventions may have different definitions or within same Convention we may have different definitions of the same word.

Conclusion

The variation in definitions of common terms such as *oil*, *ship* and *owner* across IMO conventions is not a regulatory weakness but a reflection of purposeful design. Each convention is structured around a distinct objective—safety, environmental protection, or liability—and its definitions are aligned accordingly to ensure effectiveness within that domain.

SOLAS focuses on safety and therefore defines oil in terms of its fire risk and operational hazards. MARPOL addresses environmental protection and frames oil in relation to pollution control and emission standards. Liability conventions such as CLC and the Bunker Convention extend definitions further to support economic principles like *polluter pays*, *strict liability* and *compulsory insurance*, ensuring that responsibility is clearly assigned and enforceable.

This contextual approach ensures that conventions remain practical, enforceable and economically rational. It also highlights an important lesson for maritime professionals: regulatory interpretation must always consider the intent and philosophy behind a convention, rather than relying solely on literal definitions.

Ultimately, the diversity in definitions strengthens the IMO framework by enabling precise regulation across complex and varied maritime challenges. A deep understanding of these nuances is therefore essential for effective compliance, sound operational decision-making and robust maritime governance.

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Vikrant Rai is a Marine Mercantile Department (MMD) officer specialising in ship surveys, statutory certification and port state control. With expertise in SOLAS, MARPOL and ISM compliance, he ensures vessel safety, regulatory adherence and maritime operational integrity across Indian shipping operations.

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Mental Health at Sea: Bridging the Gap Between Policy and Practice

Chitra Aravind

Abstract:

Mental health holds critical importance in the maritime field, where seafarers work under demanding conditions that test emotional and psychological resilience. The maritime profession requires individuals to function for prolonged periods in isolated, confined and high-risk environments while managing complex operational responsibilities. Despite their central role in sustaining global trade and logistics, seafarers' mental health has historically remained under-recognised and under-addressed.

This article highlights the critical importance of safeguarding the mental health of seafarers. It not only aims to raise awareness but also advocates for a shift in perspective—from treating mental health as an individual burden to recognising it as an organisational responsibility. By reframing psychological well-being as an essential component of safety and operational excellence rather than a sign of weakness, the article encourages a much-needed change in mindset across maritime stakeholders.

Keywords: Mental health, Seafarers, Psychological well-being, Maritime safety, Fatigue, Leadership, Organisational responsibility, Resilience, Maritime Labour Convention (MLC), Stigma

> *Seafarers work in isolated confined high-risk environments daily*

Introduction

Seafaring is one of the world's oldest and most essential professions, connecting countries, economies and communities across oceans. While technological advancements have transformed ships and navigation systems, the human experience of working at sea continues to involve unique physical, social and psychological challenges. Risk factors affecting health include heat, cold, noise and vibration, multicultural working environments, social isolation, separation from spouses and families, piracy and criminalisation onboard.

These job demands significantly impact both physical and psychological health. Research shows that seafarers experience elevated levels of stress, anxiety, depression, burnout and, in severe cases, suicidal ideation. Work-related stress among seafarers is multidimensional, stemming from physical strain, personal and social challenges, technostress, high job demands and the continuing after-effects of the COVID-19 pandemic. These findings consistently reinforce that seafaring remains one of the most stressful and high-risk occupations globally.

The COVID-19 pandemic further intensified existing stressors. Many seafarers reported reduced well-being, fear while performing duties, inadequate health protection measures, insomnia and depressive symptoms. Studies also indicate that dispositional resilience and workplace support play a critical role in buffering stress and improving job satisfaction.

Conditions such as stress, anxiety, loneliness, depression and fatigue are therefore common yet often overlooked due to stigma or limited mental health awareness. As the maritime industry moves toward safe and sustainable operations, prioritising psychological well-being is as important as ensuring technical and physical safety. Understanding mental health challenges and promoting supportive practices help create healthier, more resilient and more productive crews, ultimately contributing to safer ships and stronger maritime operations.

Stigma of Mental Health Among Seafarers

Mental health stigma within the maritime industry remains a major barrier preventing seafarers from seeking help. Despite increasing awareness, psychological difficulties are frequently viewed as personal weakness rather than legitimate health concerns. The belief that individuals experiencing stress, anxiety, or emotional distress are "not fit for the profession" remains deeply entrenched.

Mental health issues can affect anyone, irrespective of rank, gender, experience, or competence. Having a mental health concern does not make a seafarer weak, unprofessional, or incapable. Breaking stigma begins with awareness and acknowledgment.

Common stigmas observed among seafarers include the belief that real seafarers must always appear strong and resilient, discouraging emotional expression. Fear of job loss or being declared unfit to sail leads many to avoid reporting psychological difficulties. Mental health problems are often perceived as lack of discipline or inability to cope with pressure. Awareness remains low, with mental health often associated only with severe psychiatric disorders.

Cultural and language differences in multinational crews further complicate open discussions. Living and working in close quarters increases fear of judgement or labelling by colleagues. Traditional masculine norms within a male-dominated workforce also discourage vulnerability and help-seeking behaviour.

These stigmas contribute to widespread underreporting of mental health concerns. The absence of reporting should never be mistaken for the absence of problems. Unresolved psychological distress negatively affects performance, safety, decision-making and interpersonal relationships, both onboard and ashore.

Recent Mental Health Statistics Among Seafarers

Research consistently shows that younger seafarers are particularly vulnerable to occupational stress due to limited social support, reduced self-control and challenging work environments. Mental health issues such as stress, anxiety, depression and burnout are widely reported and have a strong impact on safety and job performance.

> *"Mental health historically under-recognised and under-addressed at sea"*

Recent studies document a significant number of diagnosed mental and behavioural disorders among seafarers, with anxiety and depressive disorders being most prevalent. During the pandemic, substantial proportions of seafarers experienced anxiety, depression and post-traumatic stress symptoms.

Simplified findings indicate that approximately one in four seafarers experience depression, one in five experience anxiety, one in five have experienced suicidal thoughts and nearly forty percent report poor sleep or chronic fatigue. These challenges affect not only individuals but also teamwork, safety culture and organisational performance.

Common Mental Health Issues Among Seafarers

Mental health challenges among seafarers are shaped by a unique combination of occupational, environmental and social stressors inherent to life at sea. Long duty hours and insufficient rest contribute significantly to fatigue. Seafarers working six-hours-on/six-hours-off schedules often experience fragmented sleep, averaging around six to seven hours per day. Reports of officers falling asleep during watch underline the seriousness of fatigue-related risks.

Understanding common mental health conditions is essential for early recognition and timely support. Anxiety disorders involve excessive worry, restlessness, difficulty concentrating and sleep disturbances. Depression is characterised by persistent sadness, loss of interest, fatigue and feelings of hopelessness. Post-traumatic stress disorder may follow exposure to traumatic events such as accidents or piracy incidents. Obsessive-compulsive disorder involves intrusive thoughts and repetitive behaviours that interfere with daily functioning.

Recognising early warning signs is critical for prevention and intervention.

Figure 1: Warning Signs of Mental Illness

Who Is Responsible for the Mental Health Status of Seafarers?

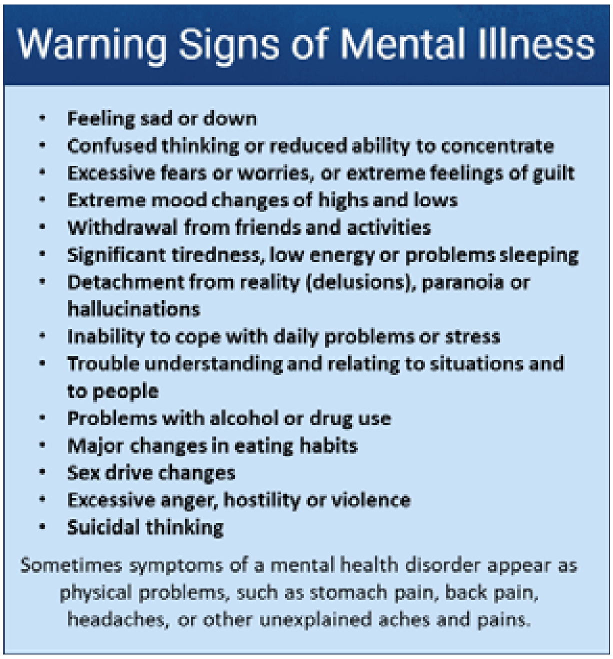
In many professional environments, individuals are often blamed—directly or indirectly—for their mental health difficulties. Support initiatives frequently focus only on strengthening personal resilience, implying that psychological struggles are solely the individual's responsibility. This perspective overlooks the role of job-related and organisational factors.

Mental well-being at sea is shaped by workload, leadership style, living conditions, communication practices, shore support, job security and company culture. Research distinguishes between job demands, such as long hours and time pressure and job resources, including social support and team cohesion.

Irregular schedules extended working hours, unclear roles and inadequate management support are major contributors to stress, particularly among junior seafarers. Ignoring these factors places undue responsibility on individuals while systemic issues remain unaddressed.

Efforts to Address Mental Health of Seafarers

Efforts to improve mental health require both organisational and individual-level interventions. Many maritime companies now provide mental health awareness training, stress management workshops and psychological first-aid programmes. These initiatives help seafarers recognise distress and respond appropriately.



Warning Signs of Mental Illness

- Feeling sad or down
- Confused thinking or reduced ability to concentrate
- Excessive fears or worries, or extreme feelings of guilt
- Extreme mood changes of highs and lows
- Withdrawal from friends and activities
- Significant tiredness, low energy or problems sleeping
- Detachment from reality (delusions), paranoia or hallucinations
- Inability to cope with daily problems or stress
- Trouble understanding and relating to situations and to people
- Problems with alcohol or drug use
- Major changes in eating habits
- Sex drive changes
- Excessive anger, hostility or violence
- Suicidal thinking

Sometimes symptoms of a mental health disorder appear as physical problems, such as stomach pain, back pain, headaches, or other unexplained aches and pains.

Figure 2: Seafarer on Work Environment

Figure 3: Crew Social Interaction Onboard

Improved internet access enables communication with family, reducing loneliness. Ethical implementation of the Maritime Labour Convention plays a critical role when applied as a genuine commitment rather than a compliance formality. Structured rest periods and adherence to work-rest regulations help prevent chronic fatigue.

Wellness policies may include confidential counselling services, peer-support programmes, mental health applications, fitness routines and leadership development initiatives. Mental health screening prior to onboarding, although still limited, represents an important step toward proactive support.

Individual Coping Strategies Used by Seafarers

Seafarers also adopt individual coping strategies to manage stress. Building trust and social support among crew members reduces isolation. Regular physical activity supports emotional balance and improves sleep. Maintaining routines creates predictability in demanding environments.

Relaxation and mindfulness practices such as breathing exercises, meditation, journaling, or prayer help manage anxiety. Engaging in hobbies supports emotional balance and personal identity.

Digital solutions such as tele-counselling and online therapy increasingly bridge the gap between seafarers and mental health professionals while at sea.

Role of Leadership in Shaping the Mental Health of Seafarers

Leadership plays a central role in shaping mental health onboard. Empathetic, fair and supportive leaders foster psychological safety, reduce stress and improve morale. Poor management and lack of social support are major contributors to mental ill-health, while transformational and authentic leadership styles act as protective factors.

> *Seafaring remains one of most stressful occupations globally*

Effective leaders identify immediate needs, provide emotional support, respect cultural practices, address bullying and harassment, promote self-care and foster no-stigma cultures. Compassionate leadership is both a human and strategic asset.

Is Investing in Mental Health a Trade-Off?

Mental health is often perceived as a trade-off against cost, efficiency, or discipline. In practice, organisations may fear that welfare initiatives slow operations or increase expenses. However, evidence shows this belief is unfounded.

Mental health is a multiplier, not a trade-off. Investment in psychological well-being leads to improved safety, productivity, retention, morale and organisational reputation. Job satisfaction drives performance, not the other way around.

Conclusion

A psychologically supportive maritime organisation fosters openness, fairness and respect. Accessible mental health services, adequate rest, safe living conditions, effective communication and strong leadership create resilient crews capable of performing safely and effectively.

True and sustainable change must originate from leadership. Moving beyond stigma and superficial compliance toward genuine care is essential. Mental health is not a liability but a responsibility and strength. When maritime organisations invest in the psychological well-being of seafarers, the benefits extend to safety, sustainability and long-term success across the industry.

About the Author

Dr. Chitra Aravind is a consultant psychologist and founder of Manas, specialising in seafarer mental health, leadership, resilience, organisational behaviour, training, counselling and policy-practice integration with global maritime focus expertise.

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- Demo of Auto Tuning of a PID Digital Controller to a given process
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Invisible Killers: Diagnostic Investigation of Hidden Fuel System Defects Leading to Loss of Propulsion

Marine Engineering Accident Investigation Series – MER

Gajanan Karanjikar

1. When the ship keeps moving... until it suddenly doesn't

In U.S. waters today, **blackouts and loss of propulsion are treated as near-fatal sins**. After several high-profile incidents where large vessels lost power or propulsion in confined channels—one of them leading to a catastrophic bridge collapse with multiple fatalities—regulators, pilots, insurers and port authorities have become extremely alert to anything that even *smells* like unstable power or unreliable engines.

When a ship suddenly loses propulsion in a narrow river, under a bridge, or near critical infrastructure, it isn't "just" a technical problem. It is an event that can shut down a major port, block a trade artery, cause loss of life and trigger claims that reach into the billions of dollars. In many of these cases, the root causes sit quietly inside the **fuel oil system**: unseen contamination, sticky fuel pumps, misbehaving control valves, or vapour lock in poorly designed or poorly managed lines. These are the **invisible killers** of reliability.

This article explores how hidden fuel system defects can lead to loss of propulsion and how marine engineers and investigators can use **systematic diagnostic and fault-tree analysis** to uncover them. Along the way, we touch on relevant codes and conventions and the serious legal and financial consequences that follow when propulsion fails at the wrong moment.

2. The deceptive simplicity of "fuel in – power out"

On paper, the main engine fuel system looks straightforward: storage tanks, settling and service tanks, heaters, filters, supply pumps, booster pumps, viscosity control, fine filtration, then high-pressure fuel pumps delivering precisely metered fuel to injectors. In practice, this chain is full of vulnerable points:

- Tank design and management (stratification, water and sludge layers)
- Heater and viscosity control performance
- Filter loading and bypass arrangements
- Booster pump NPSH margins and suction conditions
- Control valves and change-over arrangements for different fuel grades
- Local line arrangements where vapour pockets can form

Most of the time, the system "works" – until it doesn't. The danger lies in the fact that **many defects are intermittent**, appearing only under certain combinations of load, temperature, sea state or manoeuvring pattern. The engine seems fine in deep sea, but falters precisely when the ship slows down, changes fuel, starts a thruster, or begins critical pilotage.

> *Contamination remains the classic invisible killer in fuel*

Vapour lock creates failures without visible physical damage

3. Fuel pump failures: when the heart misses a beat

High-pressure fuel pumps are the **hearts** of a conventional two-stroke engine. Failure can be sudden (plunger seizure, cam follower damage) or progressive (wear leading to reduced delivery). For investigators, important questions include:

- Was there **abnormal wear** or scuffing on plungers and barrels, possibly linked to poor lubrication properties of the fuel or contaminated lube oil in the cam area?
- Did any pumps show signs of **sticky delivery valves** or sticking racks in electronically controlled systems?
- Was there evidence of **uneven injection** across cylinders – one or two units running weak, causing instability at low load?

A recurring real-world pattern is the **combination of marginal fuel quality and marginal maintenance**. Poor cleanliness, high cat-fine content, or unstable blends can accelerate wear of precision parts. At the same time, extended running between overhauls and pressure to minimise downtime mean pumps are stretched just a bit beyond their comfort limit.

In accident investigation, the challenge is often that, by the time the engine has stopped in a dangerous place, the immediate symptoms (low power, hunting rpm) have been overshadowed by emergency actions. Careful teardown and **comparative analysis of all units** – not just the one that failed spectacularly – is essential.

4. Control valves: the small components with big authority

Fuel system control valves—automatic change-over valves, pressure-control valves, temperature control valves, constant-pressure valves—are often **underestimated** because of their size. Yet they decide:

- Which fuel the engine is actually receiving
- At what pressure
- At what temperature and viscosity

A sticking change-over valve during low-sulphur / high-sulphur transitions can partially cut off supply, or allow air ingress. A mis-set or internally damaged pressure-control valve can cause delivery pressure collapse just when the engine demands more fuel for manoeuvring.

From an investigative standpoint, it's vital to:

- Benchmark actual settings against the **as-commissioned data** and maker's recommendations.
- Check for evidence of **manual tweaking** over time to "solve" other problems (e.g. filters clogging).
- Test valves on a bench where possible, simulating real flow and differential pressures.

Too often, reports simply note "fuel pressure low" without asking *why* the controlling hardware behaved as it did. In complex incidents, it's the **logic of valves and their interactions**—not just the main pumps—that tells the story.

5. Contamination: the quiet saboteur

Fuel contamination is the classic invisible killer. The bunker delivery note may look respectable, but the reality in the service tank can be very different. Common issues include:

- **Water ingress** from tank top leaks, condensation, or poor bunker handling
- **Cat-fines** (aluminium and silicon) that erode pumps and injectors
- **Unstable blends**, where asphaltenes separate, forming sludge
- Contamination with **non-conventional components** that affect ignition or viscosity behaviour

Contaminated fuel can cause:

- Filter clogging and sudden differential pressure surges
- Pump cavitation or wear
- Misfiring, cylinder knocking, or inability to maintain load
- Complete engine stop if filters block faster than the crew can respond

In US waters and elsewhere, investigators will examine **fuel samples taken before and after onboard treatment**, review bunker documentation, look at centrifuge operating data and sludge production trends and inspect filters and strainers for the type and distribution of deposits.

Liability can become complex: if a proven off-spec fuel contributed materially to loss of propulsion, claims can extend to fuel suppliers and charterers. However, owners remain under a duty to operate **proper treatment**

systems and change filters proactively, so any sign of complacency in fuel management weakens their position.

6. Vapour lock: the enemy you can't see

Vapour lock in fuel systems is especially insidious because it may not leave clear physical damage behind. It occurs when **fuel flashes into vapour** in suction lines, booster pump inlets, or high-point pockets due to:

- Excessive heating (especially close to or above boiling points under low pressure)
- Low suction head and poor NPSH margins
- Sudden changes in backpressure or flow when valves change position
- Inadequate venting of high points

In operation, vapour lock manifests as:

- Fluctuating pressure at the booster pump discharge
- Irregular engine speed and unstable combustion
- Eventual fuel starvation and loss of power, often during manoeuvring or change of mode

Because pumps and filters may appear "clean" upon later inspection, vapour-lock events are sometimes misdiagnosed as "mysterious trips" or blamed on electronics.

A disciplined investigator will:

- Map the actual fuel system piping arrangement, including **vertical runs and high points**.
- Check pump NPSH requirements against **real suction conditions** (tank level, temperature, line pressure losses).
- Review event data: temperatures in service lines, filter differentials, pressure trends leading up to the failure.

Prevention requires both sound design (adequate head, proper routing, vents and drains) and operational discipline (controlling temperature rise, especially during fuel grade change-over).

7. Fault-tree analysis: turning confusion into evidence

When you lose propulsion at a critical moment, the number of possible causes can feel overwhelming. That's where **fault-tree analysis (FTA)** becomes a powerful tool:

1. Start with the **top event**: loss of propulsion (or loss of required rpm) at a specific time.
2. Break it down into logical branches: loss of fuel, loss of air, loss of control signal, mechanical seizure, protection trip.
3. Under "loss of fuel", build sub-branches: supply pressure low, pump failure, vapour lock, filter blockage, valve malfunction, fuel quality.
4. For each branch, test against actual evidence:
   - o Was pressure low? If yes, where?
   - o Did filters show sudden loading?
   - o Were alarms consistent with air in system (fluctuating pressures)?
   - o Were control valves in the expected positions?
   - o Does metallurgical evidence match a sudden or gradual failure?

This structured approach helps avoid **anchoring bias** ("we had a pump failure, so it must be the pump again") and ensures all plausible causes are checked against data. It also produces a clearer narrative for flag States, USCG, class and courts: a transparent explanation of how the conclusion was reached.

In US waters especially, where post-casualty scrutiny is intense, a well-documented fault tree and evidence matrix can be the difference between a credible technical defence and an impression of guesswork.

8. Codes, conventions and the regulatory lens

Several international instruments shape how loss of propulsion and fuel-related failures are judged:

- **SOLAS Chapter II-1** – requires reliable propulsion and steering, safe machinery installations and arrangements to minimise the risk of total loss of power. Deficiencies in fuel system design or maintenance may be seen as breaches of this general obligation.
- **SOLAS Chapter IX (ISM Code)** – obliges the company to have procedures for safe operation, maintenance of critical equipment, reporting non-conformities and analysing incidents and near misses. Repeated fuel-related engine problems with no root-cause analysis point to ISM failures.
- **SOLAS Chapter V** – on safety of navigation, comes into play when loss of propulsion or blackout leads to grounding or collision in restricted waters.
- **Classification society rules** – specify design criteria for fuel systems, material selection, redundancy and testing. Significant deviations or undocumented modifications weaken the owner's position.
- **U.S. regulations (e.g. 46 CFR, 33 CFR)** and USCG guidance – set expectations for propulsion reliability, reporting of marine casualties and potential enforcement actions in U.S. waters.

Fuel system integrity must be treated as safety critical

Investigators and legal teams will examine whether the owner exercised **due diligence** in design, operation and maintenance of the fuel system, or whether systemic gaps in the Safety Management System contributed to the casualty.

9. Legal and financial consequences: when hidden defects become very visible

When a fuel system defect leads to loss of propulsion in a critical area—say, in a busy river, under a bridge, or near a berth—the consequences can cascade:

- **Direct costs**: emergency tugs, salvage services, repairs to engine and fuel system, dry-docking.
- **Third-party damage**: collision damage to other ships, impact to piers, dolphins, bridges or other infrastructure.
- **Port and channel disruption**: closure of waterways, with claims from terminals, port authorities and cargo interests for delay and lost revenue.
- **Pollution and environmental liability**: if the incident leads to grounding, hull damage or bunker release.
- **Off-hire and loss of earnings**: the vessel will almost certainly be off-hire during repair and investigation and charterers may seek additional damages.
- **Reputational and regulatory impact**: increased inspection by port State control, tougher terms from insurers, reputational risk with charterers and terminals.

In recent US cases, blackouts and propulsion loss have prompted **criminal investigations**, congressional scrutiny and intense media coverage. Even if the ultimate cause lies in a technical detail inside the fuel system, the wider narrative is often about **seaworthiness, corporate culture and safety management**.

Owners who can show a robust record of fuel management, proactive maintenance, serious treatment of earlier fuel-related incidents and structured engineering analysis are much better placed than those whose logs show repeated "mysterious trips" with no follow-up.

10. Conclusion: making the invisible visible

Hidden fuel system defects are true **invisible killers** of reliability. They rarely leave big clues until the moment they cause a slowdown, a trip or a complete loss of propulsion. In today's regulatory and commercial environment—particularly in U.S. waters—such events are no longer tolerated as "one of those things that happen with ships".

For marine engineers and investigators, the way forward is clear:

- Look beyond the obvious components and examine **fuel pumps, control valves, contamination patterns and line arrangements** in detail.
- Use **fault-tree analysis** to structure the investigation and defend your conclusions.
- Treat fuel system integrity as **safety-critical**, not merely an efficiency issue.
- Feed every incident and near-miss back into design and procedures across the fleet, as the ISM Code intends.

If we learn to see these invisible killers early—through data, disciplined diagnostics and a questioning mindset—then many future blackouts and propulsion losses will never happen. The ship will continue to move, quietly and safely and the world will never know how close it came to drifting out of control.

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About the Author

Capt. Gajanan Karanjikar is a Master Mariner, marine surveyor and US-based casualty investigator. He has spent decades at sea and ashore commanding vessels, mentoring officers and advising owners, insurers and regulators. His work spans shipboard command, technical surveys, flag state and class compliance and post-casualty investigations. A firm advocate of safety culture and professional seamanship, he combines traditional maritime instincts with modern forensic techniques to help the industry learn quickly and honestly from its most challenging days.

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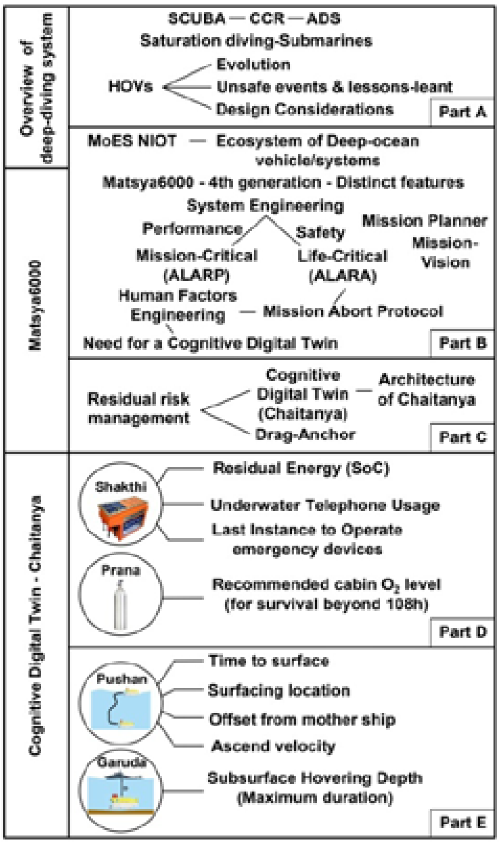
Cognitive Digital Twin “Chaitanya” for India’s Deep-Ocean Human Submersible Matsya6000-Part B

N. Vedachalam, V. Bala Naga Jyothi,
D. Sathianarayanan, S Ramesh, R. Balaji

Introduction

Safety is the key requirement for human scientific submersibles operating in challenging deep-ocean environments. Even-though adequate hardware and software redundancies are built-in for mission-critical systems, and standards for human-rating are followed to ensure the on-demand reliability of life-critical systems in Matsya6000, unforeseen emergency situations could result in cognitive incapacitation of the crew, leading to human errors. This four-part article reports the development of first-of-its-kind AI-powered Situation-aware Cognitive Digital Twin (CDT) “Chaitanya” that co-exists with Matsya6000. It comprises of 14 complex coupled-models (of numerical, data-driven and machine-learnt types) involving interactions between engineering systems, crew physiologies, human cabin micro-climate and ocean environment. Chaitanya updated with essential sensory information in real-time, simulates 15 hard-to-predict scenarios “ahead-of-time” supporting Matsya crew by redefining protocols that are optimal for their survival during the emergency period. This (second) part describes the challenges in the system engineering design of HOVs and safety-centered design of life-critical systems of Matsya6000.

> *Safety is key requirement for human scientific submersibles*



System Engineering Design of HOVs

The overview of a deep-water HOV is shown in **Figure.1** Pressure-rated personnel sphere for human occupancy (human cabin) equipped with an entry hatch and acrylic view ports, house systems required for control of HOV, communication aids and life-support systems required for the crew. Penetrators enable electro-optic communication between the human cabin and exostructure systems. Propulsion system comprises of batteries and thrusters to enable the vehicle maneuverability in multiple degrees of freedom, variable buoyancy enabling systems comprising of pumps and compressed air bottles for descend and ascend operations, navigation systems for position determination and safe vehicle maneuvering, Ship-HOV communication and data telemetry systems, manipulator arms to perform tasks, Titanium exostructure covered with hydrodynamic fairing, emergency surfacing systems, entanglement release and emergency recovery systems.

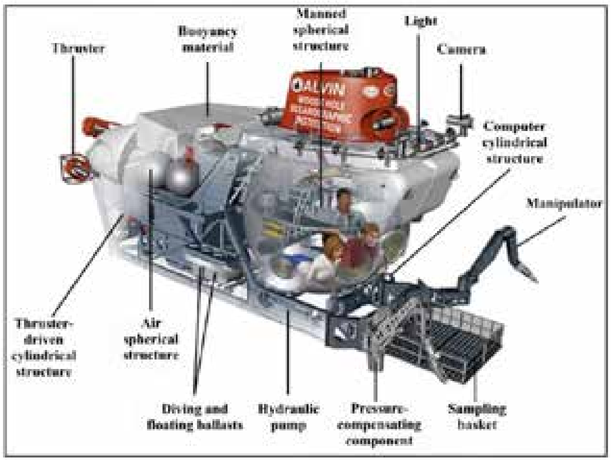


Figure.1. Subsystems of a HOV Alvin

System engineering of HOV has to address the key operational challenges including human cabin water-tight integrity, reliability of the human cabin life-support systems, navigation system accuracy, reliable ship-HOV communication, collision avoidance with forward objects and avoiding manipulator entanglement with ocean-floor objects. Safe launching and retrieval of the deep-water HOV in the dynamic offshore environment is a major challenge. Due to the limited battery endurance and the life-support systems, the HOV is normally taken on-board the mother ship (MOSHIP) to the deployment location. Once the HOV is launched on the sea surface, the HOV shall be off-hooked from deployment slings by the divers. Once it surfaces after the mission, the slings shall be hooked to the HOV for retrieval back into the MOSHIP. The design of these systems has to consider the dynamic loads during various sea states. As a Design Vs Operational trade-off, deep-water battery-powered HOVs (weighing ~20t carrying three persons in a titanium alloy human cabin of ~2m diameter with human life-support systems) support 12-18h of mission (maneuvering with 3 knots speed for 4h) and 96h during emergency.

The International Association for Classification Societies (IACS) provide clear guidelines for the design of HOV including the structural design of the human cabin, hydrostatic stability, human cabin life support systems (during a normal operating period of 12h and emergency endurance of 96h), emergency power supply, communication between the HOV and deployment vessel, emergency drop weight systems during unavailability of the service drop weights, emergency jettisoning systems for enabling ascent of during loss of vehicle buoyancy or entanglement with the sea floor objects and procedures for emergency retrieval of the stranded HOV from the deep-ocean using ship-based drag anchor.

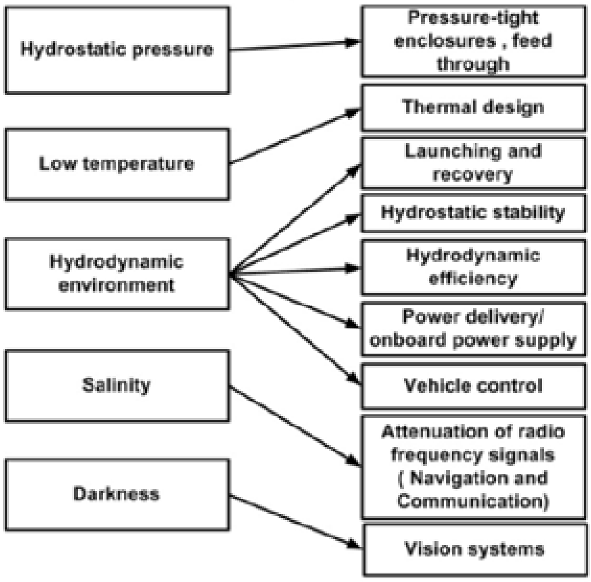


Figure.2. Challenges in realising deep-ocean HOV

Hydrostatic pressure

The challenges in the design of the HOV operating in the harsh deep-ocean environment are mapped in **Figure.2.** The thickness of the pressure-rated enclosures used in HOV (to house humans and electronic systems) should be sufficient to overcome these axial and circumferential stresses caused by the crushing external hydrostatic pressures (eg.606bar at 6000m water-depth). The design and fabrication of the pressure-rated enclosures should consider the operating ambient temperature variations, shape, dimensions and weight limitations, material of construction, fabrication properties, creep properties under external hydrostatic pressure, cyclic pressurising effects, collapse strength, elastic-plastic behavior, internal heat dissipation requirements, corrosion allowance and adequate factor of safety. The design of the spherical human cabin is carried out based on the design rules of IACS agencies such that the overall out-of-roundness (OOR) < 1 % of the nominal inside diameter and local shell tolerance of < 0.5% of the nominal outside radius, else it poses penalty on increased overall shell thickness and weight. The thickness of human cabin of HOVs built using Ti-alloy is summarised in **Table.1.**

Table 1.Thickness of the human cabin of HOVs

Inner diameter	Diving Depth	Thickness
2.1m	6000m	73-78mm
1.5m	11000m	90mm
1.8m	11000m	120mm

Low temperature and humidity

In order to protect from sea water, HOV's electrical and electronic systems are housed inside nitrogen-filled pressure-rated enclosures and mounted on the exostructure. These internal systems produce heat resulting in the increase of temperature inside the enclosure. The electronic systems are sensitive to temperature and thermal cycling. Based on the Failure-In-Time Determination for Electronic Systems (FIDES) standard, the failure rate of a microcomputer increases from 1000 FIT at 10ºC to 9000FIT at 60ºC. The design of the thermal management system should consider the temperature of the external sea water, fluid velocity, thickness of the enclosure, thermal conductivity of the enclosure material, characteristics of the internal heat sources, quantity of heat to be dissipated, heat flux density and the heat dissipation surface availability. As the static nitrogen medium is a poor conductor of heat, the heat transfer between the power electronic devices and electronic circuit boards heat sinks are enhanced by fixing the heat sinks directly on the internal walls of the enclosure so that the heat is exchanged to the external sea water. The circulating fans help to reduce the hot spot temperature by convectively spreading the heat and mobilising it to the cooler enclosure internal surfaces. Computational fluid dynamics analysis is used to optimise the thermal design. The presence of humidity inside the enclosures leads to condensation of water vapour on the relatively cooler parts of the enclosure. The increase in the relative humidity due to the moisture released by the human perspiration is to be managed with active dehumidification systems based on the guidelines of IACS.

Hydrostatic Stability

The surface and submerged stabilities are the key requirements for safe operation of HOVs. In the surfaced condition, the metacentric height, which is the distance between the centre of gravity (CG) of the HOV and its metacenter is important. A larger metacentric height implies greater initial stability against overturning.In the submerged condition, to be stable in the roll axis, known as transverse stability, the centre of buoyancy (CB) must be above the CG.As represented in **Figure.3,** when the HOV is heeled by a small angle, the hydrostatic moment should cause it to return to the upright condition. If the CG is above CB, the hydrostatic moment tends to topple the HOV. Thus the measure of transverse stability is determined by the distance BG and should be positive.

The buoyancy and the stability of the HOV are managed using syntactic foam for fixed ballast, main ballast tank, variable ballast tank and trim weights, which are located in the exostructure. Main ballast tanks allow major adjustment of the vehicle weight enabling it to operate submerged and on the water surface. The variable ballast tank helps to achieve fine weight adjustments during buoyancy variations due to water salinity, which varies 2.8% over 6000m range, and when the submersible picks up scientific samples from the sea floor. If the materials used in the construction of the HOV do not compress at the same rate, the buoyancy of the HOV changes substantially as it descends, which decides the thrust power requirements when operating in deep waters.

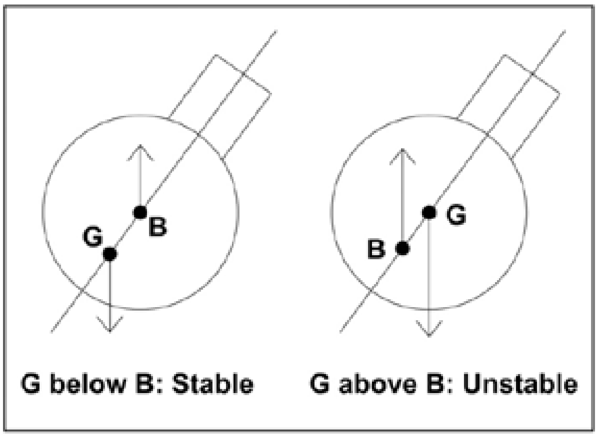


Figure.3. Hydrostatic stability for HOV

Hydrodynamics and Vehicle Control

Precise vehicle attitude control is essential to carry out effective seabed mapping and physical interventions. When operated in the ocean environment, the HOV experiences hydrodynamic forces (kinetics) resulting in changes in the vehicle attitude (kinematics). The HOV attitude is represented in 6 degrees of freedom (DoF) including surge, sway and heave in linear orientation, and pitch, roll and heading/yaw (also called Euler angles) in the angular orientation. To maintain the HOV attitude during the action of the external forces and moments, equivalent counter forces and moments have to be generated by the vehicle actuators, such as thrusters in the respective DOF. Hydrodynamic analysis has to be carried out to estimate the power requirements for attitude control and for vehicle propulsion at the desired speed in multiple DoF during various sea states and water currents. The added mass is an important component due to the effect of forces and moments caused by the acceleration of the fluid around the HOV.

The precision of the vehicle attitude control depends on the accuracy of the identified hydrodynamic parameters of the vehicle. The drag force and the added mass coefficients in multiple DOF are normally determined using the scaled-down model tests and by numerical models based on the Navier-Stokes and continuity equations. In the David-Taylor model basin approach, which is based on the force-response principle, the hydrodynamic parameters are determined by the HOV thrusters and precision vehicle on-board attitude and acceleration measurement sensors. The drag force coefficients are identified from the thrust force required for moving the vehicle at a constant velocity. The identified parameters allow the control system to precisely manage movement, predict motion, and compensate for environmental disturbances, thereby implementing auto-depth, auto-heading and automatic position keeping functions.

Navigation and positioning

The precision of the underwater position data determines the navigation, control and longevity of the HOV used for complex subsea operations. As the terrestrial Global Positioning System (GPS) signals are attenuated by the saline seawater, deep-ocean HOV are equipped with the navigation system **(Figure.4)** comprising high precision Fibre Optic Gyro (FOG) or Ring Laser Gyro (RLG)-based Inertial Navigation Systems (INS) aided by a Doppler Velocity Log (DVL) and acoustic base line positioning systems (APoS).

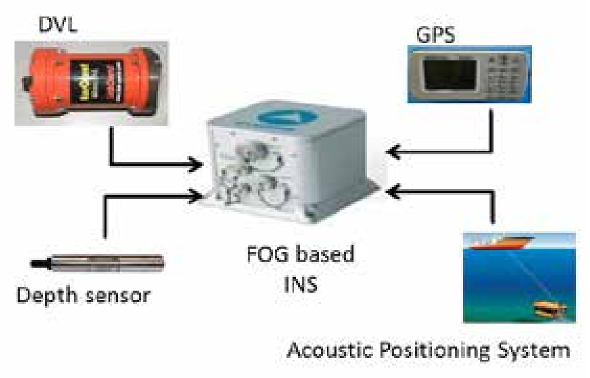


Figure.4. Architecture of aided- inertial navigation system

The navigation system initialised with the position input from an external GPS works in a dead reckoning (DR) mode during the underwater mission. In the DR mode, the navigational algorithm estimates the current position based on the inputs from the navigation sensor suite and the last known or computed position. The position is updated from the inputs from the APoS. The DR algorithm uses the tuned Kalman filter to estimate the current position along with their uncertainties during sensor outages. The DVL and the accelerometers mounted on the vehicle frame measures the vehicle velocity and accelerations, respectively, in the body frame (BF) coordinates. The measured (BF) velocity is transformed to navigation frame velocity resolved in the North and East directions to compute the position of the vehicle with respect to the navigation frame.

With the present technological trend with gyroscope having a bias stability of 0.0035°/h and with the DVL in the bottom tracking and water tracking modes, it is possible to achieve position accuracies of better than 0.5 and 1.8% of the distance travelled, respectively. The position accuracy of the DVL-aided INS could be improved using the APoS. Based on the distance between the transceivers, APoS are classified into Ultra-short baseline (USBL), Short base line (SSBL) and Long base line (LBL) systems. The principle of the USBL system in which the position of the HOV with respect to the deployment vessel is computed based on the measured slant range and bearing angle is shown in **Figure.5.**

> *Unforeseen emergencies can cause cognitive incapacitation of crew*

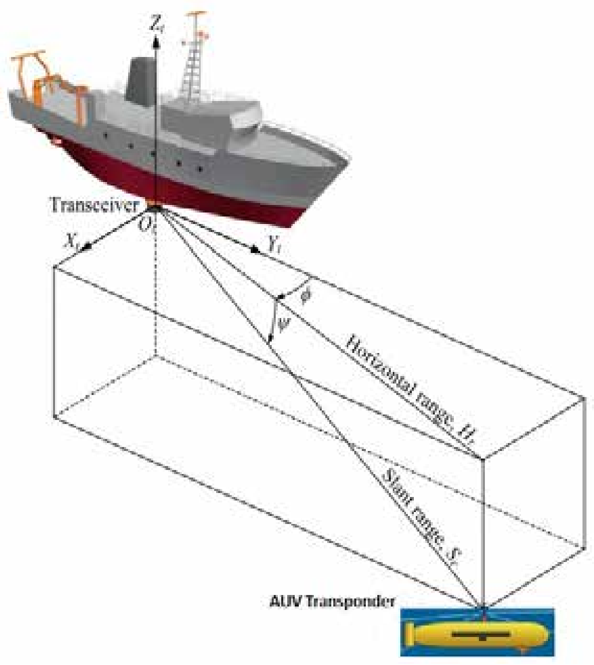


Figure.5. Position computation of HOV using APoS

HOV-MOSHIP communication

An Underwater Acoustic Telephone (UAT) is an important component of HOV. According to IACS rules, periodic voice communication (every 15min) between the HOV and MOSHIP is essential to ensure the health of the crew and HOV. In the absence of voice communication, the HOV shall initiate the ascent to the surface. Influenced by the sea water attenuation, multiple reflections and the influence of temperature and salinity variations with depth, the operational slant range of present UATs are limited to 12kms slant range for an electrical power of 300W. During 90's phase shift keying (PSK) and quadrature amplitude modulation (QAM) were used as they offered more bits/sec per Hz of occupied bandwidth, but required a receiver that can track the channel and compensate for the time-varying multipath and phase distortion (coherent detection).

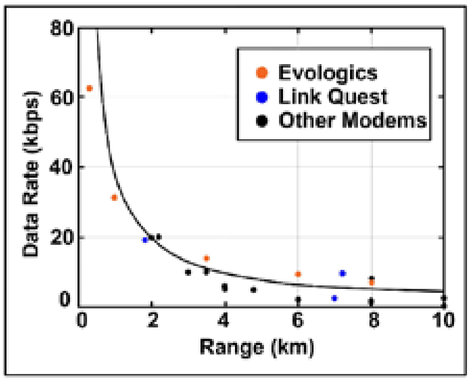


Figure.6. HOV slant range Vs achieved telemetry data rates

> *AI-powered cognitive digital twin supports crew survival decisions*

Recent acoustic telemetry modems with hemispherical beam patterns and optimised for vertical and slant channels operating in 4-14 kHz range offer adaptive communication data rates of ~6 kbps up to 12km **(Figure.6).**

Launching, recovery and emergency support

Safe launching and recovery of HOV in the dynamic offshore environment is a major challenge. The launching and recovery of the HOV are done using human-riding aft A-Frames, port/star-board located cranes and in the moon pool of the deployment vessel. Once it is launched in the sea surface, the HOV shall be off-hooked from deployment slings by the divers, and when its surfaces, the slings have to be hooked to the HOV for recovery back into the deployment vessel. The reliability of the deployment vessel dynamic positioning system handling winch, ship board communication systems and emergency support systems are essential, as the occupants needs to be rescued before the life-support system gets exhausted.

MoES-NIOT HOV Samudrayaan-Matsya6000

As explained in the first part of this article, HOV's enable researchers to directly observe and interact with the deep-ocean environment that are difficult to achieve using remotely-operated and autonomous vehicles. Their ability to support nuanced judgments during complex deep-sea missions in real-time, have led to numerous ground-breaking discoveries, such as the discovery of the hydrothermal vents, investigation of shipwrecks including Titanic, exploration of the Mariana Trench, ocean-floor geology and minerals, and discovery of chemosynthetic life in the hadal-depth environments. Subsequent to the bathyscaphe Trieste that descended up to 10900min the Mariana Trench in 1960, 1st generation human scientific submersible Alvin was developed in 1964. The 2nd generation human scientific submersibles (Nautile6000, Shinkai6500, MIR6000, RUS6000, Consul6000 and Jaiolong) developed during 1970-2010 featured higher operational range and energy efficiency. The 3rd generation hadal-depth submersibles developed over the period 2012-2023 (Deep Sea Challenger, Triton and Fendouzhe) pushed technological boundaries to unprecedented levels.

Under the Deep Ocean Mission, a key component of the Blue Economy initiative by the Government of India, Ministry of Earth Sciences-National Institute of Ocean Technology (MoES-NIOT) is indigenously developing a state-of-the-art deep-ocean battery-powered human scientific submersible Matsya6000. The submersible is designed to carry 3 humans up to 6000m water depth on a 12h mission, and capable of supporting 96h of emergency. The mission-critical systems (MCS) of Matsya are qualified as a part of harbor wet-tests during Jan and Feb-25 **(Figure.7).** Preparations are underway in validating her life-critical systems (LCS) and demonstrating her functionality in shallow waters during 2026. Distinct features (for increased human safety and reliable performance) including welded Ti-alloy exostructure, 80mm thick electron beam welded Ti-alloy human cabin (HC), on-board pressure-balanced oil-filled Li-Po batteries, redundant power, control, communication and positioning system architecture, human-rated emergency drop-weight system "Rakshan", drag-anchor based rapid locate and rescue system " Apath Bandu", AI-enabled real-time crew health monitoring "Dhanvantari", subsurface hovering capability and the "Situation-aware" Cognitive Digital Twin (CDT) identifies Matsya6000 as the 4th generation deep-ocean human scientific submersible.

Figure.7. Matsya6000 undergoing qualification test in harbor

Safety-centred System Engineering of Matsya6000

Ensuring crew safety and reliable performance of Matsya6000 operating in extreme deep-water environments, characterised by high hydrostatic pressure, low temperature, absolute darkness and lack of access to GPS, is challenging. Compared to the conventional submarine emergency response and crew rescue systems (delivery of Emergency Life Support Stores/ELSS, Submergence crew Rescue Vehicles/SRV and coordination of ISMERLO) that are matured, deep-ocean submersibles are challenged by extreme operating depths and human life-support systems that are limited to 96h. Hence managing emergency situations arising out of subsystem failures/degradations (specifically emergency power, O_2-support, positioning, delayed retrievals) are challenging, that are compounded due to psychological stress factors (Matsya is un-tethered, hostile deep-ocean environment, fear of fault aggravation and time-to-surface). Based on the experiences gained (for >2 decades) by Deep Sea Technologies team of NIOT in design, development and operations of unmanned deep-ocean submersibles and systems, reliability and safety-centered system engineering (SE) approach is followed for the design of Matsya6000 **(Figure.8).**

System Engineering (SE) based on ISO/IEC 15288 and ISO/IEC 19760 standards provides guidelines for the development of system architecture, evaluating design trade-offs, balancing technical risks, defining interfaces, providing oversight of verification and validation activities. Since the evolution of concept of reliability in 1920, methodologies for determining the reliability and safety requirements for complex systems are matured, and classified on basis of deterministic and probabilistic approaches. In deterministic approach, SE is based on straight-forward safety principles for the operational requirements. In probabilistic approach, the adequacy of reliability and risk-reduction are verified and accepted with the aid of quantitative reliability and risk-assessment methods. Quantitative reliability estimations using numerical methods based on field-failure data and published failure models serve as a yardstick for comparing alternate technologies, continuous improvements and maintenance planning of safety-critical systems. For realistic results, Failure-In-Time (FIT) estimates of systems/components should be based on engineering and historical data, and the stated probabilistic estimate has to include a measure of uncertainty. The initial estimates of the Probability of Failure (PoF) are made by comparison of similar equipment, historical data (heritage), handbooks & expert elicitation/Delphi approach.

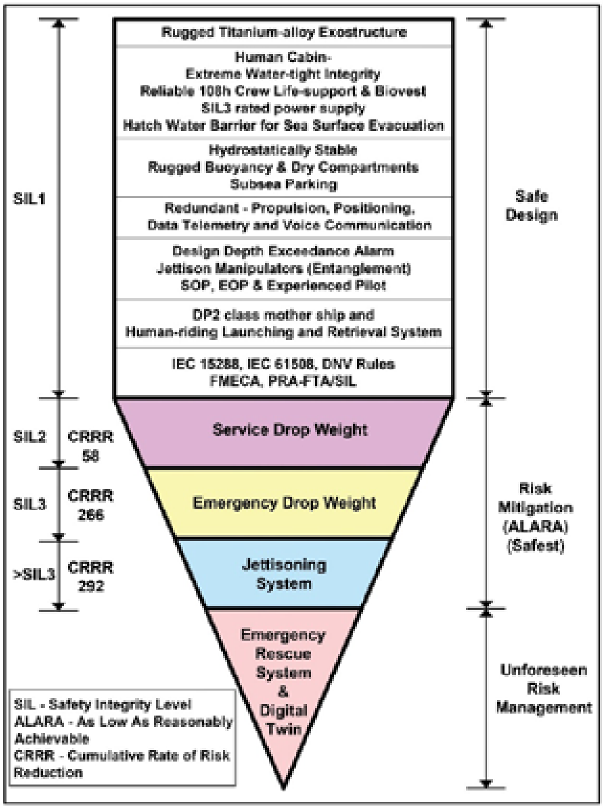


Figure.8. Risk mitigation and residual risk management

Methodology for management of risk in mission and life-critical systems are based on the principle of ALARP (As Low As Reasonably Practicable) and ALARA/ALATA (As Low As Reasonably Achievable/As Low As Technically Achievable), respectively. For a risk to be ALARP, it must be possible to demonstrate that the resources and time involved in reducing the risk further would be grossly disproportionate to the benefit, and hence the principle of ALARP is based on the scientific judgment on the trade-off between the risk, cost and performance. But ALARA/ALATA involves implementing a safest solution, regardless of cost. For Matsya6000, the principle of ALARP is followed for redundancy definition of mission-critical systems (MCS), while ALARA/ALATA is followed for life-critical systems (LCS). The IEC 61508 standard deals with safety-related systems and IEC 61511 for implementing safety-related instrumented systems (SIS) based on the principles of the safety life cycle and Safety Integrity Level (SIL) concepts. Probabilistic Reliability Assessment (PRA) tools are scenario-based risk assessment techniques that quantify the likelihoods of various possible failure scenarios and their consequences, as well as uncertainties in the likelihoods and risks/consequences.

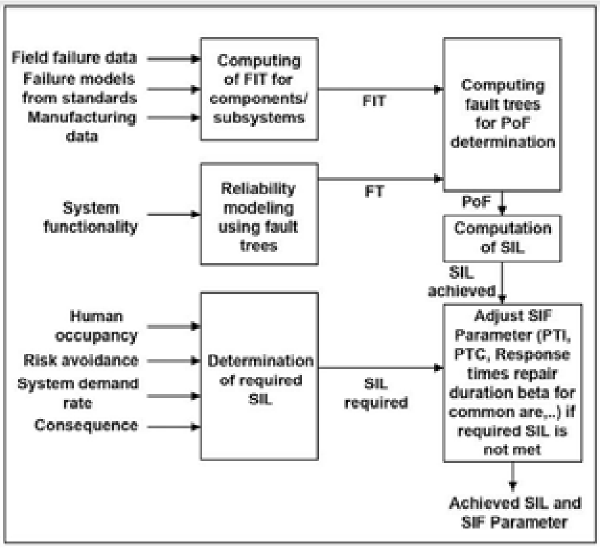


Figure.9. Reliability & risk assessment method adopted for Matsya

The PRA approach adopted for carrying out system design reliability for MCS and on-demand reliability (ODR, also called safety reliability) for LCS of Matsya6000 is shown in **Figure.9.** The initial step in reliability and risk assessment is the computation of the failure rate (FIT) of the components or subsystems based on the field-failure databases (such as OREDA, IEEE), failure models from standards (FIDES, NSWC), manufacturers estimate, historical data (heritage), handbooks and expert elicitation. The system functionality is modeled using fault trees (FT), taking careful consideration of the common cause failures and degradation patterns (β). The modeled FT are simulated for the required period (with the component/subsystem failure data as inputs) to obtain the PoF over the calculated period. The PoF serve as inputs for computing the SIL, which is compared against the SIL required, and identification of the maintenance intervals. For modeling and simulating, FTA and SIL modules of TOTAL-GRIF software are used.

For Matsya6000, three typical life-critical scenarios include submersible unable to ascend on its own due to extreme loss-of-buoyancy (LOB); pilot unable to release the emergency rescue buoy (ERB); and vehicle entangled with an ocean-floor object and pilot unable to jettison robotic manipulators. The buoyancy management systems of Matsya6000 include syntactic foam (with water absorption of <3% at 6000m water depths and a crush pressure of 920 kg/m³) for fixed buoyancy, Main Ballast System (MBS) for providing 1.5m free-board and descent speed of 30m/min, Variable Ballast System (VBS) for finer buoyancy correction (0-300kg), 10 numbers (6x100 kg & 4x50 kg) of dispensable service drop weights (SDW) for enabling energy-efficient descend and ascend. The configuration of human-rated buoyancy management system "Rakshan" comprising of combination of SDW, EDW and Emergency Jettisoning System (EJS) (Trim System, Manipulators and Sampling Tray) in-place for overcoming the extreme LOB situation is shown in **Figure.10.**

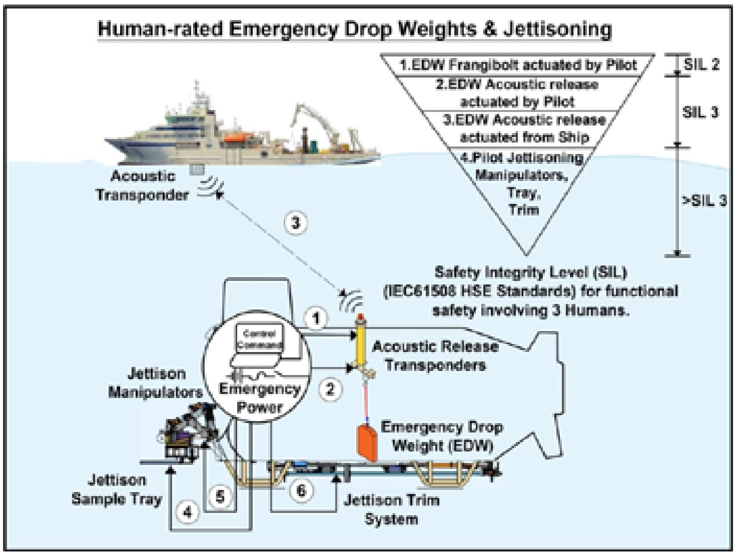


Figure.10. Human-rated ballast management system- Rakshan

The SDW shall be operated using hard push-buttons (without automation) from the human cabin (HC) by the pilot (reliable Frangibolts & SIL3 power supply network inside the HC fed by multi-level redundant batteries located internal and external to HC). The EDW has 3 levels of operational redundancy, involving two different technologies, based on shape memory alloy (SMA) based frangibolts (FB) and customised Acoustic Transponder cum Responder Release (ATRR). The EDW can be released by the pilot by means of actuating the FB from the HC (SIL3-rated power supply and manual switches, hard-wired) and the ATRR actuated either by the pilot (using customised responder feature) or from the ship through acoustic command. The jettisoning of trim system, manipulators and sampling tray shall be done by the pilot from HC (FB & SIL3-rated power supply).

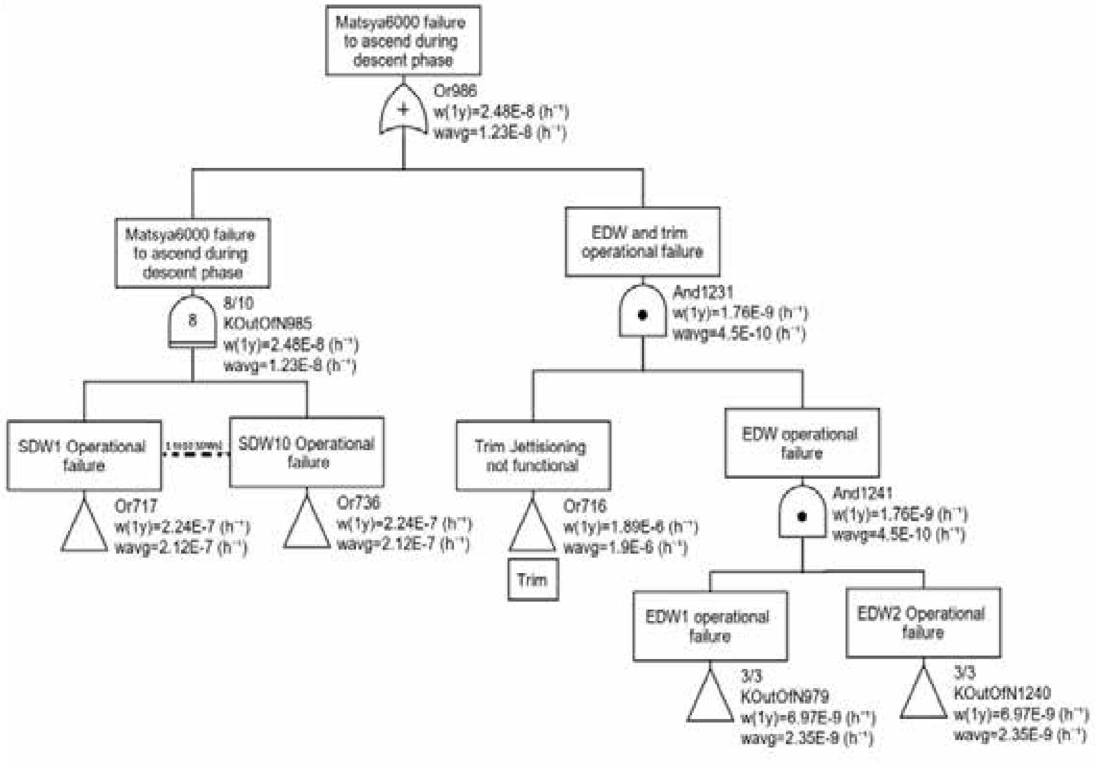


Figure.11. ODR analysis for emergency ballast management system

Based on the functionality, FT is made and simulated with FIT data of the SDW, EDW and EJS subsystems/components **(Figure.11)** using TOTAL-GRIF PRA software. The configuration has an ODR of 1.23x10^{-8} failures/h (Event Or986), complying with IEC61508 HSE SIL3, which meets the human-rated application, involving 3 people. The outcome of the PRA is mapped in **Figure.12,** in which the safety features denoted as A, B, C and D, correspond to the features indicated (as 1 to 4) in the inverted triangle in **Figure.10.** The compliance of the ERB to human-rated requirements (by involving multiple redundant features in power, penetrator, FB coils) is also shown in **Figure.12** (above). Thus, based on ALARA/ALATA principles, life-critical systems of Matsya6000 are designed to comply with ODR SIL3. The reliability of the MCS (Navigation-Positioning System, as an example) computed based on the principles of ALARP is shown in **Figure.12** (below). It is evident that redundancies for MCS are defined based on the trade-off between desired failure-rate reduction and overall increase in the weight of Matsya6000.

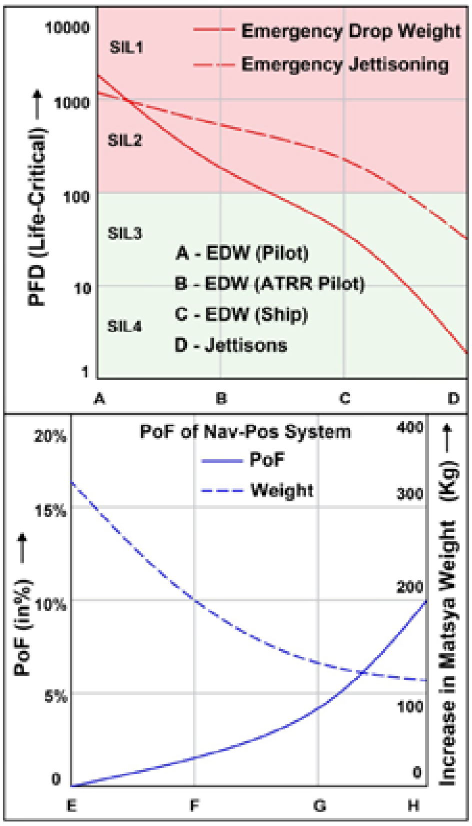


Figure.12. Redundancy definition for MCS and LCS

In the next issue...

The systematic efforts to reduce human errors including definition of mission abort protocol, progress in digital-twin technologies and overall architecture of CDC-Chaitanya shall be discussed.

Abbreviations

ABS	American Bureau of Shipping
ADS	Atmospheric Diving Suit
ALARA	As Low As Reasonably Achievable
ALARP	As Low As Reasonably Practicable
APoS	Acoustic Base Line Positioning Systems
AUV	Autonomous Underwater Vehicles
BF	Body frame
CB	Centre of buoyancy
CCR	Closed Circuit Re-breather
CDT	Cognitive Digital Twin
CG	centre of gravity
CO2	Carbon Dioxide
DCS	Decompression Sickness
DDC	Deck Decompression Chamber
DNV	Det Norske Veritas
DoF	Degrees of freedom
DR	Dead Reckoning
DSC	Deep Sea Challenger
DT	Digital Twin

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DVL	Doppler Velocity Log
FIDES	Failure-In-Time Determination for Electronic Systems
FOG	Fibre Optic Gyro
GPS	Global Positioning System
HOV	Human-Occupied Vehicles
HROV	Hybrid ROV
IACS	International Association of Classification Society
IMCA	International Marine Contractors Association
INS	Inertial Navigation Systems
LARS	Launching and Retrieval System
LBL	Long Base Line
MoES-NIOT	Ministry of Earth Sciences-National Institute of Ocean Technology
MOSHIP	Mother Ship
O2	Oxygen
OOR	out-of-roundness
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
RLG	Ring Laser Gyro
ROVs	Remotely-Operated Vehicles
SCUBA	Self-Contained Underwater Breathing Apparatus
SOE	Safety Operational Envelope
SSBL	Short base line
UAT	Underwater Acoustic Telephone
USBL	Ultra-short baseline
WHOI	Woods Hole Oceanographic Institution

Acknowledgements

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Title Dual-Fuel Gas-Burning Diesel Engines for Marine Propulsion: A Comprehensive Technical Analysis

PART 4: - Engine types in service and in development, service experiences, environmental performance

Kaushik K Seal, Saptarshi Basu

Abstract

Dual-fuel (DF) marine engines have emerged as one of the most practical and scalable solutions for reducing emissions in the maritime industry. By enabling operation on both conventional liquid fuels and cleaner gaseous fuels such as liquefied natural gas (LNG), these engines provide a flexible pathway toward regulatory compliance and decarbonisation. This paper presents a consolidated analysis of dual-fuel engine technology, focusing on service experience, environmental performance, economic implications and future developments.

Extensive fleet data demonstrates that DF engines have matured into highly reliable propulsion systems, with cumulative operating hours exceeding hundreds of millions and gas-mode availability consistently above 95%. Environmental performance shows significant reductions in SOx, NOx, particulate matter and CO_2 emissions compared to conventional fuels. However, methane slip remains a critical challenge that requires continued technological innovation.

From an economic perspective, dual-fuel engines involve higher capital costs but offer strong lifecycle savings through reduced fuel consumption, lower emissions penalties and operational flexibility. As LNG infrastructure expands and alternative fuels such as bio-LNG and synthetic methane become available, dual-fuel engines are expected to play a central role in the maritime energy transition.

Keywords: Dual-fuel engines, LNG propulsion, methane slip, marine emissions, CII, FuelEU Maritime, lifecycle cost, gas combustion, IMO Tier III, decarbonisation

1. Introduction

The maritime industry is at a critical inflection point, driven by increasingly stringent environmental regulations and growing global pressure to reduce greenhouse gas emissions. The International Maritime Organization (IMO) has established ambitious targets, including a 40% reduction in carbon intensity by 2030 and a pathway toward net-zero emissions by 2050. These developments have accelerated the adoption of alternative fuels and propulsion technologies.

Conventional heavy fuel oil-based propulsion systems are increasingly incompatible with these requirements. As a result, shipowners and operators are exploring viable transitional technologies that can deliver immediate emissions reductions while maintaining operational reliability and economic viability. Dual-fuel engines have emerged as a leading solution in this context.

The fundamental advantage of dual-fuel engines lies in their ability to operate on both conventional fuels and cleaner gaseous fuels such as LNG. This capability allows operators to optimise fuel usage based on cost, availability and regulatory requirements. Furthermore, dual-fuel engines provide a future-ready platform capable of accommodating emerging fuels such as bio-LNG and synthetic methane.

Two-stroke dual-fuel engines dominate large ocean-going vessels due to their high efficiency and power output, while four-stroke engines are widely used in ferries, offshore vessels and auxiliary systems where flexibility and modularity are essential.

2. Dual-Fuel Engine Overview

2.1 Operating Principle

- Dual-fuel engines can run on:
    - **Gas (main fuel)**
    - **Diesel (pilot fuel for ignition)**

Gives:

- Fuel flexibility
- Better cost control
- Compliance with regulations

2.2 Two-Stroke vs Four-Stroke

Two-Stroke Engines

- One power stroke per revolution
- Very **high power & torque**
- Used for **large ships (main engines)**
- Efficient at **low speed**

Four-Stroke Engines

- One power stroke every 2 revolutions
- **Smoother operation**
- Better for:
    - Variable loads
    - Auxiliary engines

Technical Overview

1. Design & Speed

- **Two-stroke:**
    - Slow speed (<120 rpm)
    - Large size, high torque
- **Four-stroke:**
    - Medium speed (300–1000 rpm)
    - Smaller, compact

2. Dual-Fuel Operation

- Both use **pilot fuel to ignite gas**

Two-stroke (ME-GI type)

- Gas injected at **high pressure directly**
  No knocking, better combustion

Four-stroke (Otto cycle)

- Gas + air mixed before combustion
  Lower NOx
  But risk of **knock/misfire**

3. Fuel System

- Two systems required:
    - **Liquid fuel system (diesel)**
    - **Gas system (FGSS)**

FGSS includes:

- Tanks
- Compressors
- Piping
- Safety systems

4. Combustion Differences

- **Two-stroke:**
    - Diesel-type combustion
    - Lower methane slip
- **Four-stroke:**
    - Lean burn
    - Very low NOx
    - Higher methane slip

5. Standards

- Performance → **ISO 3046**
- Emissions → **IMO NOx Code**

Performance (Simplified)

1. Power & Efficiency

- **Two-stroke:**
    - Very high power
    - Efficiency ~50%
- **Four-stroke:**
    - Lower power
    - Efficiency ~44–48%

2. Fuel Flexibility

- Can use:
    - LNG
    - LPG
    - Diesel
    - Biofuels
    - Future fuels (methanol, ammonia)

3. Emissions

- Gas mode:
    - ↓ CO_2 (~20%)
    - ↓ NOx
    - ≈ Zero SOx & PM
- Issue:
    - **Methane slip** (higher in 4-stroke)

4. Diesel Mode

- Works like normal diesel engine
- Needs:
    - **SCR or EGR** for Tier III

5. Reliability

- Both types are **well proven**
- Long life:
    - 2-stroke: up to 80,000 hrs
    - 4-stroke: up to 60,000 hrs

High availability (>95%)

Economic Assessment

1. Capital Cost (CAPEX)

- DF engines cost more due to:
    - Gas system (FGSS)
- 2-stroke DF → generally higher cost

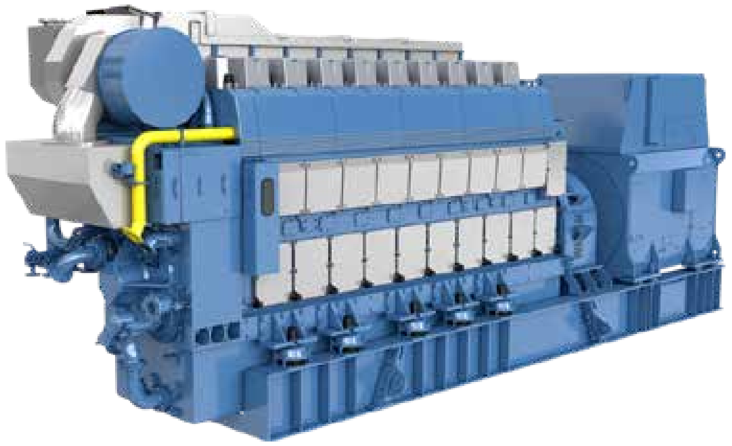
2. Fuel Cost Advantage

- Gas usually **cheaper than oil**
- Saves:
    - Fuel cost
    - Scrubber cost
    - Emission penalties

3. Operating Cost (OPEX)

- Slightly higher maintenance (gas system)

> ***Dual-Fuel Engines drive maritime decarbonisation transition forward today***



- But:
  - o Cleaner combustion
  - o Less wear
    Overall cost can be lower

3. Selected Dual-Fuel Engine Technologies

3.1 Bergen B36:45 Series (Case Study)

The **Bergen B36:45** engine is a modern **medium-speed dual-fuel engine**. It works on **lean-burn gas combustion** and is used in ships and power plants.

Key Features

- **Power output:** Up to **12 MW** (≈ **600 kW per cylinder**)
- **Cylinder size:**
  360 mm bore × 450 mm stroke

Engine Configurations

- **Inline (B36:45L):**
  6, 8, 9 cylinders
- **V-type (B36:45V):**
  12, 16, 20 cylinders

Performance

- **Efficiency:**
  Around **48%–50%**
- Can be improved further with:
  Heat recovery systems

Emissions

- Very **low NOx and SOx**
- Can be reduced even more with additional systems

Design Notes:

1. Modular, robust, easily serviceable architecture
2. Convertible to liquid fuel operation
3. Enhanced load responsiveness, minimum derating at high ambient
4. Optimised for low lifecycle costs, minimum noise/vibration
5. Certified for low emissions across operating regimes.

3.2 Engine Evolution and Fuel Adaptation

Modern engines incorporate advanced fuel injection, computer-controlled timing, selective catalytic reduction (SCR), exhaust gas recirculation (EGR) and aftertreatment to meet IMO Tier III and EU Stage V standards.

4. Performance Analysis (Simplified)

4.1 Efficiency & Fuel Economy

- D/F engines can reach **~50% efficiency**
- Advanced systems (combined cycle) → **>55% efficiency**
- Using gas fuel:
  - o **25–32% lower fuel consumption** than diesel (depending on conditions)
- Modern **two-stroke engines**:
  - o Now almost as efficient as four-stroke
  - o Improved due to:
    - ■ Lower losses
    - ■ Better slow-speed design

4.2 Emissions Performance

- When using LNG:
  - o **NOx ↓ up to 85%**
  - o **SOx ↓ >95%**
  - o **PM ↓ significantly**

Meets:

- **ECA requirements**
- **MARPOL regulations**
- Can also run on liquid fuel:
  - o With aftertreatment (SCR/EGR)
  Provides **backup + flexibility**

4.3 Reliability & Flexibility

- High reliability because:
  - o Strong design
  - o Fewer parts (especially 2-stroke)
  - o Planned maintenance
- **Four-stroke engines**:
  - o Better for:
    - ■ Manoeuvring
    - ■ Variable loads
  - o But:
    - ■ More complex maintenance
- **Dual-fuel advantage**:
  - o Can switch fuels anytime
  Helps with:
  - o Fuel price changes
  - o Availability issues
  - o Emission compliance

5. Economic Considerations

5.1 Capital and Life-Cycle Costs

1. Dual-fuel engines have a higher CAPEX (by 15–30%) due to fuel system complexity, emission control and automation integration [8,10].
2. OPEX savings realised through fuel flexibility—LNG and alternative fuels often cheaper or less volatile than distillate fuels on a $/energy basis.
3. Maintenance costs generally lower for two-stroke because of fewer moving parts, but advances in four-stroke engine service intervals have narrowed the delta.

4. Payback period for D/F installations estimated at 3–7 years, highly dependent on fuel cost differentials and emission compliance incentives.

5.2 Operational Cost Flexibility

1. The ability to hedge against fuel market volatility and secure regulatory incentives for emissions reduction is a core economic driver for D/F adoption.
2. Dual-fuel systems are favoured for newbuilds and major retrofits in fleets facing global emissions standards and noise/vibration constraints.

6. Modern Adoption Trends & Market Dynamics

1. D/F engines are increasingly adopted for deep-sea vessels (two-stroke dominant) and ferries, tugboats and power plants (four-stroke) as shipping pursues decarbonisation.
2. Global D/F marine engine market is expected to exhibit a CAGR of 7–8% between 2025–2033; drivers include stricter IMO/EU emission mandates, rising LNG infrastructure and operational flexibility.
3. High initial investment, fuel infrastructure development and requirement for skilled personnel remain adoption barriers especially in emerging markets.

7 Troubleshooting and Operating Limits

7.1 Knocking & Pre-Ignition (Simplified)

Main Causes of Knocking

1. High Gas Pressure (>8.5 bar)

- Too much gas before ignition
- Causes **auto-ignition (uncontrolled burning)**

Symptom:

- Sharp knocking sound
- Very fast pressure rise

2. Late Pilot Injection

- Not enough time for mixing

> *LNG cuts emissions but methane slip remains challenge*

Symptom:

- Knocking
- Soot in exhaust

3. Poor Gas Quality (Methane Number <70)

- More propane/butane → unstable combustion

Symptom:

- Knocking at high load / acceleration

How System Controls It (Automatic ECU Action)

Problem	Action
Knock detected	Delay pilot injection + reduce gas pressure
High gas pressure	Reduce supply pressure
Poor gas quality	Increase pilot fuel
High temperature (>420°C)	Reduce load or switch to diesel

Alarm triggered after repeated knock events

7.2 Misfire & Combustion Stability (Simplified)

Causes of Misfire

1. Too Little Pilot Fuel (Low Load)

- Flame not strong enough

Symptom:

- Power loss
- Unburned gas in exhaust

2. Gas Pressure Fluctuation

- LNG tank pressure drops

Symptom:

- Rough running
- Power fluctuations

3. Very Low Air Temperature (<0°C)

- Slow combustion

Symptom:

- Hard starting
- Rough running

Safe Operating Range (Gas Mode)

Engine runs smoothly when:

- Gas pressure: **3.5–8.5 bar**
- Pilot fuel: **2–10%**
- Exhaust temp: **300–420°C**
- Load: **25–100%**
- Air temp: **–10°C to +50°C**

Unstable Conditions (Avoid)

- Pilot fuel **too low (<2%) → misfire**
- Pilot fuel **too high (>12%) → inefficient**
- Gas pressure **too low (<3 bar) → weak combustion**
- Gas pressure **too high (>9 bar) → knocking risk**

8. Retrofit Options and Implementation Strategy

Which Engines Can Be Converted?

Engine Type	Suitability
MAN B&W L-series	☑ Excellent
Wärtsilä 46F	☑ Excellent
Caterpillar	👍 Good
MAN V-series	⚠ Moderate (complex)
Daihatsu / HiMSEN	✕ Limited
2-stroke slow-speed	✕ Not possible

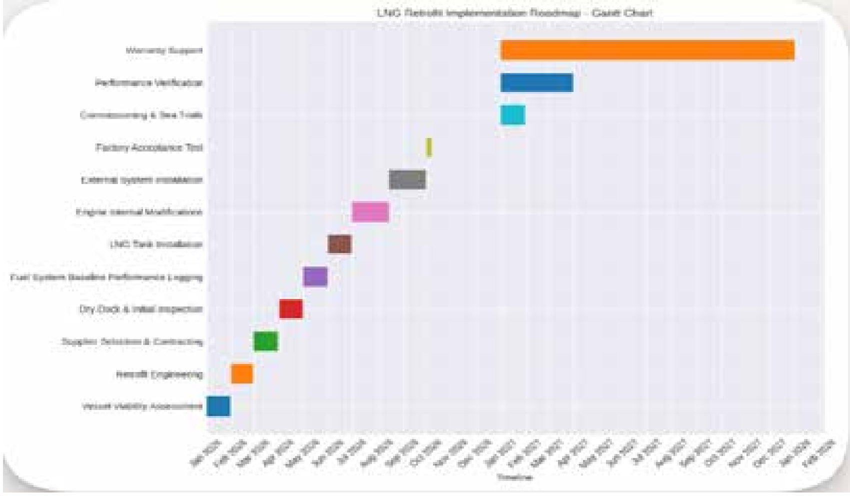
When Retrofit is NOT Possible

- Engine badly worn (high blow-by)
- Heavy corrosion
- Fuel system damaged
- No space for gas system (V-engines)
- High thermal damage

2. What is Done in Retrofit

A. Engine Modifications

- Gas admission valves



- Pilot fuel system upgrade
- Cylinder head changes
- New piston/rings
  Cost: **$120K–$205K**

B. New External Systems

- Gas Valve Unit (GVU)
- Double-wall gas pipes
- Gas detection system
- Control & automation system
- LNG bunkering setup
  Cost: **$190K–$510K**

C. Installation & Services

- Labour & overhaul
- System integration
- Crew training
- Spare parts
  Cost: **$65K–$155K**

Total Retrofit Cost

$375K – $870K per engine

3. Why Retrofit? (Economics)

- Fuel savings can be very high
- Example:
  - Retrofit cost: ~$3M
  - Annual saving: ~$3.3M

Payback ≈ **~1 year**

4. Implementation Roadmap

Phase 1: Planning (Months 1–3)

- Check vessel condition
- Check LNG availability (ports)
- Get class & regulatory approval
- Engineering design (CAD, HAZOP)
- Select suppliers

Phase 2: Preparation (Months 4–6)

- Dry dock inspection
- Record baseline performance:
  - Fuel consumption
  - Emissions
- Install LNG tanks (if needed)

Phase 3: Retrofit Execution (Months 7–12)

Step 1: Engine Work

- Modify engine internally

Step 2: Install Gas System

- Piping, GVU, detection

Step 3: Testing (FAT)

- Check:
  - Fuel consumption
  - Emissions
  - Safety systems
  - Changeover (gas ↔ diesel)

5. After Retrofit

Commissioning

- 100-hour gradual running
- Test all modes (gas + diesel)
- Crew training

Performance Checks

- Fuel efficiency within limits
- NOx meets Tier III
- Methane slip controlled
- Smooth fuel switching

Warranty Support

- 24/7 technical help
- Remote monitoring
- Spare parts support

6. Simple Flow (PERT Logic)

Planning → Preparation → Execution → Operation

- Each stage depends on the previous
- This is the **critical path**

Final Takeaway

Retrofit is:

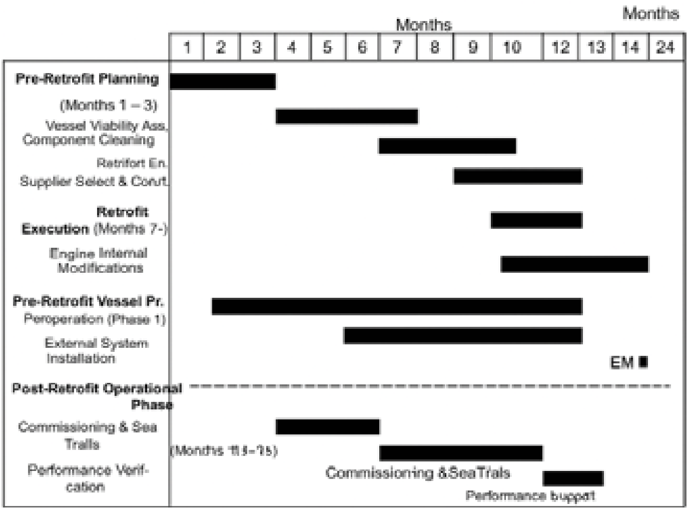
- **Technically feasible (mainly 4-stroke engines)**
- **Economically attractive (fast payback)**
- **Complex but structured process**

Key success factors:

- Good engine condition
- Proper planning
- Strong safety systems

9. Vessel Applications and Market Adoption

1. Where Dual-Fuel (DF) Engines Are Used



LNG Carriers (LNGCs)

- **Most common users of DF engines**
- Use their **own cargo (LNG) as fuel**
- Consume **Boil-Off Gas (BOG)** → no wastage

  Very **efficient and economical**

Container Ships

- Prefer **ME-GI engines**
- Operate at **high power and steady load**
- Benefits:
  - High efficiency
  - Almost **zero methane slip**
  - Meets **Tier III without SCR (no urea)**

Oil & Chemical Tankers

- Increasing use of DF engines
- Can use cargo like:
  - **LPG / Ethane as fuel**

  Creates a **closed-loop system (cargo = fuel)**
- Strong safety systems required (and available)

Bulk Carriers

- Adoption is **growing**
- Mainly large vessels (Capesize, Newcastlemax)

Drivers:

- Lower fuel cost
- Better **CII rating (important for chartering)**

2. Why DF Engines Are Adopted

Fuel Flexibility

- Can switch between:
  - LNG
  - Oil fuels

Choose cheapest fuel anytime

Lower Operating Cost (OPEX)

- Up to **~30% savings possible**
- Reasons:
  - Cheaper LNG (sometimes)
  - Lower lube oil consumption

Environmental Compliance

- Meets:
  - **SOx limits (no sulphur)**
  - **NOx Tier III**
  - **CII requirements**

Helps "future-proof" the vessel

Lower Maintenance

- Cleaner combustion means:
  - Less wear
  - Fewer deposits
  - Longer overhaul intervals

Higher reliability + lower cost

3. LNG Carriers – Key Market

Market Status

- Almost **100% new LNG ships = dual-fuel**
- Steam turbines → **now obsolete**
- Around:
  - **~700 LNG ships globally**
  - ~60% are DF capable

> *Fuel flexibility enables cost control and regulatory compliance*

Engine Types (Typical)

- **Large LNGC (160k–180k m^3)**
  - ~22,000–27,000 kW
- **Mid-size LNGC**
  - ~18,000–22,000 kW
- **Small LNGC / FSRU**
  - ~12,000–18,000 kW

Why LNG Carriers Prefer DF

- Use **BOG as fuel** → **saves money**
- Avoid:
  - Costly reliquefication ($50–200/ton)
- Very **efficient fuel utilisation**

10. Emission Performance

Why LNG is Used

LNG is preferred because of stricter IMO regulations and the push for cleaner shipping. It produces fewer harmful emissions than Heavy Fuel Oil (HFO), but it also has some challenges.

1. Emission Reduction (LNG vs HFO)

SOx (Sulphur Oxides) – ~100% Reduction

- LNG has almost **no sulphur**
- So, it produces **negligible SOx**
- No need for **scrubbers**

PM (Particulate Matter) – ~90% Reduction

- LNG has **no heavy hydrocarbons or ash**
- Results in **very low soot formation**
- Cleaner engines and better air quality

NOx (Nitrogen Oxides) – 10–30% Reduction

- Depends on **combustion temperature**
- LNG engines can meet **IMO Tier III** easily by:
  - Lean-burn combustion
- Exhaust Gas Recirculation (EGR)

  Baseline reduction is small, but **compliance is easier**

CO_2 (Carbon Dioxide) – 20–25% Reduction

- Methane (CH_4) has more hydrogen, less carbon
- Produces **more water, less CO_2**

But:

- This is **Tank-to-Wake (TTW)**
- Real benefit may reduce due to:
  - Methane leakage (upstream)
  - Methane slip (engine)

2. Methane Slip (Main Problem)

What is it?

Unburned methane released into atmosphere

Why serious?

- Methane is:
  - **28–34× stronger than CO_2 (100 yrs)**
  - **84× stronger (20 yrs)**

Where does it happen?

- Mainly in **Otto-cycle engines (ME-GA)**
- During:
  - Valve overlap (scavenging loss)
  - Incomplete combustion

Solutions

ME-GI (Diesel Cycle)

- Gas injected **after ignition**
- No premixing → **almost zero methane slip**

ME-GA (Otto Cycle)

- Uses:
  - **EGR**
  - **Adaptive combustion control**
- Reduces but does not eliminate slip

3. IMO Compliance

3.1 NOx Tier III

Requires **~80% reduction**

ME-GI Options

- **EGR**
  - Recirculates exhaust gas
  - Lowers combustion temperature
- **SCR**
  - Uses urea to convert NOx → $N_2 + H_2O$

ME-GA

- Uses **EGR as standard**
- Works in both:
  - Gas mode
  - Diesel mode

3.2 SOx Regulations

- LNG has **no sulphur**
- Fully compliant without:
  - Scrubbers
  - Chemicals
  - Extra space

3.3 GHG Targets (IMO Strategy)

- **CII** → 40% reduction by 2030
- **Total GHG** → 50% reduction by 2050

4.0 Role of Dual-Fuel (DF) Engines

Why Important

1. Immediate Benefits

- ~20% CO_2 reduction
- Almost zero SOx and PM

2. Future Fuel Ready

- Can use:
  - Bio-methane
  - E-methane
- No major engine changes required

3. Path to Hydrogen

- LNG systems help transition to:
  - Hydrogen fuel engines in future

The drive towards LNG as a marine fuel is predominantly fueled by increasingly stringent international regulations, primarily from the International Maritime Organization (IMO) and the global push for decarbonisation. LNG's emission profile represents a significant step forward compared to conventional Heavy Fuel Oil (HFO), though it is not without its own challenges.

11. Performance Characteristics

Performance Characteristics

The operational behaviour of dual-fuel engines differs significantly between **high-pressure Diesel-cycle engines (ME-GI)** and **low-pressure Otto-cycle engines (ME-GA)**. These differences are primarily driven by combustion methodology, pressure development and control of ignition.

Combustion Stability and Cylinder Pressure

- **ME-GI (Diesel Cycle):** Direct high-pressure gas injection into compressed air results in **stable and controlled combustion**.
  - Predictable pressure rise
  - High cylinder pressure stability
  - Comparable to conventional diesel operation
  - Benefits: Improved engine longevity and strong low-speed torque
- **ME-GA (Otto Cycle):** Premixed gas-air mixture leads to **rapid combustion after ignition**.
  - Faster pressure rise
  - Greater sensitivity to operating conditions

Knock Risk and Combustion Limits

- In **ME-GA engines**, high gas concentration at higher loads can result in:
  - Rapid flame propagation
  - Auto-ignition of end-gas → **engine knock**
- **Implications of knock:**
  - Severe mechanical stress
  - Risk of engine damage
- **Operational mitigation:**
  - Load limitation
  - Ignition timing adjustment
  - Efficiency trade-offs
- **ME-GI engines:**
  - No knock tendency due to controlled injection-based combustion

Fuel Efficiency and SFOC

- **ME-GA engines:**
  - **~3.5% improvement in SFOC** with optimised EGR
  - Reduced pumping and throttling losses
- **ME-GI engines:**
  - Stable efficiency across wider load range
  - Better consistency under varying operating conditions

Part-Load Performance

- **ME-GA limitation:**
  - Increased ignition delay at low loads
  - Leads to:
    - Incomplete combustion
    - Reduced efficiency
    - Combustion instability
- **ME-GI advantage:**

> *High efficiency deliver lower lifecycle operating costs*

  - o Consistent combustion regardless of load
  - o Superior low-load performance

Efficiency Improvement Strategies

To enhance performance and overcome limitations, modern dual-fuel engines employ advanced optimisation techniques:

1. Adaptive Cylinder Control

- Real-time combustion monitoring using pressure sensors
- Individual cylinder-level fuel and gas adjustment
- Ensures optimal combustion under all conditions

2. Exhaust Valve Timing Optimisation

- Improves compression ratio and scavenging efficiency
- Enhances power output and reduces fuel consumption

3. EGR Optimisation (ME-GA)

- Controls combustion temperature
- Improves efficiency while reducing methane slip

4. High Cetane Pilot Fuel

- Reduces ignition delay
- Improves combustion stability and part-load efficiency

ME-GI engines offer **robust, stable and reliable performance** across the full load range, making them ideal for deep-sea operations. ME-GA engines provide **efficiency advantages under optimised conditions**, but require advanced control systems to manage knock and part-load challenges. The future direction lies in combining these strengths through improved combustion control and digital optimisation.

12. Operational Modes

Operational Performance Comparison: ME-GI vs ME-GA

The performance of dual-fuel engines differs significantly between **high-pressure Diesel-cycle (ME-GI)** and **low-pressure Otto-cycle (ME-GA)** concepts, particularly in combustion stability, efficiency and operational limits.

Combustion Stability and Cylinder Pressure

- **ME-GI (Diesel Cycle):** Direct high-pressure gas injection into compressed air results in **stable and predictable combustion**.
  - o Smooth pressure rise
  - o High cylinder pressure stability
  - o Comparable to conventional diesel engines
  - o Advantage: Better durability and low-speed torque
- **ME-GA (Otto Cycle):** Premixed gas-air charge leads to **rapid combustion after ignition**.
  - o Faster pressure rise
  - o Risk of uneven combustion

Knock Risk and Load Limitations

- In **ME-GA engines**, high gas concentration at load can cause:
  - o Rapid flame propagation
  - o Auto-ignition of end-gas → **engine knock**
- **Knock consequences:**
  - o Severe mechanical stress
  - o Potential engine damage
- **Operational response:**
  - o Load limitation
  - o Ignition timing adjustments
  - o Trade-off with efficiency
- **ME-GI engines:**
  - o No knock risk due to controlled injection combustion

Fuel Efficiency and SFOC

- **ME-GA advantage:**
  - o **~3.5% improvement in SFOC** with optimised EGR
  - o Reduced pumping and throttling losses
- **ME-GI advantage:**
  - o Higher baseline efficiency stability
  - o Better performance across load range

Part-Load Performance

- **ME-GA limitation:**
  - o Increased ignition delay at low loads
  - o Leads to:
    - ■ Incomplete combustion
    - ■ Reduced efficiency
    - ■ Stability challenges
- **ME-GI advantage:**
  - o Consistent combustion independent of load
  - o Superior low-load operation

Efficiency Improvement Strategies

To optimise dual-fuel engine performance, several advanced strategies are applied:

1. Adaptive Cylinder Control

- Real-time monitoring using cylinder pressure sensors
- Individual cylinder tuning (gas + pilot injection)
- Ensures uniform combustion and maximum efficiency

2. Exhaust Valve Timing Optimisation

- Improves compression ratio and scavenging
- Enhances power output and fuel efficiency

3. EGR Optimisation (ME-GA)

- Balances combustion temperature
- Reduces methane slip and improves efficiency

4. High Cetane Pilot Fuel

- Reduces ignition delay
- Improves combustion stability and part-load efficiency

Strategic Insight

- **ME-GI engines:**
  o Robust, stable and reliable across all loads
  o Best suited for deep-sea, high-load operations
- **ME-GA engines:**
  o More efficient under optimised conditions
  o Requires advanced control systems to manage knock and part-load limitations

Fuel Oil Mode:

o The engine operates identically to a conventional ME-C engine, running on 100% liquid fuel (HFO, MDO, or VLSFO).

o **Use Case:** This mode is used when LNG is unavailable, during specific manoeuvres where gas operation might be less stable, or

for short periods as mandated by flag or port state regulations.

Minimum Pilot Oil Mode:

o This is the primary gas mode. The engine runs almost entirely on natural gas, with only a very small amount of liquid pilot fuel (typically **0.5-3%** of the total fuel energy) injected to ignite the gas-air mixture.

o **Significance:** This mode maximises the economic and environmental benefits of using LNG, drastically reducing SOx, PM and CO_2 emissions while relying on the pilot fuel only for ignition reliability.

Specified Dual-Fuel Mode:

o In this mode, the ratio of gas to liquid fuel is actively controlled and can be set to a specific value (e.g., 50% gas, 50% liquid). This is not a common operational mode for steady-state sailing but is crucial for:

- **Process Stability:** Ensuring smooth combustion during transient operations like load changes or when switching between fuel modes.
- **Fuel Quality Management:** If the gas quality (e.g., Methane Number) is poor, the engine control system can automatically increase the liquid fuel fraction to maintain power and prevent knock.
- **Burning Boil-Off Gas (BOG):** In LNG carriers, this mode can be used to efficiently manage the BOG in conjunction with the liquid fuel.

13. Specific Engine Designs and Technical Innovations

13.1 MAN 5160DF Architecture

Key Design Features:

1. **Sealed Plunger (SP) Injection Pumps:**
   - Fuel and lube oil completely separated
   - Leakage fuel recycled without sealing oil
   - Benefit: reduced fuel consumption 1–2% vs. conventional pumps
2. **SaCoSone Control System:**
   - Adaptive combustion control per-cylinder
   - Fuel quality manager adjusts for LNG composition variation (nitrogen content 10–20% in NBOG)
   - Cleaning cycle for HFO operation transition (automated MDO/MGO flushing)
3. **Turbocharger Configuration:**
   - Single TCA turbocharger (modern design: TCA77, TCA88, TCA88-25)
   - VTA (Variable Turbine Area) wastegate system
   - Lambda control for optimal boost pressure vs. load

Environmental Monitoring:

13.2 Hyundai HiMSEN H27DF Architecture

Design Innovations:

1. Modularised Feed System:
   - All cooling water and lubricating oil components integrated into cast feed block
   - Direct accessibility without multi-pipe interconnections
   - Thermal stress reduction through optimised flow channels
2. HiEMS (Hyundai Intelligent Equipment Management Solution):
   - Cloud-based engine monitoring
   - Real-time performance analytics; fleet management
   - Predictive maintenance: bearing wear trends, fuel quality monitoring
   - On-shore remote diagnostics via secure VPN
3. Composite Piston Design:
   - Two-piece construction: forged alloy steel crown + ductile iron skirt
   - High swirl intake ports for improved gas-air mixing
   - Optimised bowl shape (Hermite Spline Curve geometry)

13.3 Wärtsilä 46F Retrofit Characteristics

SPEX Turbocharging System (Single Pipe Exhaust):

Pulse Charging (Part Load):

• Exhaust valves open sequentially

• Pressure waves drive turbine pulses

• Improves turbocharger response at low engine speed (400–500 rpm)

Constant Pressure (High Load):

• Exhaust gases blend in common manifold

• Steadier turbine flow; higher efficiency at MCR

• Wastegate bypass controls excess pressure

14. Limitations and Challenges

Despite the advantages, the widespread adoption of LNG propulsion faces several technical and logistical hurdles.

Challenges of LNG Propulsion (Simplified)

Even though LNG has many benefits, it also has some **technical and operational challenges**.

14.1 Technical Limitations

1. Low-Pressure (Otto-Cycle) Engines

- Good for **NOx Tier III compliance**
- But have some drawbacks:

Lower power density

- Produce less power per size
- Engine becomes **larger for same output**

Methane slip & knocking risk

- Unburned methane emission
- Risk of unstable combustion

2. Dual-Fuel Injectors

- Very **complex components**
- Handle:
  - o Gas
  - o Liquid fuel (pilot)

Challenges:

- Need **efficient cooling**
- Risk of **carbon deposits (coking)**
- Can block injector nozzles

3. Reduced Volumetric Efficiency

- Gas replaces part of air in cylinder
  Less oxygen available

Result:

- Slight **reduction in engine power** (derating in gas mode)

14.2 Fuel Quality Issues

1. Methane Number (MN)

- Indicates **resistance to knocking**

High MN (>80) → Good
Low MN (<70) → Risky

- Low MN gas (more propane/ethane):
  - o Causes **knocking**
  - o Engine must:
    - ▪ Reduce load
    - ▪ Increase pilot fuel

2. Boil-Off Gas (BOG) Variation (LNG Carriers)

Fuel composition changes during voyage:

Early Stage

- More **Nitrogen (N_2)**
  Safe (high MN)
  But **low energy content**

Later Stage

- More **ethane/propane**
  Higher energy
  But **high knocking risk (low MN)**

3. Role of Engine Control System

- Continuously adjusts:
  - o Fuel mix
  - o Injection timing
  - o Pressure

Ensures:

- Safe operation
- Stable combustion
- Efficiency

15. Comparative Economic Analysis

15.1 Total Cost of Ownership (10-Year)

Base Case (Typical Vessel)

- 25 MW engine
- 7,000 hours/year
- 80% load
- Discount rate: 8%

A. Conventional Engine (HFO – No Retrofit)

Main Costs (10 years)

- Fuel (HFO): **~$157M**
- Lube oil: **~$1.2M**
- Emission penalties: **~$0.6M**
- Overhaul: **~$0.6M**
- Maintenance: **~$0.75M**

Total TCO: ~$160M

B. LNG Dual-Fuel Retrofit

Main Costs (10 years)

- Retrofit cost: **$3M**
- LNG fuel: **~$144M**
- Lube oil: **~$1.18M**
- Emission penalties: **$0 (compliant)**
- Overhaul: **~$0.6M**
- Maintenance: **~$0.9M**
- LNG setup: **~$0.8M**

Total TCO: ~$151M

Overall Benefit

Savings: ~$9.3M over 10 years
~6% cost reduction

Key Insight

- Fuel cost dominates total cost
- LNG saves money mainly by:
  - o Lower fuel price
  - o No emission penalties

15.2 Investment Decision (Simplified)

When Retrofit is Worth It

- Payback: **< 3 years**
- IRR: **> 15%**
- NPV: **Positive**

Fuel Price Advantage

- LNG price varies but often cheaper
- DF engine allows switching → **risk protection**

Funding Options

Green Financing

- Lower interest loans (EIB)
- Better ship value (Poseidon Principles)

Scrubber vs Retrofit

Scrubber

- Cost: **\$2–3.5M**
- Ongoing cost: **high (chemicals + waste)**

Dual-Fuel Retrofit

- Similar initial cost
- But:
  - o Lower fuel cost
  - o No emission penalties

Better long-term economics

Final Takeaway

LNG retrofit:

- Higher upfront cost
- But:
  - o Lower fuel cost
  - o No penalties
  - o Faster payback

Over time → **more economical than HFO + scrubber**

16. Future Directions and Emerging Technologies

16.1 Methane Slip Reduction

Advanced Combustion Strategies:

1. **Pre-Combustion Chamber Re-introduction (pilot concept stage):**

- Small pre-chamber with spark plug for gas mode ignition
- Eliminates need for pilot diesel injection
- Potential methane slip reduction: 30–50%
- Status: Laboratory demonstration; 3–5-year timeline for marine prototype

2. **Selective Catalytic Reduction (SCR) Integration:**

- SCR reactor on exhaust line converts methane to CO_2 + H_2O + N_2
- Methane slip reduction: 80–90%
- Cost adder: \$150K–\$250K per engine
- Status: Available option; adoption limited by space constraints on retrofits

16.2 Bio-LNG and Green Hydrogen Integration

Bio-LNG (Biogas sourced from waste/biomass):

- Well-to-tank CO_2 reduction: 70–90% (biogas from anaerobic digestion/landfills)
- Price premium: \$1–\$3/MMBtu above fossil LNG
- Infrastructure compatibility: Direct drop-in replacement; no engine modification needed
- Status: Emerging in Northern Europe (5–10% market availability); scaling phase

Hydrogen-Ready Dual-Fuel Engines (Future development):

- Pilot: Small hydrogen injection + main fuel gas
- Challenges: Hydrogen embrittlement of steel components; tank volume requirements; port infrastructure
- Timeline: 2030–2035 for maritime certification
- GHG Reduction Potential: 100% CO_2 equivalent (if hydrogen from renewable electricity)

16.3 Advanced Engine Control Systems

Artificial Intelligence (AI)-Based Optimisation:

- Real-time gas quality assessment from combustion signature
- Predictive maintenance alerts: bearing wear, gas valve drift
- Load prediction from weather/ route data; pre-optimised operating parameters
- Status: Prototype testing on MAN SaCoSone system; commercial availability 2026–2027

17. Regulatory & Standards Framework

17.1 Key Standards for Dual-Fuel Engines

ISO 3046-1

Used for **engine rating**

- Defines:
  - o Power (MCR)
  - o Efficiency
- Based on standard conditions:
  - o 1 bar, 25°C, 45% humidity

ISO 3046-4

Used for **engine testing**

- Covers:
  - o Factory Acceptance Test (FAT)
  - o Fuel consumption measurement
  - o NOx emission testing

IMO MARPOL Annex VI

Main **emission regulation**

- Controls:
  - o Fuel sulphur
  - o NOx emissions
- Tier III limit:
  - o Very strict NOx limits for ships

IMO IGC Code

Applies to **gas-fuel ships (LNG)**

- Covers:
  - o Tank design & certification
  - o Safety systems
  - o Crew training
  - o Emergency procedures

DNV (Class Rules)

For **engine approval**

- Requires:
  - o Prototype testing
  - o Material certification
  - o Reliable control systems

ISO/IEC 60945

For **electronic systems**

- Ensures:
  - o Safe operation of control systems
  - o Cybersecurity of marine equipment

18. Conclusion:

- Both **two-stroke and four-stroke dual-fuel engines** are now **proven and widely used**.

Two-Stroke DF Engines

- Very **high efficiency (~50%)**
- High power → best for **large ships**
- Very **low NOx and methane slip**
- Need **SCR/EGR in diesel mode**

Four-Stroke DF Engines

- More **flexible and compact**
- Suitable for:
    - Ferries
    - Offshore vessels
- Can use many fuels (LNG, methanol, etc.)
- Meet **Tier III in gas mode**

Economic View

- Higher initial cost
- But:
    - Fuel savings
    - Lower emission penalties

☞ Overall cost-effective over time

Industry Trend

- Dual-fuel becoming **mainstream**
- ~50% of new ships expected to be DF

18.1 Technical Summary (Simplified)

Combustion Design

- High swirl, efficient combustion
- Strong pistons (steel + cast iron)

Gas System

- Low-pressure gas supply (3.5–8.5 bar)
- Safe design (double protection systems)

Pilot Fuel

- Small amount (2–5%) for ignition
- Controlled electronically

18.2 Performance & Emissions

Environmental Benefits

- NOx ↓ **85–90%**
- CO_2 ↓ **13–17%**
- PM ↓ **85–95%**
- SOx = **zero**

Efficiency

- Gas mode: **46–49%**
- Diesel mode: **42–47%**

Economics

- Fuel savings: **$2–3M/year (typical vessel)**
- Payback: **~1 year**
- 10-year benefit: **$8–14M**

18.3 Retrofit Recommendation

Good Candidates

- Vessel age: **8–15 years**
- Operates in **regulated waters**
- LNG available at ports
- High fuel cost exposure

Not Suitable

- Vessel >20 years
- Poor engine condition
- No LNG infrastructure
- Weak financial condition

18.4 Key Success Factors

- Strong **IMO regulations**
- LNG bunkering availability
- Fuel price management
- Crew training
- Predictive maintenance

18.5 Final Recommendations

For Ship Owners

- Do **10-year cost analysis**
- Prefer ships operating in **ECA zones**
- Plan retrofit during overhaul
- Involve class early

For Manufacturers

- Reduce methane slip
- Improve automation (AI control)
- Expand retrofit kits
- Develop future fuels

For Policymakers

- Support IMO regulations
- Provide **green finance incentives**
- Expand LNG infrastructure
- Standardize safety rules

References and Data Sources

Technical References

- **MAN Energy Solutions**: 51/60DF and L32/40DF manuals and project guides
- **Hyundai HiMSEN**: H27DF project guide and performance data
- **Wärtsilä**: 46F product guides and technical documents
- **Standards**: ISO 3046-1, ISO 8178-4, MARPOL Annex VI

Regulatory References

- IMO MARPOL Annex VI (including MEPC.305(73))
- IMO NO_x Tier III Technical Code
- IGC Code for gas-fuelled ships

Economic Data Sources

- LNG prices: FRED, U.S. EIA
- Marine fuel costs: Clarksons, World Bank
- Retrofit cost data: Industry projects (2020–2024)

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