ISSN 2250-1967

MARINE INDIA ENGINEERS REVIEW

JOURNAL OF THE INSTITUTE OF MARINE ENGINEERS (INDIA)

Volume : 20 Issue : 3 February 2026 ₹ 90/-

BEYOND COMPLIANCE: Engineering Accountability at Sea

The Institute of Marine Engineers (India)

IMEI HOUSE, Plot No.94, Sector-19, Nerul, Navi Mumbai.

Tel: +91 – 8454847896/ 022-27711663
Email: training@imare.in. Website: https://imare.in/

REGISTRATION OPEN FOR Following DGS APPROVED COURSES

- Basic Training for Ships using Fuels covered within IGF code ***Course Id – 5311*** (OFFLINE) – (5 Days) - 23rd Feb 2026 / 09th March 2026 /23rd March 2026
- Assessment, Examination and Certification of Seafarers ***Course Id – 1062*** (OFFLINE) – (12 Days) - 09th March 2026 / 11th May 2026
- Advanced Training for Ships using Fuels covered within IGF code ***Course Id – 5312*** (OFFLINE) – (5 Days) - 10th Feb 2026 / 02nd Mar 2026
- MEO Cl. I (FG) : 2- months course (OFFLINE) - 2nd March 2026 / 2nd May 2026 / 1st July 2026 / 1st Sep 2026 (followed by Simulator course) **Discount on combined bookings of Class I Course with Simulator**
- MEO (CEO – NCV) – STCW 2010: 2 month course (OFFLINE) – 02nd March 2026 / 01st July 2026 / 02nd November 2026
- MEO (SEO – NCV) Part-A - STCW 2010: 2-month course (OFFLINE) – Commencing Soon
- MEO (SEO – NCV) Part-B - STCW 2010: 4-month course (OFFLINE) – 02nd May 2026
- MEO Cl. IV (NCV) - STCW 2010 - 4 months course (OFFLINE) – Commencing Soon
- MEO (CEO – NCV) BRIDGING COURSE: 15 Days (OFFLINE) – 01st April 2026 / 01st June 2026 / 03rd Aug 2026 / 01st Oct 2026 / 01st Dec 2026
- MEO (NCV – SEO) BRIDGING COURSE: 1 Month (OFFLINE) – Commencing Soon
- MEO CL. II (FG): 4-month Course (OFFLINE) – 2nd March 2026 (Discount on combined bookings of Class II Courses with Simulator)
- REFRESHER & UPDATING TRAINING (RUT - 4 DAYS) COURSE FOR REVALIDATION OF COC FOR ALL ENGINEERS and ETOs (OFFLINE) – 2nd March 2026/ 2nd May 2026/ 1st July 2026/ 1st Sep 2026
- ENGINE ROOM SIMULATOR MANAGEMENT LEVEL (3 DAYS) COURSE FOR MEO CLASS I (OFFLINE) – 26th Feb 2026/ 2nd March 2026/ 28th April 2026/ 2nd May 2026
- ENGINE ROOM SIMULATOR MANAGEMENT LEVEL (5 DAYS) COURSE FOR MEO CLASS II (OFFLINE) – 24th Feb 2026 / 2nd March 2026/ 26th March 2026 / 1st Apr 2026/ 25th Apr 2026/ 2nd May 2026/ 26th May 2026/ 1st June 2026/ 25th June 2026
- ENGINE ROOM SIMULATOR OPERATIONAL LEVEL (3 DAYS) COURSE (OFFLINE) - Commencing Soon
- MEO Cl. IV(FG) non mandatory course (2months duration) – On request

For Payment: Visit https://imei-mum.marineims.com/course/register

For enquiries contact on training@imare.in

For registration of Courses, visit:
https://imeimum.marineims.com/course/register

Features:
Experienced Faculty, Individual Attention

AMET City College
(Post Sea Training Centre)

AMET, the Pioneer of Maritime Education with 32 + years of existence announces its expansion into the furtherance of Seafarers Career Path through AMET CITY COLLEGE, a Post Sea Training Institution situated at Villivakkam, the heart of the Chennai City.

S.NO	ID	COURSE	Duriation
		ENGINE ROOM SIMULATOR	
1	3241	Diesel Engine Combustion Gas Simulator MEO Class I	3 Days
2	3221	Engine Room Simulator - (Management level) MEO Class II	5 Days
3	3121	Engine Room Simulator - (Operational level) MEO Class IV	3 Days
		NAVIGATION SIMULATOR	
4	4211	Global Maritime Distress Safety System (GMDSS)	12 Days
5	2121	Radar Observer Simulator - (ROSC)	10 Days
6	2122	Automatic Radar Plotting Aids - (ARPA)	5 Days
7	2123	Electronic Chart Display And Information Systems - (ECDIS)	6 Days
8	2221	Radar And Navigation Simulator (RANSCO)	6 Days
		ADVANCED MODULAR COURSES	
9	5312	Advanced Training for Ships using Fuels covered within IGF code (AIGF)	5 Days
10	5112	Advanced Training for Oil Tanker Cargo Operations (TASCO)	10 Days
11	5122	Advanced Training for Gas Tanker Cargo Operations (GASCO)	10 Days
12	5113	Advanced Training for Chemical Tanker Cargo Operations (CHEMCO)	10 Days
13	1061	Vertical Integration Course For Trainers - (VICT)	10 Days
14	6421	Medical Care (MC)	10 Days
		BASIC MODULAR COURSES	
15	5311	Basic Training for Ships using Fuels covered within IGF code - (BIGF)	4 Days
16	3123	High Voltage Safety And Switch Gear - (Operational Level)	1 Days
17	6101	Basic Safety Training [BST= EFA+FPFF+PST+PSSR]	12 Days
18	6621	Security Trng. for Seafarer with Designated Security Duties - (STSDSD)	3 Days
19	5121	Basic Training for Liquified Gas Tanker Cargo Operations (BTLG)	5 Days
20	5111	Basic Training for Oil and Chemical Tanker Cargo Operations (BTOC)	7 Days
21	5211	Crowd Management, Passenger Safety & Safety Traning - (PSF)	3 Days
22	6511	Ship Security Officers - (SSO)	3 Days
23	6411	Medical First Aid (MFA)	4 Days
		REFRESHER COURSES	
24	1118	Revalidation / Refresher and Updating Training for Engineers and ETO (REO)	4 Days
25	6412	Refresher Training in Medical First Aid Course (RMFA)	1 Day
26	6122	Refresher Training for Proficiency in FPFF	Half Day
27	6112	Refresher Training for Proficiency in PST	Half Day

		COMPETENCY COURSES	
28	3231	MEO Class I	2 Months
29	3211	MEO Class II	4 Months
30	-	MEO Class IV (Value Added)	2 Months
31	2211	Chief Mate (FG) Phase - I	3 Months
32	2212	Chief Mate (FG) Phase - II	3 Months
33	2111	Second Mate (FG)	4 Months

ADMISSION
+91-91760 79666
+91-91760 44766

PRINCIPAL : +91 94449 62378

DIRECTOR : +91 91768 34833 , +91 88258 77750

ametcitycolleggeadmissions@gmail.com

R.R. Towers, 61/54, Jawaharlal Nehru Inner Ring Road (200 Feet Road) Villivakkam, Chennai - 600 049

The Institute of Marine Engineers (India)

MUMBAI BRANCH ALONG WITH NAVI MUMBAI & GUJARAT CHAPTERS

CORDIALLY INVITE YOU FOR THE

Technical Seminar and Annual Meet 2026

SAVE THE DATE
27 FEBRUARY 2026

Venue:
Mumbai Cricket Association, MCA Club Lawns BKC, Mumbai

For any queries or sponsorship details,
Pls contact: Mr. Suraj : 9967481448; mumbai@imare.in

EDITORIAL

Shipping has always been comfortable with clear, hard limits—steel thickness, pressure ratings, safety margins, and written procedures. What feels different today is that the main limit affecting decisions is no longer technical. It is time. In early 2026, time—not technology—has become the most restricted resource for the maritime industry.

Across recent industry developments, one pattern is clear: the gap between a decision and its consequences is shrinking. Regulatory changes, fuel rules, cyber events, and operational errors now lead to financial loss, reputational damage, or compliance action very quickly. In other safety-critical industries, this has already forced a shift from slow, step-by-step decision-making to faster, real-time control. Shipping is now facing the same challenge, often without being fully prepared for it.

Traditionally, shipping has relied on gradual change. The industry tested new ideas carefully, delayed major investments, and waited for clear regulatory direction. That approach worked when change was slow and predictable. Today, uncertainty has become permanent. In this environment, the ability to adapt is more valuable than trying to predict the future. Progressive companies are therefore planning ships, contracts, and training systems to remain flexible, rather than committing fully to one fuel, one technology, or one rule set.

Recent events in other high-risk industries highlight an important lesson. Serious incidents rarely happen because people lack knowledge or ignore rules. More often, they occur when skilled professionals operate within written limits that no longer match real operating conditions. Decisions may be technically correct, still become unsafe when time pressure removes safety buffers. This is a situation familiar to marine engineers—whether during maintenance deferrals, machinery operation, or tight commercial schedules.

There is also a clear lesson from the information-technology sector. The strongest organisations were not those that chose the "right" system early, but those that built systems flexible enough to change. Shipping is moving in the same direction: machinery arrangements that allow retrofits, documentation that can support inspections and audits, and training that develops judgement rather than simple rule-following.

These changes place marine engineers at the centre of company strategy. Choices made in the engine room—about maintenance, redundancy, fuel handling, and data quality—now affect compliance, reputation, and commercial trust as much as technical performance.

The February message is therefore not only about decarbonisation or disruption. It is about pace. Companies that succeed will be those that align technical capability, quick decision-making, and clear accountability. In a world where consequences arrive faster than ever, being prepared is no longer just good practice—it is a strategic advantage.

This is the first in five-part series on evolution of alternative fuel engines. This article examines modern dual-fuel two-stroke marine engines, tracing their evolution and comparing technologies. It highlights high-pressure gas injection as the benchmark, delivering low methane slip, high efficiency, full power capability, and strong alignment with future decarbonisation regulations.

The second article is the concluding Part 3 on shipbuilding contracts and pitfalls. The article examines how shipbuilding contracts function in real shipyards, showing how site-team actions, refund guarantees, liquidated damages, warranties, and documentation discipline determine legal outcomes, and arguing that disciplined execution—not drafting alone—prevents disputes in modern shipbuilding projects.

The third article analyses ship recycling's evolution into a regulated, ESG-aligned industrial activity, examining Basel, Hong Kong Convention and EU SRR frameworks, global capacity constraints, and India's leadership in compliant yards. It positions ship recycling as a circular-economy pillar, delivering material recovery, climate benefits, worker safety, and sustainable end-of-life management for ageing fleets.

The fourth article explains how ocean thermodynamics drive cyclone intensification in the Bay of Bengal, using NIOT buoy observations and a novel OAEE-TS algorithm. By integrating subsurface temperature, salinity, and heat-content data, it demonstrates improved prediction of rapid intensification, supporting better forecasting, early warning, and disaster preparedness in a warming ocean

The fifth article provides a comprehensive technical guide to LNG carrier sea trials, explaining preparation, test sequences, measurement methods, and acceptance criteria. It highlights how sea trials validate hydrodynamic performance, dual-fuel propulsion, automation, vibration, noise, safety systems, and regulatory compliance, serving as a practical reference for engineers, surveyors, and LNG operations professionals.

The last article investigates modern shipboard blackouts as system-level failures involving automation logic, power management systems, electrical protection, and human–machine interaction. Using investigative case frameworks, it explains how hidden configuration errors escalate into casualties, and outlines technical, operational, and regulatory measures to prevent blackouts and strengthen electrical resilience on bulk carriers.

Mani Ganapathi Ramachandran
Honorary Editor
Head – Engineering, HIMT
editormer@imare.in

THE INSTITUTE OF MARINE ENGINEERS (INDIA)
MUMBAI BRANCH ALONG WITH ITS CHAPTERS
GUJARAT AND NAVI MUMBAI

In association with

पत्तन, पोत परिवहन
एवं जलमार्ग मंत्रालय
MINISTRY OF
PORTS, SHIPPING
AND WATERWAYS

IRCLASS
Indian Register of Shipping

Platinum Sponsor

Theme: Maritime Landscape 2030 Opportunities and Challenges

INMARCO
2026

Request you to kindly "save the date" for

International Maritime Conference cum Exhibition 2026

WHEN 27th to 29th Oct 2026

WHERE Westin, Powai, Mumbai

ABOUT THE CONFERENCE:

Since its inception in 1982, INMARCO has always witnessed an overwhelming response from the Maritime sector which in turn had inspired IME(I) to organise INMARCO quadriennially.

Papers are invited from Engineers, Manufacturers, Designers, Shipbuilders, Operators, Students, Educators, Researchers, Recyclers, Adjudicators, Salvors, Class, Administrators, Marine Infrastructure Companies, Port Operators, Surveyors, Maritime Lawyers, Navies, Coast Guard and other Maritime related stakeholders.

Sessions on current topics with emminent panelists and moderators.

Curated Competitions for Students from MTIs, Maritime Universities and Marine Divisions of Engineering Colleges.

Contact us for more details: info@inmarco.in | inmarco@imare.in Mr. Suraj Negi +91 9967481448

MARINE ENGINEERS REVIEW INDIA

JOURNAL OF THE INSTITUTE OF MARINE ENGINEERS (INDIA)

Administration Office
IMEI House
Plot No. 94, Sector - 19, Nerul,
Navi Mumbai 400 706.
Tel. : +91 22 2770 16 64
Fax : +91 22 2771 16 63
E-mail : editormer@imare.in
Website : https://imare.in/

Editor
Mani Ganapathi Ramachandran

Printed, Published and Edited by:
Mani Ganapathi Ramachandran on behalf of The Institute of Marine Engineers (India). Published from 1012 Maker Chambers V, 221 Nariman Point, Mumbai - 400 021, printed by Corporate Prints, Shop No.1, Three Star Co-op. Hsg. Society, V.P Road, Pendse Nagar, Dombivli (E) - 421 201.
District – Thane

Print Version: **Corporate Prints**

Typesetting & Web designed by:
Kryon publishing (P) Ltd.,
www.kryonpublishing.com

In This Issue

ARTICLES

COLUMNS

Cover Credits: **Kryon**

HIMT

26 YEARS EXCELLENCE IN EDUCATION SINCE 1998

D. G. Shipping Approved

REFRESHER COURSES

Location - **Chennai & Vizag***

COURSES	DURATION
Refresher Training For Proficiency In FPFF (R-FPFF)	1 Day
Refresher Training For Proficiency In PST (R-PST)	1 Day
Refresher Training For Advanced Training In Fire Fighting (Includes RFPFF) (R-AFF)	1 Day
Refresher Training For Proficiency In PSCRB (Includes RPST) (R-PSCRB)	1 Day
Revalidation / Refresher and Updating Training for Engineers and ETO (REO)	4 Days
Revalidation / Refresher and Updating Training for Masters and Deck Officers (RUT)	4 Days
Refresher Training For Medical First Aid (R-MFA)	1 Day
Refresher Training For Medical Care (R-MC)	1 Day

NO EXIT EXAMS (Only Institute Assessments)

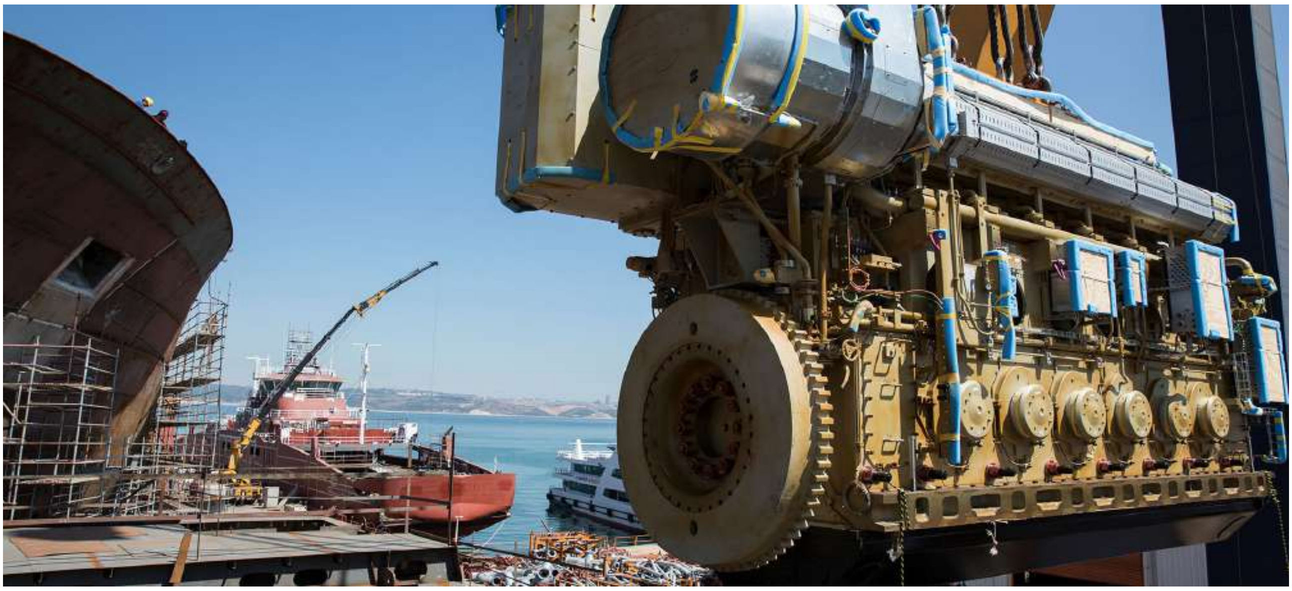
*RUT available only in Chennai

Scan to book

98404 00000
help@himtmarine.com
www.himt.co.in

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

Part 1: Historical Development and High-Pressure Gas Injection



Kaushik K. Seal
Saptarshi Basu

Abstract

The maritime industry is undergoing a decisive shift toward cleaner propulsion technologies as regulatory pressures, market expectations and decarbonisation strategies converge. Dual-fuel (DF) engines—capable of operating on both conventional liquid fuels and gaseous fuels such as LNG, ethane, LPG and methanol—represent the most widely adopted transitional solution for oceangoing vessels. This article presents a structured analysis of modern dual-fuel two-stroke engines, with particular emphasis on high-pressure gas-injection (HPGI) systems used in MAN B&W ME-GI engines.

The paper reviews the historical evolution of DF concepts, clarifies the combustion fundamentals underpinning diesel-cycle versus Otto-cycle engines and examines methane-slip mechanisms that influence environmental outcomes. The article also describes fuel-quality sensitivities, safety architectures, operational considerations and comparative performance characteristics. While multiple DF technologies coexist, high-pressure direct injection remains the benchmark for achieving low methane slip, high thermal efficiency and full power capability. The article concludes by outlining future developments, regulatory pressures and decarbonisation pathways expected to influence DF technology adoption between 2025 and 2040.

Keywords: ME-GI, ME-GA, X-DF, LNG, methane slip, HPGI, VCR, pilot ignition, diesel-cycle, decarbonisation

1. Introduction

Global shipping faces a pivotal transformation driven by greenhouse-gas (GHG) reduction mandates under MARPOL Annex VI, the IMO GHG Strategy and the EU Emissions Trading System (ETS). LNG has emerged as a practical alternative fuel, supported by maturing bunkering infrastructure and favourable emissions characteristics. Dual-fuel propulsion systems enable vessels to utilise gaseous fuels when desirable and revert to liquid fuels when required by operational or commercial constraints. This flexibility has made DF engines the dominant choice for LNG carriers and increasingly attractive for tankers, container ships and multipurpose vessels.

The IMO's target of a 40 percent reduction in carbon intensity by 2030 and a 50 percent reduction in total GHG emissions by 2050 has accelerated investments in DF engines. LNG offers meaningful reductions in SOx, particulate matter and NOx emissions, while lifecycle GHG reductions depend heavily on controlling methane slip. This article focuses on the evolution, design and performance of modern DF technologies, especially high-pressure gas-injection systems.

1.1 Historical Background

Dual-fuel combustion traces back to the 1930s when scarcity of liquid fuels encouraged experiments with

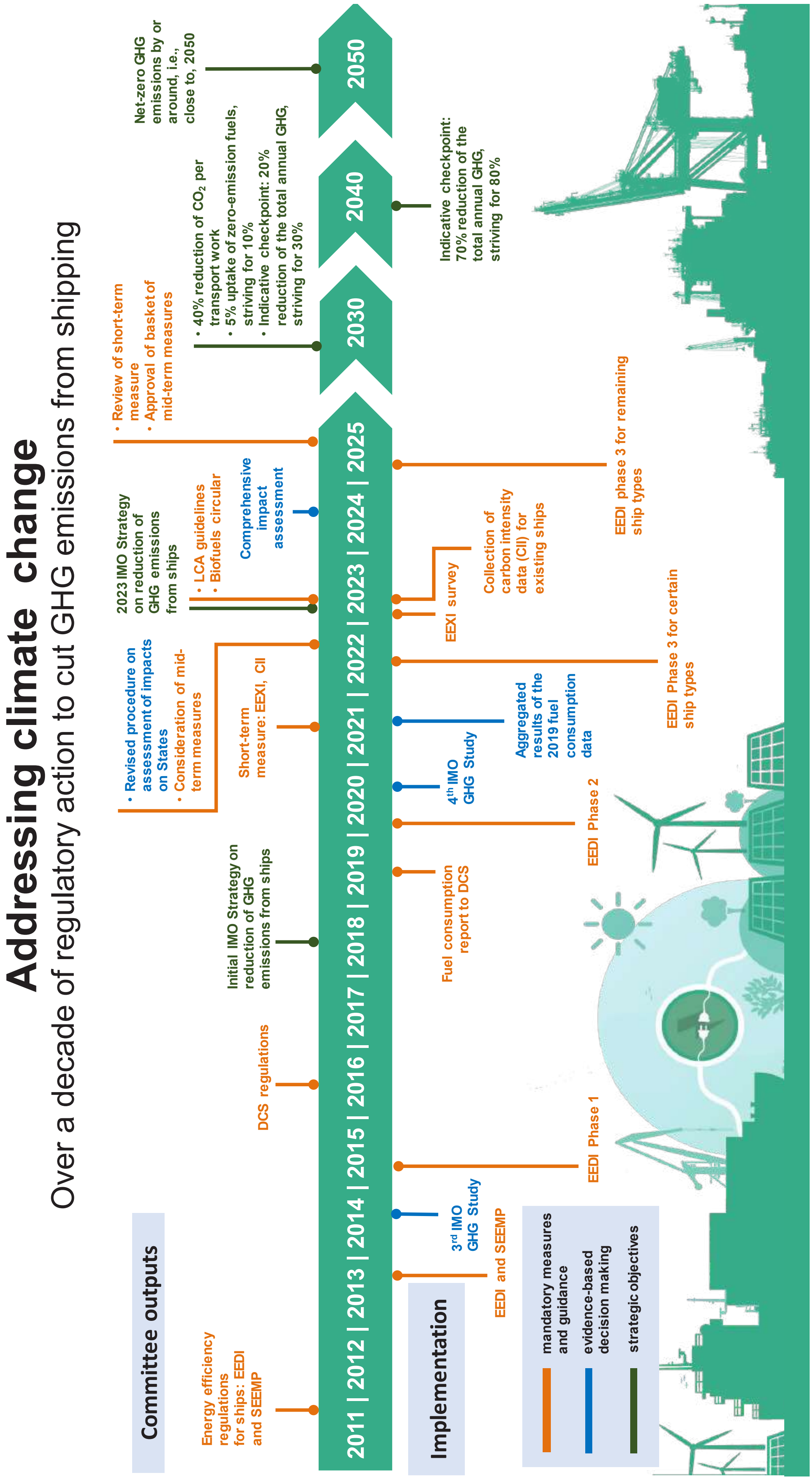


Figure 1: Drivers for Dual-Fuel Engine Adoption

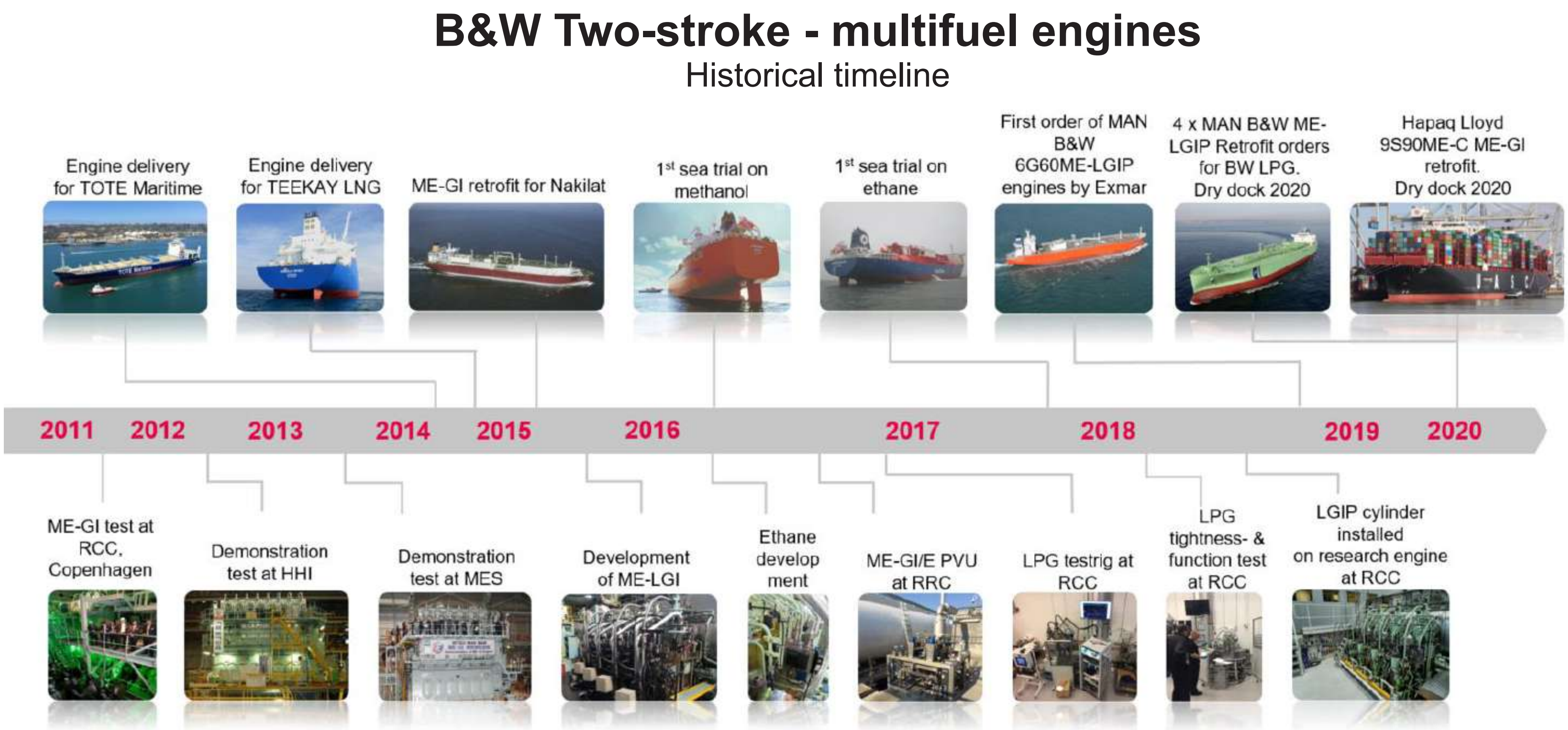


Figure 2: Evolution of Dual-Fuel Engine Technology

gaseous-fuel supplementation in stationary diesel engines. These early systems relied on a small pilot-diesel injection to ignite a premixed gas-air charge. Maritime applications advanced significantly in the 1990s when MAN B&W introduced the 12K80MC-GI-S engine at the Chiba power plant. Operating successfully for over 20,000 hours in gas mode, this installation validated the high-pressure direct-injection concept and demonstrated that diesel-cycle combustion could be preserved while using gas as the primary fuel.

Progress continued through the 2000s with the development of test beds in Copenhagen, collaborative work with major shipyards and parallel research into liquid-gas injection for methanol, ethanol, LPG and DME. Commercial momentum accelerated after 2012, when the first ME-GI-powered LNG-fuelled container vessels for TOTE were commissioned. By 2025, DF engines account for nearly 100 percent of new LNG-carrier orders and a growing share of global newbuilds across multiple segments.

1.2 Dual-Fuel Engine Families

Modern DF two-stroke engines fall into three categories:

a) High-Pressure Gas Injection (Diesel Cycle)

Example: MAN B&W ME-GI

Gas is injected at 250–300 bar during the final few crank-angle degrees before top-dead-centre (TDC). No gas is present during the compression stroke. Pilot-diesel injection provides ignition, preserving true diesel-cycle combustion. This approach achieves the lowest methane slip values (<0.3 g/kWh).

b) Low-Pressure Gas Admission (Otto Cycle)

Examples: MAN ME-GA, WinGD X-DF

Gas is introduced at 5–16 bar into the scavenge air, forming a lean premixed charge. A pilot injection initiates combustion. These systems generally have lower CAPEX but higher methane slip (historically 3–6 g/kWh, now reduced to ~1–2 g/kWh using EGR or iCER).

c) Variable Compression Ratio Otto-Cycle Engines

Example: WinGD X-DF2.0 with VCR

VCR improves efficiency and reduces methane slip by adjusting the compression ratio dynamically using hydraulics in the crosshead assembly.

1.3 Research Scope and Objectives

This article aims to:

- Provide a clear explanation of dual-fuel combustion principles.
- Compare design philosophies of high- and low-pressure DF engines.
- Examine methane-slip mechanisms and mitigation strategies.

Combustion concept	Diesel cycle	Otto cycle
Power density	Unchanged	Power reduced
Gas-mode efficiency	Increased	Unchanged
Diesel-mode efficiency	Unchanged	Reduced
Gas quality/requirements (LCV)	Insensitive	Sensitive
Methane number dependent	No	Yes
Pilot fuel oil (amount)	MDO/HFO (3-5%)	MDO (approx. 1%)
High ambient temperature	Insensitive	Sensitive
Combustion processes	Diesel process	Premixed
Cylinder max. pressure variations	Stable and low	Unstable and high
Knocking during load change	None	Possible
Misfiring	None	Possible
Methane slip	0.1% of SFOC	2-4% of SFOC
Global warming potential (GWP)	Reduced by 20%	Increased
Scavenge air receiver explosion risk	No	Yes
Crankcase explosion risk	No	Yes
Exhaust receiver explosion risk	No	Yes

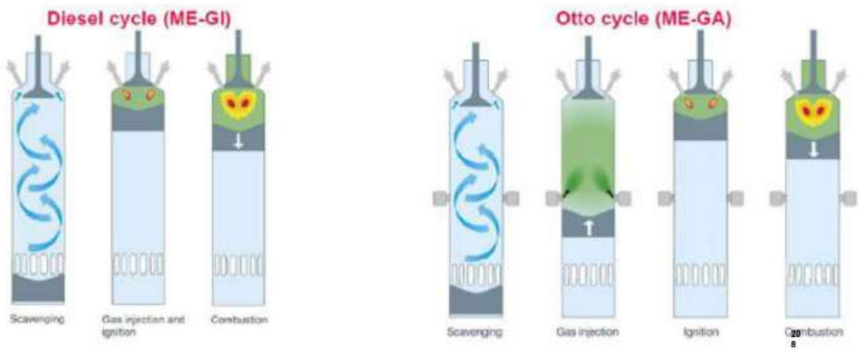


Figure 3: Comparison of ME-GI, ME-GA and X-DF Cycles

Pilot-diesel injection provides ignition, preserving true diesel-cycle combustion

- Summarise safety and control systems that enable safe DF operation.
- Address fuel-quality considerations relevant to LNG and other gaseous fuels.
- Discuss operational practices and emerging trends influencing DF technology.

2. Thermodynamic and Combustion Fundamentals

2.1 Diesel-Cycle and Otto-Cycle Principles

The thermodynamic cycle determines combustion stability, efficiency and emissions.

Diesel Cycle (ME-GI)

- Compression ratio: 14:1–25:1
- Fuel ignited by spontaneous auto-ignition of pilot diesel
- Gas injected at high pressure near TDC
- Supports stratified combustion and high thermal efficiency

Otto Cycle (ME-GA and X-DF)

- Compression ratios typically 8:1–12:1
- Premixed charge ignited by pilot injection
- Lean combustion (lambda ~1.8–2.2) minimises NOx
- More susceptible to knock and pre-ignition

2.2 Combustion Processes

Premixed Combustion in Low-Pressure Engines

Gas introduced during scavenging mixes with air to create a homogeneous charge. Pilot injection ignites the mixture. Excessively lean or rich mixtures can lead to misfire or knock, requiring careful lambda control.

Direct-Injection Combustion in ME-GI Engines

Gas is introduced only after compression, into an environment already heated to ignition-ready temperatures by the pilot flame. The injected gas forms a stratified mixture, ensuring controlled heat release and minimal unburned methane.

2.3 Methane Slip Mechanismsh

Methane slip arises when unburned methane escapes to the exhaust stream. Key mechanisms include:

1. **Crevice Trapping:** Gas retained in piston-ring packs and gasket cavities fails to combust.
2. **Flame Quenching at Cold Walls:** Temperature gradients near the liner extinguish the flame.
3. **Incomplete Low-Load Combustion:** Low temperatures and slow flame propagation reduce burn completeness.

Feature	ME-GI (Diesel cycle)	ME-GA (Otto cycle)
Gas pressure	High pressure (250–300 bar)	5–13 bar LP gas admission
Combustion	Non-premixed	Premixed
Methane slip	**0.1–0.3 g/kWh**	**2–4% of SFOC** (higher)
Power Density	Unchanged	Lower
Knock / Pre-ignition	None	Possible
Sensitivity to gas quality	Low	High
NOx emissions	Diesel-like; need EGR/SCR	Inherently lower
FGSS requirement	HP pump + vaporizer	LP cryogenic compressor/pump

Figure 4: Placeholder – Cylinder Pressure Profiles for Diesel and Otto Cycles

4. **Scavenge Loss (Low-Pressure Engines):** Some gas exits before exhaust-valve closure.

High-pressure engines avoid these modes by injecting gas directly into an already igniting charge.

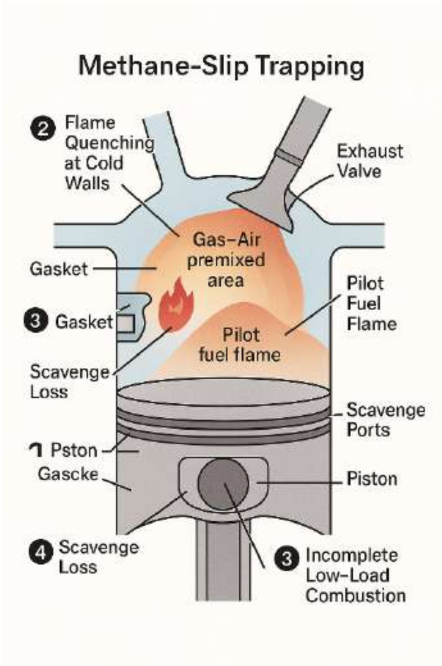


Figure 5: Methane-Slip Mechanisms

3. MAN ME-GI Engine: High-Pressure Gas Injection System

3.1 System Architecture

The ME-GI system combines the following major subsystems:

- **High-Pressure Fuel Gas Supply:** LNG is pumped to 250–300 bar, vaporised, heated and delivered to the engine through double-wall piping.
- **Gas Valve Train (GVT):** Distributes high-pressure gas to each cylinder with continuous annular hydrocarbon monitoring.

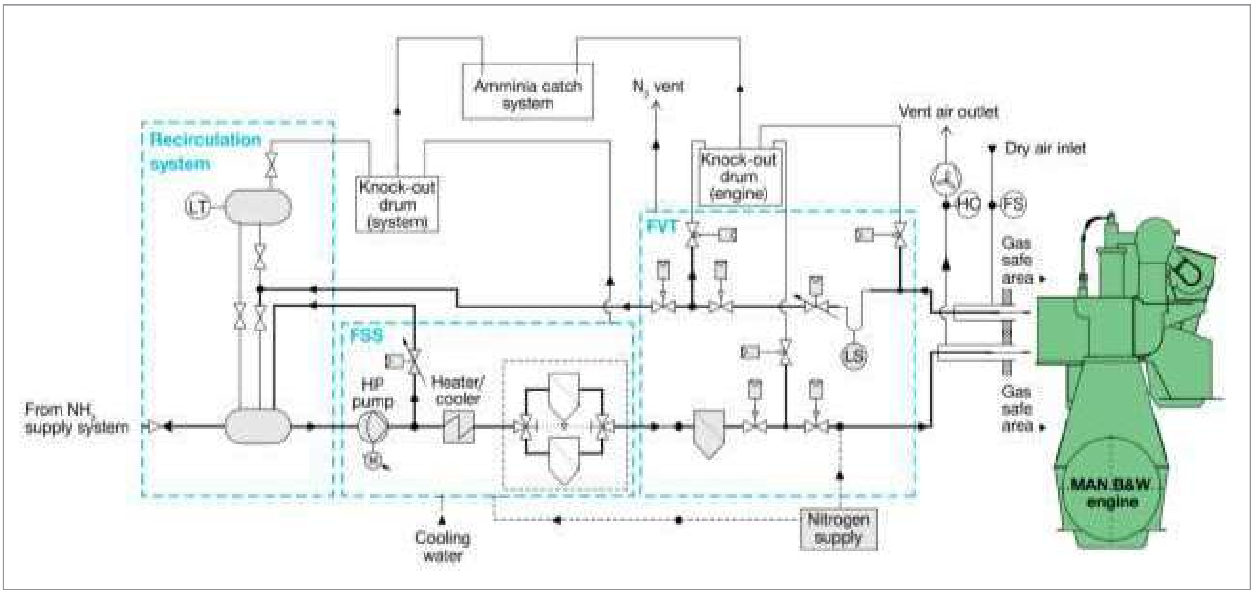


Figure 6: ME-GI System Layout

- **Electronic Gas Injection (ELGI):** Two gas injection valves per cylinder, hydraulically actuated using 240–260 bar control oil.
- **Pilot Fuel System:** Provides stable ignition with less than 5 percent energy share at full load.
- **Hydraulic Power Supply:** Feeds control oil to actuate gas valves, exhaust valves and pilot valves.
- **Hydraulic Cylinder Units:** Cylinder-specific blocks that manage valve operation.

3.2 Major Components

- **Gas Injection Valves:** Double-walled, high-pressure components with sealing-oil barriers.
- **Pilot Valves:** Provide repeatable ignition and redundancy.
- **Tacho Sensors:** Supply accurate crank-angle signals for precise combustion timing.
- **Control Valves and Actuators:** Enable flexible injection profiles for efficiency and load stability.

3.3 Gas Admission vs. Gas Injection

ME-GI High-Pressure Injection

- Maintains diesel-cycle combustion
- Eliminates premixed charge
- Achieves minimal methane slip
- No derating in gas mode

ME-GA Low-Pressure Admission

- Uses Safe Gas Admission Valves (SGAVs)
- Requires EGR to stabilise combustion
- Cheaper but less energy-efficient under some conditions

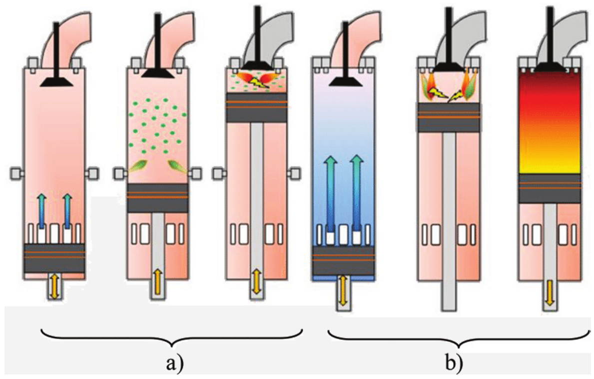


Figure 7: HP vs. LP Gas Introduction Methods

3.4 Knock Detection and Control

Knock is monitored through:

- In-cylinder pressure sensors
- Accelerometers detecting vibration signatures
- ECU algorithms computing a Knock Index

Corrective measures include reducing gas flow, increasing pilot fuel, or switching to diesel mode. These controls protect the engine while maximising gas utilisation.

> *“Methane slip directly influences CII ratings and ETS exposure”*

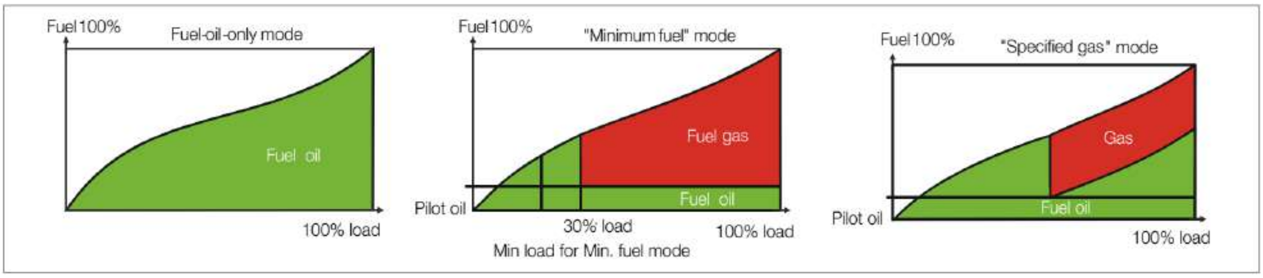


Figure 8: Fuel Switching Process

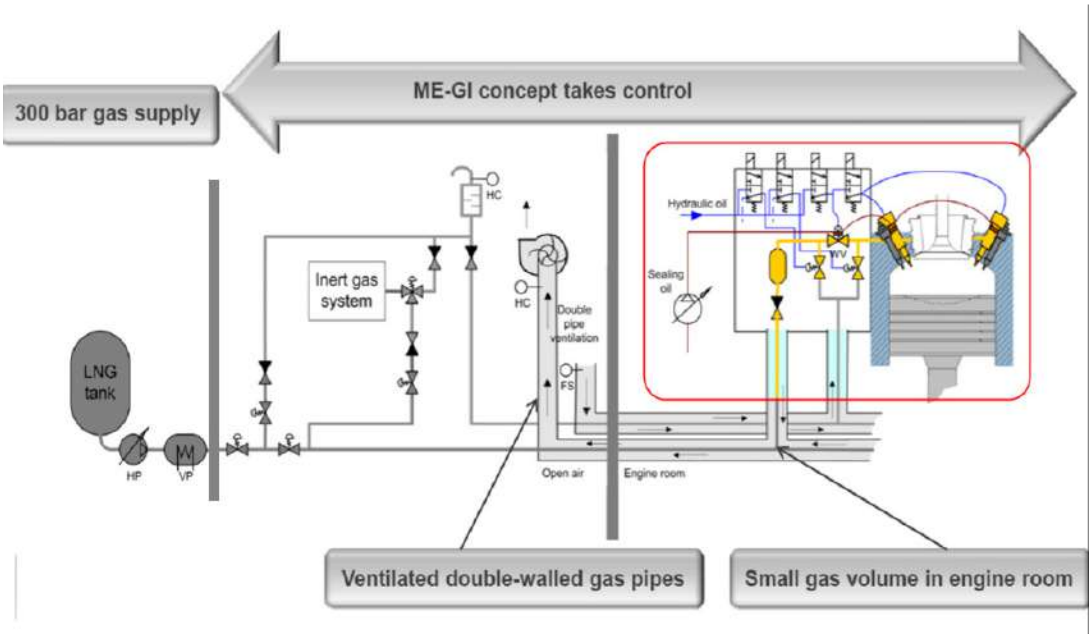


Figure 9: ME-GI Safety Systems

3.5 Operating Modes

1. **Gas Mode -** Air is compressed, pilot fuel ignites and gas injection begins approximately 2–5 degrees after pilot start. Combustion follows diesel-cycle behaviour.
2. **Diesel Mode -** Gas valves are isolated and purged. Engine behaves like a conventional ME series diesel.
3. **Fuel Switching -** Transition between fuels typically occurs within 30–60 seconds without power interruption.

Figure 8: Fuel Switching Process **3.6 Performance Characteristics**

- **Methane Slip:** 0.2–0.3 g/kWh (industry low)
- **Fuel Efficiency:** Equal to or better than diesel operation
- **Power Output:** Full SMCR in gas or diesel mode
- **Emissions:** Low NOx, near-zero SOx and PM

3.7 Safety Architecture

- **Double-Wall Piping -** Annular space continuously ventilated and monitored.
- **Hydrocarbon Detection -** Sensors placed along the piping, GVT, cylinder-head vents and engine room.
- **Valve Position Monitoring -** Ensures commanded and actual valve states match.
- **Inert-Gas Purging -** Automated multi-cycle depressurisation and nitrogen purging guarantee safety after gas shutdowns.
- **Fail-Safe Operation -** Redundant gas valves and pilot injectors ensure continued operation even with component failures.

4. Fuel-Quality and Contamination Considerations

4.1 Methane Number (MN)

MN measures knock resistance. Aging LNG reduces MN as heavier hydrocarbons accumulate, limiting load capability in Otto-cycle engines.

> *Fail-safe operation is ensured through redundancy*

4.2 LNG Aging and Composition Drift

Boil-off rates of 0.10–0.15 percent per day alter gas composition. Ethane and propane enrichment affects combustion properties.

4.3 Particulates

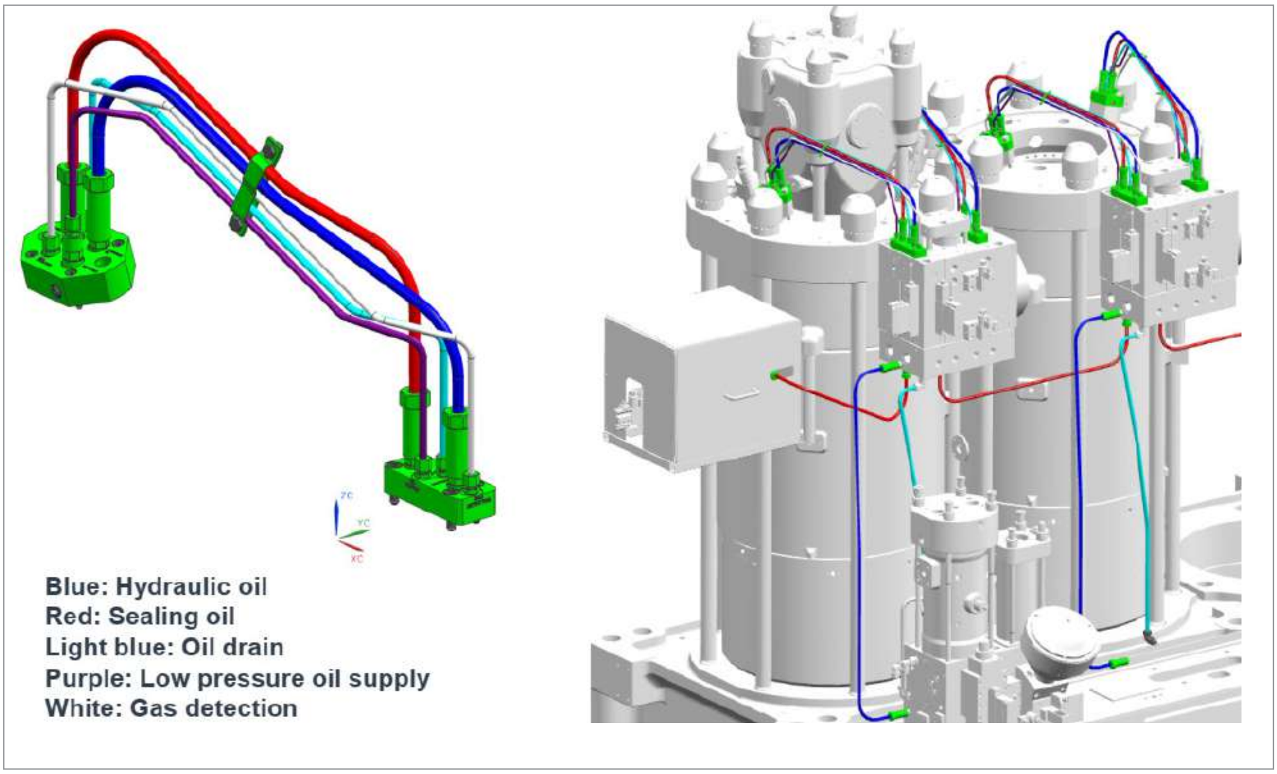
ME-GI systems tolerate up to 5 mg/m^3, while X-DF engines require levels below 2 mg/m^3 due to premixing sensitivity.

4.4 Moisture

Water content in LNG can cause flame quench and incomplete combustion.

4.5 Corrosive Contaminants

H_2S, chlorides and fluorides can damage components by forming acids at high temperature.



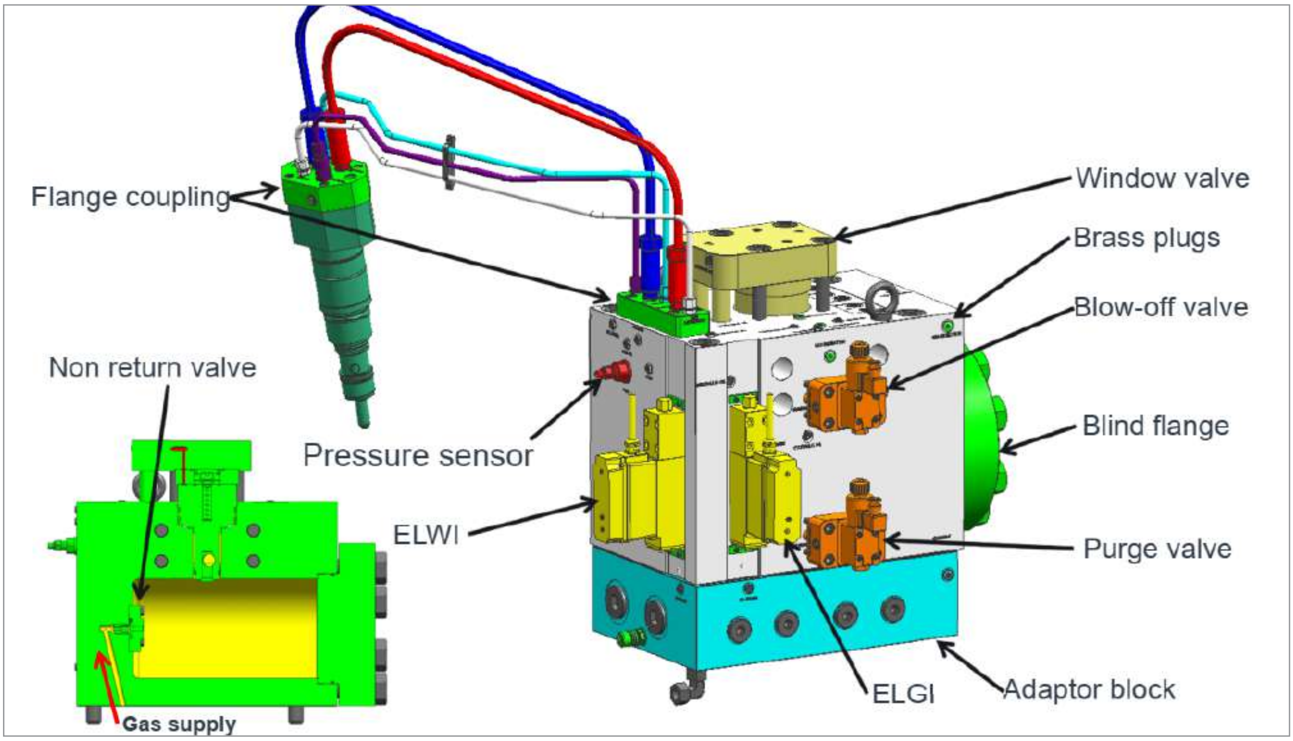


Figure 10: MEGI engine details

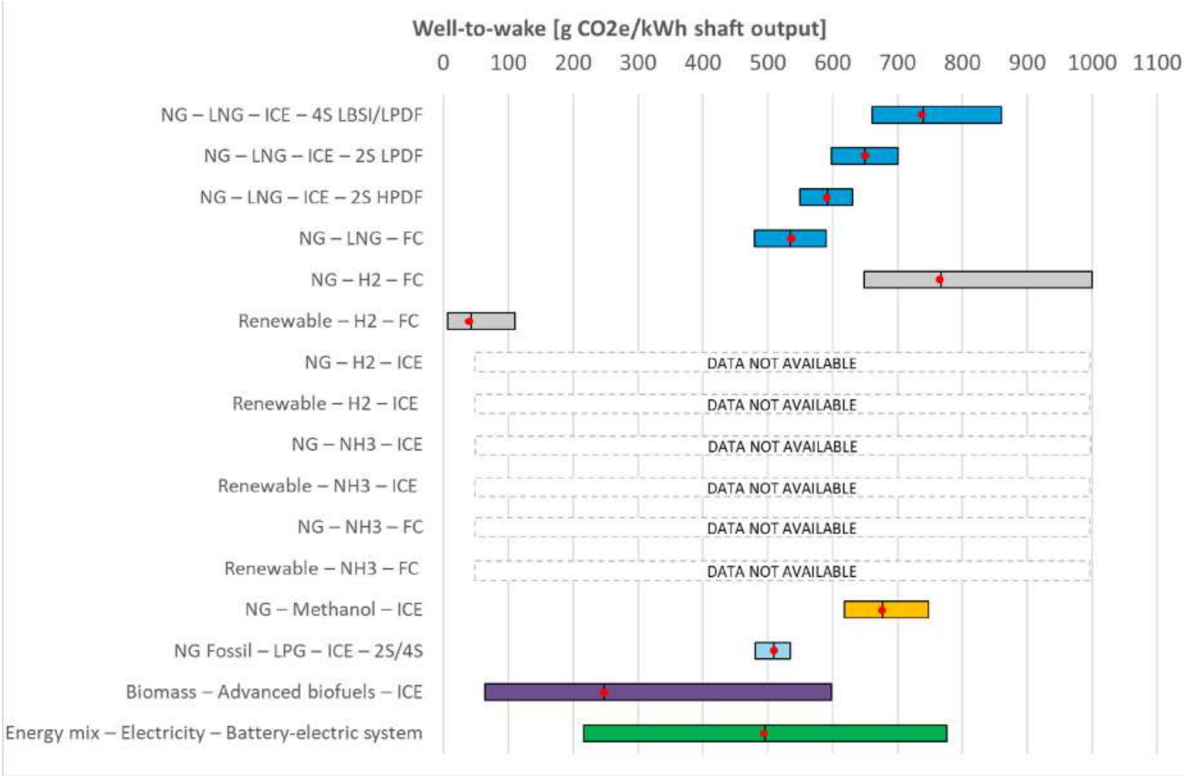


Figure 11: Comparison of Alternative Marine Fuels

5. Alternative Fuel Pathways

5.1 Ethane (ME-GIE)

Ethane propulsion is increasingly attractive for LEG carriers. The ME-GIE system uses similar high-pressure injection hardware to ME-GI, enabling seamless fuel flexibility.

5.2 Methanol (ME-LGIM)

Methanol burns cleanly, reduces NOx and is compatible with renewable production pathways. As a liquid fuel at ambient conditions, it simplifies onboard storage.

5.3 LPG (ME-LGIP)

Widely used in VLGCs, enabling operators to use cargo as fuel.

5.4 Ammonia (Development Stage)

Challenges include low flammability, NOx formation and material compatibility.

6. Operational Guidelines

6.1 Tuning Strategies

ME-GA engines can be tuned for efficiency, stability, or slip reduction. ME-GI engines focus on injection optimisation and pilot-fuel calibration.

6.2 Maintenance

- ME-GI gas valves inspected every 8,000 hours
- HP supply pumps serviced at 16,000 hours
- SGAV nitrogen-purge checks conducted monthly

6.3 Troubleshooting Common Issues

- Increased methane slip: injector wear or mixture imbalance
- Pre-ignition: low MN or turbocharger abnormalities

7. Regulatory and Economic Perspectives

7.1 Methane Slip Requirements

IMO and EU policies are shifting toward well-to-wake GHG accounting. Methane slip directly influences CII ratings and ETS exposure.

7.2 EU ETS Implications

Methane is priced at its CO_2-equivalent value, increasing the cost penalty for engines with high slip. ME-GI engines significantly reduce ETS obligations.

7.3 Economic Performance

Depending on fuel prices and vessel type, DF propulsion payback periods may range from 1 to 14 months.

8. Future Outlook (2026–2040)

2026–2030

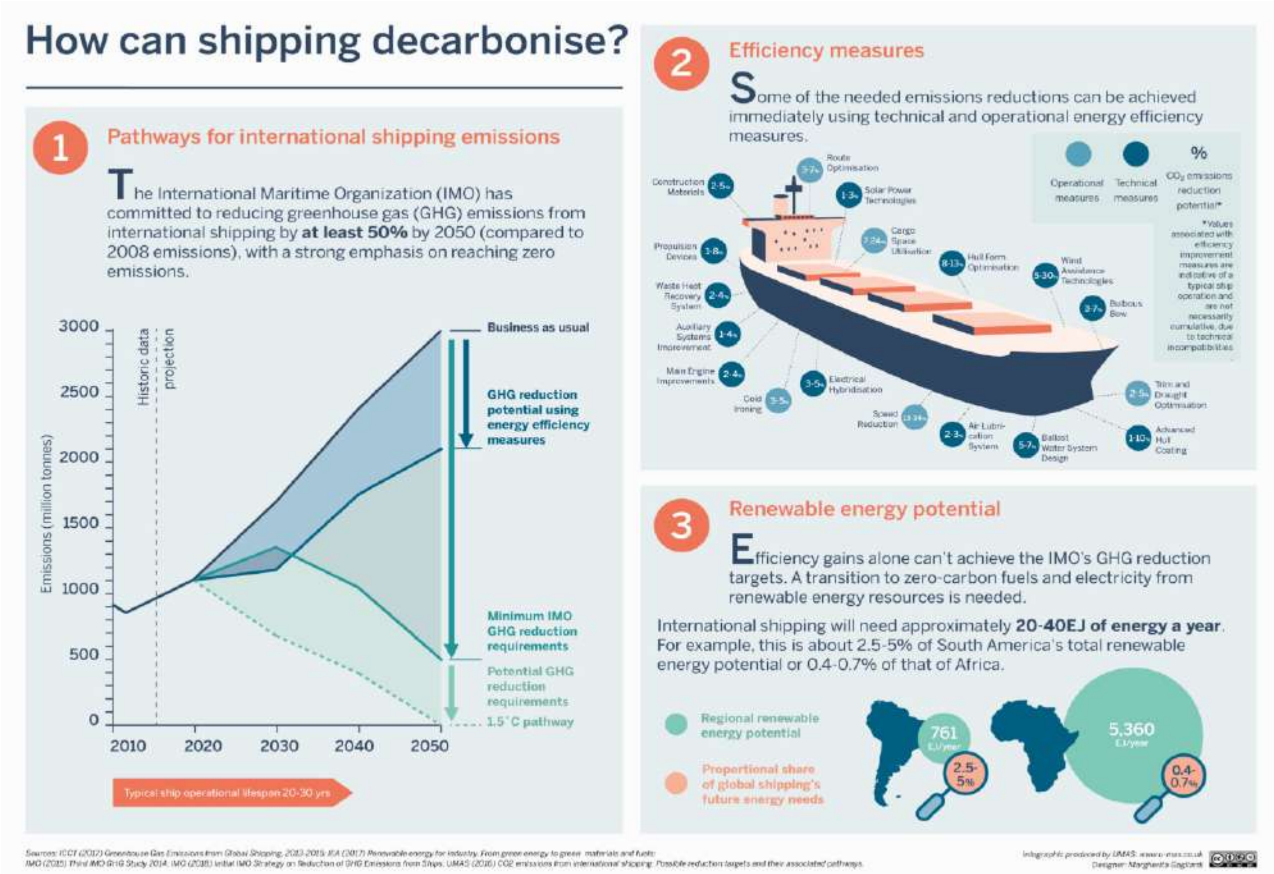


Figure 12: Technology Roadmap to 2040

- Retrofitting of EGR/iCER/VCR systems
- Standardised MN monitoring
- Improved cryogenic filtration

2030–2035

- Commercial ammonia DF engines
- High-pressure hydrogen-injection pilot studies
- Expanded production of bio-LNG and e-methane

2035–2040

- E-fuels dominate newbuild specifications
- Hybrid systems reach >60 percent total efficiency
- Integration of onboard carbon capture with DF engines

Summary

The paper "Dual-Fuel Gas-Burning Diesel Engines for Marine Propulsion: A Comprehensive Technical Analysis – Part 1" provides an in-depth examination of the historical development, thermodynamic principles, system architecture, performance characteristics and safety philosophy of modern two-stroke dual-fuel marine engines, with particular emphasis on high-pressure gas-injection (HPGI) technology.

The document traces the evolution of dual-fuel engines from early experiments in the 1930s and the landmark 1994 MAN B&W 12K80MC-GI-S stationary engine to the current dominance of electronically controlled ME-GI/ME-GA (MAN) and X-DF (WinGD) platforms in LNG carriers, container ships, tankers and gas carriers.

Three distinct technological families are compared:

1. High-Pressure Gas Injection (Diesel-cycle) – MAN ME-GI/ME-GIE/ME-LGIM
   - Gas injected at ~300 bar near TDC
   - Maintains true diesel-cycle thermodynamics
   - Pilot fuel <1–5 % of total energy
   - Methane slip: 0.2–0.3 g/kWh (lowest in the industry)
   - Full SMCR power in gas mode, no derating
   - Highest thermal efficiency, virtually identical to pure diesel operation
2. Low-Pressure Gas Admission (Otto-cycle) – MAN ME-GA & baseline WinGD X-DF
   - Gas admitted at 5–16 bar into scavenge air
   - Premixed lean-burn combustion (λ ≈ 2.0–2.2)
   - Pilot fuel 8–12 %
   - Higher methane slip (originally 3–6 g/kWh, now reduced to ~1.0–1.8 g/kWh with EGR/iCER)
3. Advanced Low-Pressure with Variable Compression Ratio – WinGD X-DF VCR (introduced 2024–2025)
   - Hydraulically actuated VCR via crosshead pin
   - Reported fuel consumption improvement of 5.8 % (gas mode) and 6.9 % (diesel mode versus fixed-CR X-DF

- Methane slip reduced to ~0.83 % of gas consumed

The paper places particular emphasis on the MAN ME-GI high-pressure gas-injection system, describing in detail:

- Cryogenic high-pressure pump and vaporizer (250–300 bar)
- Double-wall ventilated piping with continuous HC detection
- ELGI (electronic gas injection) valves with hydraulic actuation and sealing oil
- Redundant pilot fuel system
- Seamless fuel switching in <60 seconds without power loss
- Comprehensive safety philosophy (double block-and-bleed, inert-gas purging cycles, knock control, valve position feedback on every valve)

Methane slip mechanisms (crevice trapping, wall quenching, low-load incomplete combustion, scavenging losses) are rigorously explained, showing why diesel-cycle HPGI engines are essentially immune while Otto-cycle engines require EGR, iCER, lambda optimisation or VCR to reach acceptable levels.

Additional topics include alternative fuels (ethane ME-GIE, methanol ME-LGIM, LPG ME-LGIP, future ammonia), fuel-quality challenges (Methane Number, ageing, H_2S, halogens, particulates), regulatory drivers (IMO 2030/2050, EU ETS, FuelEU Maritime), economic payback calculations and operational/maintenance guidelines.

By September 2025, dual-fuel engines have achieved near-100 % market share in newbuild LNG carriers and strong penetration in container ships and large tankers, driven by both environmental regulations and attractive LNG-HFO price spreads.

Conclusion:

High-pressure gas-injection engines (MAN ME-GI) are currently the most mature and efficient dual-fuel solution for large ocean-going ships. By keeping the diesel cycle and injecting methane at **~300 bar** after scavenge-port closure, they deliver:

- **Very low methane slip** (<0.3 g/kWh)
- **Full power and torque** in gas mode
- **Diesel-like or better thermal efficiency**
- **Instant switching** between gas and oil fuel
- **Proven reliability** across millions of operating hours

In an ME-GI engine, the cylinder contains **air only during compression**. Gas is injected just before TDC, so there is no risk of auto-ignition despite methane's high-octane rating. A **small pilot-diesel shot** (1–5%) auto-ignites first, creating multiple flame kernels. The high-pressure methane jets mix with these flames and burn in a **controlled, stratified** diesel-like manner. This ensures stable ignition, accurate timing, complete methane combustion and **minimal methane slip**—something impossible with compression ignition of pure methane in a large two-stroke engine.

Low-pressure Otto-cycle engines (ME-GA and classic X-DF) are cheaper but once had higher slip and lower efficiency. New technologies—especially **variable compression ratio (VCR)** and **intelligent EGR**—have reduced methane slip to **below 1%** and improved fuel consumption, sometimes outperforming ME-GI at certain loads.

From a **well-to-wake GHG** perspective, ME-GI and modern X-DF VCR engines burning fossil LNG provide **20–28% lower emissions** than HFO, often with **12–18-month payback**. With **bio-LNG or e-LNG**, lifecycle GHG reductions reach **80–90%**, making advanced dual-fuel engines a central decarbonisation pathway for the next 15–20 years.

References

1. MAN Energy Solutions (2023–2025) – ME-GI, ME-GA and LGI technical papers.
2. WinGD (2024–2025) – X-DF VCR and iCER documentation.
3. IMO (2023–2025) – Methane-slip measurement and GHG guidelines.
4. ICCT (2024) – Methane emissions from LNG-fuelled ships.
5. DNV (2025) – Maritime Forecast to 2050.

About the Authors

Kaushik K. Seal Director of Slabs Consultancy and President of IMEI. Formerly associated with Maersk, StormGeo, DNVand Anglo-Eastern. A Chartered Engineer and Fellow of RINA and IMEI with extensive experience in sustainability, maritime digital solutionsand propulsion technologies.

Email: kkseal@gmail.com

Dr. Saptarshi Basu Maritime technologist and educator with over 25 years' experience as Chief Engineer, superintendentand academic leader. Chartered Engineer with expertise in marine engineering, environmental managementand training-method development.

Email: tigermariner@gmail.com

Pitfalls in Shipbuilding Contracts - Operational Realities and Legal Remedies in Shipbuilding (Part 3)

Narayana Prakash

Introduction

No contract, however elegantly drafted, is worth more than its execution. In shipbuilding, the most sophisticated clauses on refund guarantees, delivery schedules and warranties are ultimately tested not in courtrooms but on the shipyard floor—by site engineers interpreting drawings, suppliers struggling with timelines and project managers balancing commercial pressure against technical feasibility.

This third and final part of the series *"Pitfalls in Shipbuilding Contracts"* examines how contractual theory translates into daily shipyard reality. It explores how site-team actions can affect legal rights, how refund guarantees and liquidated-damage (LD) regimes operate under stress and how warranty obligations extend long after delivery.

Drawing from real-world case studies and comparing standard forms such as the SAJ and BIMCO NEWBUILDCON, it concludes by proposing an integrated framework where legal precision, engineering discipline and operational control coexist to produce dispute-free shipbuilding.

1. From Contract Table to Dockyard: The Human Interface

Once the contract is signed, lawyers retreat and engineers take charge.

Yet the contract continues to live through the day-to-day decisions of the site team—the owner's representatives and shipyard managers who supervise construction, approve drawings and sign certificates.

1.1 Site Teams as the Contract's Front Line

The site team is the owner's eyes and ears. Its role is to monitor progress, verify quality and ensure compliance with the specification. However, every communication, approval, or instruction issued by that team carries potential legal consequence. A casual direction—"fit this instead of that"—can convert into a variation order if the builder later claims cost and time impact.

Most disputes trace back to mismanaged site interactions rather than malicious intent. The law does not excuse informality; it interprets it. Hence, understanding the contract is as essential for site engineers as for lawyers.

1.2 Authority and Accountability

Shipbuilding contracts normally define an "Owner's Representative" empowered to issue instructions binding on the owner. Others in the site office—inspectors, superintendents, class surveyors—have advisory status only. When boundaries blur, the yard receives mixed messages and ambiguity escalates into claims.

Best practice requires a clear delegation matrix, indicating who may:

- Issue instructions affecting cost or schedule,
- Approve drawings or trials,
- Sign milestone certificates or delivery protocols.

A disciplined communication hierarchy prevents unauthorised commitments and preserves contractual integrity.

2. The Operational Impact of Refund Guarantees

2.1 The Purpose and Structure

A refund guarantee is the financial backbone of a newbuilding contract. It secures repayment of instalments if the shipbuilder defaults, fails to deliver, or the contract is terminated. Usually issued by a bank, it provides comfort to financiers and confidence to owners.

Two main types exist:

1. Unconditional (on-demand) – payment triggered upon written demand, independent of the underlying dispute.
2. Conditional – payable only after proof of builder default, offering weaker protection.

Under English law and international practice (URDG 758), refund guarantees are autonomous from the main contract. Once triggered correctly, the guarantor must pay, even if the builder contests default.

2.2 Operational Relevance

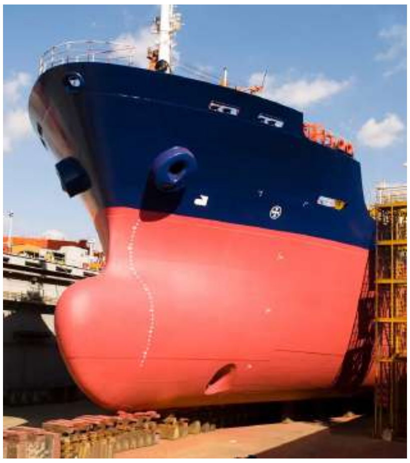
For site teams, refund guarantees may appear remote, yet their practical influence is immense.

- Cash-flow assurance: Owners release stage payments only upon receipt of valid guarantees.
- Procurement dependency: Builders rely on instalments to fund materials; any delay in guarantee issuance stalls production.
- Risk perception: Weak or conditional guarantees raise financier anxiety, leading to payment freezes and schedule slippage.

A shipyard's first operational milestone—the start of steel cutting—often hinges on the bank's confirmation of guarantee authenticity. Engineers unaware of this linkage may misinterpret payment delays as technical rather than financial.

2.3 Typical Pitfalls

1. Expiry Mismanagement: Guarantees that lapse before delivery create exposure.
2. Local Bank Guarantees: Difficult to enforce internationally.
3. Non-compliant Wording: Absence of "on-demand" phrase or wrong governing law.
4. Failure to Replace: When extensions are not obtained, the buyer may suspend work or terminate.



Best Practice: Every progress meeting should include a financial-compliance checklist ensuring guarantees remain valid, properly worded and extend automatically until delivery acceptance.

3. Delivery Delays and Liquidated Damages

3.1 The Reality of Delay

In modern shipbuilding, delay is more norm than exception. Supply-chain congestion, steel shortages, class approval backlogs and regulatory revisions frequently push delivery beyond contractual dates.

To balance risk, contracts include Liquidated Damages (LDs)—a pre-agreed sum per day or per week of delay.

LDs offer certainty: they compensate the buyer without requiring proof of actual loss and limit the builder's exposure to a known amount. Yet their simplicity masks operational complexity.

3.2 The LD Mechanism

Typically, LDs apply after expiry of permissible extensions for:

- Force majeure events,
- Owner-caused delays,
- Regulatory changes, or
- Other justified suspensions.

The builder must notify delay causes within a fixed window—often 14 days. Failure to do so forfeits entitlement to extension. Site teams frequently overlook this procedural formality, only to find months later that the shipyard has lost its contractual defence.

Similarly, buyers must reserve their rights to claim LDs in writing; silence or informal tolerance may amount to waiver.

3.3 Force Majeure: The Over-Used Shield

During COVID-19 and subsequent supply crises, many builders invoked force majeure (FM) to escape LDs. Tribunals, however, construe FM narrowly. Predictable industry risks—supplier delay, labour shortage, or government permit backlog—rarely qualify.

The NEWBUILDCON form, learning from past abuses, limits FM to events "beyond reasonable control and not foreseeable at the date of contract." Builders must demonstrate causal connection, not merely inconvenience. The SAJ Form remains looser, granting wider exemptions that owners should contractually narrow.

3.4 LD Enforcement and Caps

LDs must be genuine pre-estimates of loss, not penalties. Excessive or arbitrary rates risk invalidation. Courts generally uphold LDs if:

- They were negotiated between commercial entities;
- The rate is proportionate to the potential loss of charter revenue or financing cost.

Contracts often cap total LDs at 5–10 percent of the contract price. Once this ceiling is reached, the owner's remaining remedy is termination. Hence, LD management is as much strategic as procedural.

4. Warranty Principles and Post-Delivery Liabilities

4.1 The Function of Warranty

The warranty clause bridges the transition from construction to operation. It assures the owner that the delivered vessel is free from defects in material, workmanship and design for a defined period—usually 12 months from delivery or completion of first voyage.

Warranty obligations coexist with, but differ from, performance guarantees. The latter test design parameters before delivery; the former address hidden defects discovered after delivery.

4.2 Scope and Limitations

Standard warranties cover:

- Defects arising from builder error,
- Non-compliance with specification and
- Components supplied by subcontractors.

They exclude:

- Normal wear and tear,
- Owner negligence or misuse,
- Defects in equipment modified post-delivery.

Financial Caps: Liability is usually limited to repair or replacement cost, excluding consequential losses like

off-hire or loss of profit. Builders resist "open-ended" exposure; owners must therefore secure insurance for consequential risks.

4.3 Notification and Rectification Procedure

Owners must notify defects promptly in writing, typically within 30 days of discovery and before warranty expiry. Site or superintendent logs alone are insufficient; formal notice is mandatory. Builders then have the right to inspect and decide whether to repair at yard, afloat, or in service.

Disputes arise when owners conduct unilateral repairs and claim reimbursement without consent. Tribunals often reject such claims unless the defect posed safety risk demanding immediate action.

4.4 The Chain of Responsibility

Modern vessels integrate thousands of components from global suppliers. Builders act as assemblers coordinating sub-vendors. Warranty claims may thus cascade through multiple tiers. Effective warranty management requires:

- A traceable supplier database,
- Back-to-back warranty clauses with identical duration,
- Prompt claim forwarding to manufacturers.

The NEWBUILDCON form mandates builders to assign sub-vendor warranties to owners upon delivery, ensuring continuity. The SAJ Form lacks this clarity, often causing confusion when defects arise in third-party systems.

5. Case Studies: Operational Lessons from Real Disputes

Case 1 – Scottish Owner v Shipyard

Background: The owner relied on verbal assurances rather than formal refund guarantees. The yard defaulted mid-build, leaving half-finished hulls and unpaid suppliers.

Outcome: Arbitration held refund guarantee absence fatal; the buyer recovered nothing.

Operational Lesson: Financial safeguards are as critical as technical ones. Always verify guarantee authenticity before first instalment.

Case 2 – Canadian Ferry Project

Background: Prototype hybrid ferries contracted under aggressive delivery schedule. Specifications promised "innovative propulsion integration" without feasibility analysis.

Impact: Engineering teams struggled with untested technology; delays accumulated; LD exposure exceeded 8 percent cap.

Outcome: Parties renegotiated delivery timetable, converting LDs into extended warranty support.

Lesson: Ambitious specifications must be balanced by realistic build programs and contingency buffers.

Case 3 – Chinese Shipyard v European Owner (2019 ICC Arbitration)

Issue: Installation of additional fire-safety systems following rule change.

Finding: Tribunal classified the change as "owner's variation," not regulatory obligation.

Lesson: Contracts must define how post-signing regulatory changes are shared; ambiguity breeds cost disputes.

Case 4 – Korean Shipyard Sanction Disruption (2025)

Context: Multiple LNG carrier contracts cancelled due to geopolitical sanctions.

Operational Impact: Yards halted production, faced stranded inventory and triggered refund claims.

Legal Finding: Courts upheld refund obligations despite external political causes; sanctions did not constitute FM because risks were foreseeable.

Lesson: Political foresight and insurance instruments are as vital as force-majeure drafting.

Case 5 – Chinese Yard v Anonymised Owner (Repeated Sea-Trial Failures)

Facts: Vessel failed four consecutive sea trials due to design vibration.

Evidence: Detailed daily reports by owner's site manager demonstrated persistent defect.

Result: Tribunal ruled in owner's favour; refund guarantee honoured in full.

Operational Lesson: Comprehensive site documentation is decisive evidence; precision in reporting outweighs rhetoric in arbitration.

6. Comparative Perspective: SAJ Form vs NEWBUILDCON

6.1 SAJ Form (Shipbuilders' Association of Japan)

Strengths

- Widely accepted across Asia; predictable structure and precedent.

- Familiar to banks and insurers.

Weaknesses

- Builder-friendly bias: Broad force-majeure clause and weak hierarchy provisions.
- Refund ambiguity: Allows local-bank guarantees unless modified.
- Warranty vagueness: Limited clarity on sub-vendor responsibility.

Operational Consequence:

Yards may exploit flexibility to defer responsibility; owners must add riders specifying hierarchy, refund structure and defect liability.

6.2 BIMCO NEWBUILDCON

Strengths

- Internationally balanced and comprehensive.
- Clear definition of "Permissible Delay," structured variation procedure and explicit LD framework.
- Stronger warranty and post-delivery support provisions.

Advantages to Site Teams

- Annex A (Specification) integrated by reference with cross-linked change-order mechanism.
- Clause-based communication hierarchy protecting both sides.
- Standardised notices reduce procedural disputes.

Limitations

- Complexity: requires tailored guidance for smaller yards.
- Higher administrative load to maintain documentation discipline.

Overall, NEWBUILDCON represents a modern synthesis—aligning contractual intent with operational feasibility if implemented with adequate training.

7. Building Contract Awareness Among Site Personnel

The gap between legal drafting and operational practice narrows only when site staff understand contractual boundaries.

Training Essentials

1. Contract Induction: Before mobilisation, brief all team members on key clauses—authority, variation, warranty, LD and documentation requirements.
2. Pocket Guides: Provide concise reference cards summarising "What you can approve" and "What requires management consent."
3. Escalation Protocols: Disagreements on technical interpretation should route through contract managers, not informal discussion with the builder.

4. Signature Discipline: Never sign sea-trial or delivery documents "without protest" unless satisfied that performance criteria are met.

Cultural Shift

Engineers often regard contracts as legal bureaucracy; lawyers view site feedback as operational noise. Integrating both perspectives builds mutual respect and reduces friction. Regular joint reviews—legal plus engineering—translate clauses into actionable routines.

8. Integrating Warranty and Insurance

Warranty is not insurance, yet the two must complement each other.

- Warranty covers builder's responsibility for defective workmanship.
- Insurance covers accidental loss or damage during and after delivery.

Confusion arises when failures straddle both domains—for instance, a pump breaking due to casting defect (warranty) versus destruction in fire (insurance).

Clear demarcation within the contract avoids overlapping claims and insurer disputes.

Best Practice:

Include cross-reference clauses directing casualty losses to insurance and manufacturing defects to warranty.

9. Documentation: The Hidden Arbiter

In arbitration, documentation equals truth. Tribunals give greatest weight to contemporaneous records—emails, site logs, inspection reports and signed protocols.

A well-structured document management system can determine the outcome of multimillion-dollar disputes.

Essential Records Include:

- Progress photographs and inspection certificates.
- Variation orders with cost/time approvals.
- Minutes of site meetings.
- Daily and weekly progress logs.
- Warranty-claim registers with response dates.

Digital platforms now allow timestamped entries, reducing forgery risk and enhancing evidentiary credibility.

10. The Future: Integrating Law, Engineering and Execution

The next generation of shipbuilding projects—autonomous vessels, LNG dual-fuel ships, offshore hybrids—will multiply contractual complexity. Regulatory expectations, sustainability standards and technological innovation require more agile coordination between disciplines.

Integrated Project Contracting (IPC) is emerging as a model, uniting lawyers, engineers, financiers and compliance officers in one collaborative drafting process. Key features include:

- Unified data environments linking design software to contractual milestones.
- Dynamic variation dashboards calculating real-time cost and schedule effects.
- Smart clauses referencing version-controlled specifications.

These developments mark a transition from static contracts to living systems that evolve with the project—minimising human error and interpretive gaps.

Conclusion

Integrating Law, Engineering and Execution for Dispute-Free Shipbuilding

At the heart of every shipbuilding dispute lies a disconnect—between what was written, what was built and what was intended. Contracts alone cannot prevent that disconnect; only disciplined execution can.

The Lessons of Experience Are Clear:

1. Empower Site Teams with Knowledge.

Contractual literacy is a technical competency. Engineers who understand clauses prevent violations before they occur.

2. Safeguard Finance Through Robust Guarantees.

Refund guarantees are the keel of contractual security—verify, monitor and extend them meticulously.

3. Control Delay Risk Transparently.

Manage LDs through timely notices, realistic schedules and balanced force-majeure wording.

4. Strengthen Warranty Frameworks.

Define defect scope, notice periods and back-to-back supplier obligations to ensure enforceability.

5. Align Legal Forms with Yard Practice.

Adapt SAJ or NEWBUILDCON templates to reflect actual operational capacities, not theoretical ideals.

6. Institutionalise Documentation Discipline.

Digital audit trails and version control protect both builder and owner from retrospective interpretation.

Ultimately, a shipbuilding contract is neither a weapon nor a shield—it is a navigation chart. The safest voyages are undertaken when every participant, from lawyer to welder, reads the same chart and understands its coordinates.

By integrating legal precision, engineering realism and operational transparency, the maritime industry can shift from a culture of arbitration to a culture of accountability. The true measure of a successful contract is not how well it defends a dispute, but how rarely that defence is ever needed.

Abbreviations

- **BIMCO** – Baltic and International Maritime Council: an international shipping association that publishes standard contract forms, including NEWBUILDCON.
- **EWCA Civ** – England and Wales Court of Appeal (Civil Division): used in neutral citations; e.g., [2002] EWCA Civ 1147, where "1147" is the sequential judgment number for that year. (Civ denotes the Civil Division, as opposed to Crim for the Criminal Division).
- **FM** – Force Majeure: a contractual clause excusing parties from liability for non-performance due to extraordinary events beyond their control (e.g., natural disasters, war, pandemics).
- **HKIAC** – Hong Kong International Arbitration Centre: an arbitration institution for resolving commercial and maritime disputes in the Asia-Pacific region.
- **IMO** – International Maritime Organization: a UN specialized agency responsible for regulating international shipping.
- **LD** – Liquidated Damages: a pre-agreed sum payable for failure to perform contractual obligations, typically delayed delivery of a vessel.
- **LDs** – Liquidated Damages (plural): commonly used shorthand for multiple claims or cumulative sums under LD clauses.
- **LMAA** – London Maritime Arbitrators Association: a London-based body providing arbitration services for maritime disputes, including shipbuilding and charterparty contracts.
- **MARPOL** – International Convention for the Prevention of Pollution from Ships: an IMO convention addressing ship-sourced pollution, including oil, chemicals, sewage and garbage.
- **NEWBUILDCON** – Newbuilding Contract: a BIMCO standard form used for shipbuilding contracts, covering delivery, payment, warranties and dispute resolution.
- **SAJ Form** – Shipbuilders' Association of Japan Standard Form Shipbuilding Contract: a widely used standard form contract in Asia, especially for Japanese and Korean shipyards.
- **SIAC** – Singapore International Arbitration Centre: a Singapore-based arbitration institution for international commercial disputes, widely used in shipbuilding contracts.
- **SOLAS** – International Convention for the Safety of Life at Sea: an IMO convention establishing minimum standards for ship construction, equipment and operation to ensure safety at sea.
- **URDG 758** – Uniform Rules for Demand Guarantees, ICC Publication No. 758 (2010): internationally recognised rules governing demand guarantees and counter-guarantees, often applied to refund guarantees in shipbuilding contracts.

References

- BIMCO (2007) NEWBUILDCON Standard Newbuilding Contract. Copenhagen: BIMCO.
- Indian owner vs. Korean Shipyard (2015) LMAA Arbitration Award (unpublished, anonymized).
- ICC Arbitration Award (2019), Dispute between European Owner and Chinese Shipyard (unpublished).
- London Maritime Arbitrators Association "Bulk Carrier Delay Case", LMAA Award (anonymised, unpublished).
- Shipbuilders' Association of Japan (1999) Standard Shipbuilding Contract (SAJ Form), Tokyo: SAJ.
- Chinese shipyard v. investment company [2021] EWCA Civ 1147.
- European shipyard vs. Danish owner [2009] EWCA Civ 75.
- International Chamber of Commerce (2010) URDG 758: Uniform Rules for Demand Guarantees. Paris: ICC
- Law of Shipbuilding Contract by Simon Curtis

About the Author

Narayana Prakash is a shipbuilding consultant who advises a wide range of shipowners, with a particular emphasis on micro-level details to optimise shipbuilding contracts. With over 17 years of professional experience in shipbuilding, contract review and arbitration proceedings, he has cultivated extensive expertise and a comprehensive understanding of shipbuilding contracts from both operational and legal perspectives.

Email: prakasini18@gmail.com

ANGLO EASTERN
MARITIME TRAINING CENTRE

AEMTC MUMBAI : 401, Fourth Floor, Leela Business Park, Marol, Andheri-Kurla Road, Andheri (East), Mumbai-400 059.
T. +91 22 6720 5600 / 611 / 612 |
A.O.H. +91 8657408962 / +91 9820917656
aetr.bom@angloeastern.com
Mr. Francis Akkara, Capt. Liston Pereira, Mr. Ivor Wilson

AEMTC DELHI : A-43, Ground Floor, Mohan Co-Operative Industrial Estate, Mathura Road, Delhi-110044, India.
T. +91 11 6817 0800, 0801 / +91 9811249849 / 9850
aetr.del@angloeastern.com
Capt. Prashant Gour, Ms. Sukhjeet Kaur, Mr. Suresh Kumar

Anglo Eastern Maritime Training Centre | aemaritimetrg | For more details visit website: **www.maritimetraining.in**

For Pre Sea Training Courses kindly contact **Anglo-Eastern Maritime Academy** (A Division of Anglo-Eastern Institute) **DNS Course : 011 68170837 | GME / ETO Course : 011 68170831** | aema.edu.in

MAN Energy Solution is now
MAN | PrimeServ **Everllence**

Everllence | PrimeServ Academy Partner, Mumbai
(OEM Approved Courses)

ME-C Control System Standard Operation		ME-GI Control System Standard Operation	
Feb 2026: 23 - 27	Mar 2026: 16 - 20	Feb 2026: 02 - 06	Mar 2026: 02-06 , 23-27

For bookings: aetr.bom@angloeastern.com | primeserv.academy-cph@everllence.com

WIN GD
(OEM Approved Course)

Operation Advanced Course UNIC-Controlled X Engines — **Feb 2026: 02 - 06**

Operation Advanced Course UNIC-Controlled X-DF Engines — **Mar 2026: 09 - 13**

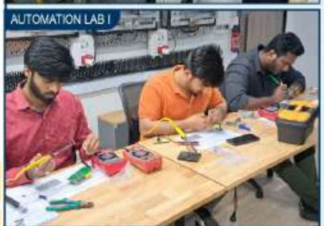
For bookings: +91 8657408962 / +91 9820917656

WÄRTSILÄ

Wartsila RT Flex Engine
Conducted by Wartsila Switzerland

Feb 2026 : 16 - 20

Mar 2026 : 23 - 27



VACANCY Faculty position

Apply Now!
talentsourcing@angloeastern.com/
aemt.bom@angloeastern.com

Training Faculty – Engineering
Qualifications and Experience

- Marine Engineer Officer Class 1 – COC from India / UK.
- With min. 1 year rank experience as Chief Engineer (Preference for experience on LNG/ LPG/ Tanker vessels).
- Experience in Ship operation, ship repair, teaching, auditing, inspections preferred.
- Training for Trainers and Assessors (TOTA) or Vertical Integration Course for Trainers (VICT).
- Other ISO / ISM / Technical Value-added courses.
- Excellent verbal and written communication skills. Should be interested in modern teaching methodologies.
- Candidate must have a passion for learning continuously and a desire to be in the teaching profession.
- Proficient in use of computers and savvy with use of various software.

1st in India & 2nd in the world to receive distinction by DNV SeaSkill Benchmarking
CERTIFIED MARITIME TRAINING PROVIDER
DNV
DNV-ST-0029

Ship Recycling in Transition: Regulation, Capacity and Sustainability

Anand M. Hiremath
Sangeeth P

Abstract

Ship recycling represents a critical but often under-examined phase of the global shipping lifecycle, linking maritime operations with industrial sustainability, resource recovery and social responsibility. As fleets age and regulatory pressures intensify, the safe and environmentally sound recycling of end-of-life ships has become both inevitable and strategically important. This paper examines the contemporary ship recycling landscape through the lenses of regulation, capacity and sustainability. It analyses the evolution from informal dismantling practices to a regulated industrial process governed by the Basel Convention, the Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships (HKC) and the EU Ship Recycling Regulation (EU SRR).

The article highlights the structural mismatch between global recycling demand and EU-approved capacity, underscoring the indispensable role of compliant yards in South Asia—particularly India. It further positions ship recycling as a practical circular-economy solution, with high material recovery rates and significant climate benefits through secondary steel production. The paper also explores the growing influence of Environmental, Social and Governance (ESG) expectations, including worker safety, hazardous-waste management and governance transparency.

Overall, the article argues that modern ship recycling, when properly regulated and executed, is not an environmental liability but a climate-aligned, resource-efficient end-of-life solution central to sustainable shipping.

Keywords: Ship recycling, Hong Kong Convention, HKC compliance, Basel Convention, EU Ship Recycling Regulation, ESG, circular economy, sustainable ship recycling, Inventory of Hazardous Materials (IHM), hazardous waste management, PFOS, asbestos, PCBs, steel recycling, climate mitigation, decarbonisation, worker safety, green yards, India ship recycling, South Asia capacity, TSDF, lifecycle approach, regulatory transition, end-of-life ships

Introduction: Why Ship Recycling Matters Today

Global shipping carries nearly 90 percent of world trade by volume, making ships among the most critical assets of the modern global economy. From container vessels transporting consumer goods to tankers carrying oil, chemicals and gas, shipping underpins globalisation itself. Ships, however, are not designed to operate indefinitely. As vessels age, maintenance costs rise, fuel efficiency declines and compliance with evolving safety and environmental regulations becomes increasingly challenging. At this stage, ship recycling becomes not only inevitable but essential.

Ship recycling represents the final stage of a vessel's lifecycle. When conducted responsibly, it enables recovery of valuable materials, safe management of hazardous substances and return of economic value to society. When poorly executed, however, it exposes workers, communities and the environment to significant risks. Consequently, ship recycling has evolved from an informal activity into a regulated industrial process governed by international conventions, national legislation and growing environmental and social expectations.

> *When conducted responsibly, it enables recovery of valuable materials, safe management of hazardous substances and return of economic value to society*

Over the past four decades, global ship recycling has shifted from Europe and North America toward Asia—particularly India, Bangladesh, Pakistan and Türkiye. This transition has been driven by the availability of skilled labour, proximity to steel re-rolling industries, favourable coastal geography and the ability to process large volumes of end-of-life ships efficiently. Today, South Asia and Türkiye together handle the majority of global ship recycling, with India emerging as a leader in compliance, infrastructure and operational scale.

Simultaneously, the industry is undergoing a profound transition. The entry into force of the Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships (HKC) in 2025, increasing emphasis on Environmental, Social and Governance (ESG) performance and growing recognition of circular-economy and climate-change considerations are reshaping regulatory and commercial expectations. This article examines current ship recycling practices, the governing legal frameworks, the role of circular economy and ESG principles and why India is well positioned to remain a global hub for sustainable ship recycling.

India (approx. 7.0 mGT) and Bangladesh (approx. 6.8 mGT) together account for a significant share of global ship recycling capacity, while Pakistan (approx. 3.7 mGT) and Türkiye (approx. 2.5 mGT) contribute at smaller but meaningful scales. Despite this installed capacity, utilisation remained low in 2024.

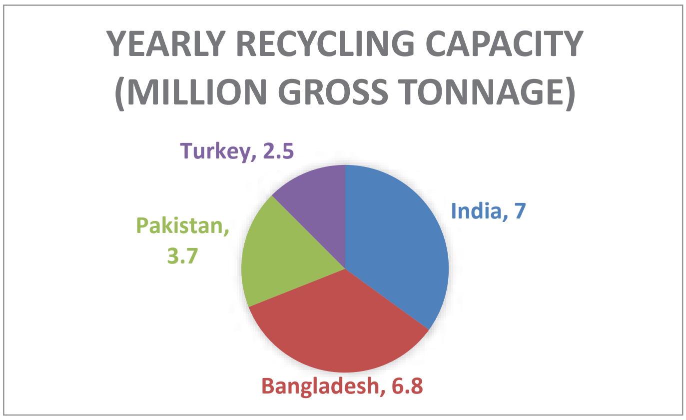


Figure 1 presents estimated annual ship recycling capacity by country in million gross tonnes.

India hosts the highest number of active ship recycling yards (153), followed by Pakistan (136), Bangladesh (100) and Türkiye (28). This extensive operational base places India in a strong position to absorb future growth in recycling demand.

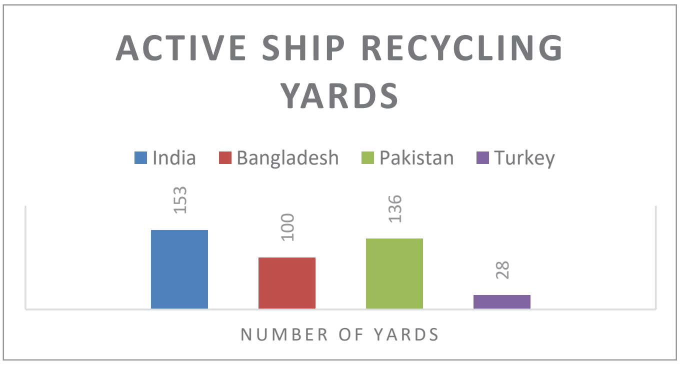


Figure 2 illustrates the number of active ship recycling yards across major recycling nations.

The global ship recycling industry experienced a historic slowdown during 2024–2025, reflecting subdued freight markets, extended vessel trading life and regulatory transition ahead of HKC entry into force. Only 324 ships—approximately 4.6 million gross tonnes—were recycled worldwide, the lowest annual volume since 2005. Bangladesh dismantled the highest number of vessels (130), followed by India (101) and Türkiye (84).

Measured by gross tonnage, South Asia dominated global recycling activity, with Bangladesh and India together accounting for the majority of recycled GT worldwide.

1. The Ship Recycling Process: From Anchorage to Final Clearance

Modern ship recycling is a structured and carefully controlled industrial process. It does not begin with cutting steel, but with documentation, planning and regulatory approvals that often commence months before a vessel reaches a recycling yard.

> *Gas-free certificates are issued to confirm that enclosed spaces are safe for hot work*

Inventory of Hazardous Materials (IHM)

A central requirement under modern ship recycling regulations is the Inventory of Hazardous Materials (IHM). The IHM identifies hazardous substances present on board, including asbestos, polychlorinated biphenyls (PCBs), ozone-depleting substances, heavy metals, PFOS-containing firefighting foams, HBCDD insulation and other regulated chemicals. Ships are required to maintain this inventory throughout their operational life, ensuring transparency and traceability.

The IHM allows recycling facilities to prepare appropriate dismantling plans, select suitable personal protective equipment for workers and arrange downstream waste treatment in advance. In practice, it forms the foundation of safe and environmentally sound ship recycling.

Arrival, Gas-Freeing and Pre-Cleaning

Once a ship reaches the designated anchorage near a recycling yard, it

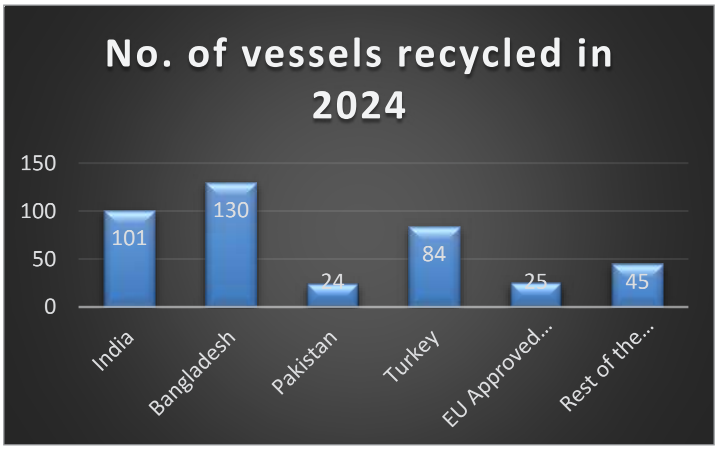


Figure 3 shows the number of vessels recycled by region in 2024

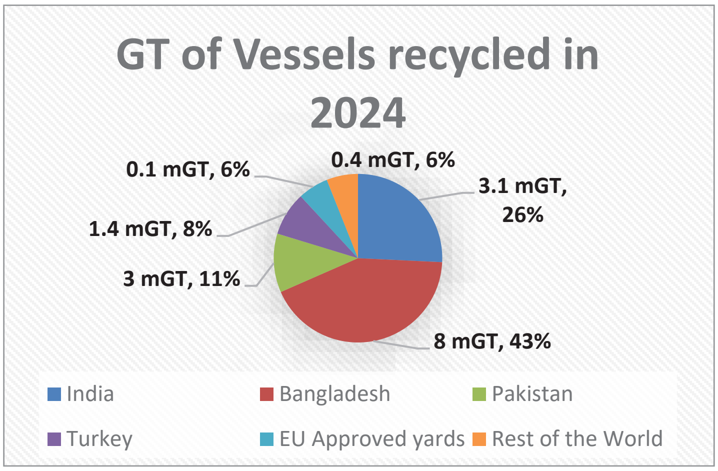


Figure 4 presents the global distribution of recycled gross tonnage in 2024

undergoes inspections and pre-cleaning operations. Fuel tanks, slop tanks and machinery spaces are cleaned and remaining oils, residues and gases are removed. Gas-free certificates are issued to confirm that enclosed spaces are safe for hot work. This step is critical in preventing fires, explosions and occupational accidents.

Only after safety clearance is granted does the ship move to the recycling plot. At this stage, port authorities, customs officials and environmental regulators verify documentation and compliance with national and international requirements.

Dismantling and Material Recovery

Dismantling follows a planned and sequenced approach. Loose equipment, furniture and reusable components are removed first. Machinery such as generators, pumps, compressors and motors is dismantled for reuse or refurbishment. Structural cutting then proceeds from the upper decks downward, with steel plates and sections cut into manageable blocks.

Recovered steel is transported to secondary cutting areas and subsequently to re-rolling mills, where it is converted into construction-grade steel. Non-ferrous metals such as copper, aluminium and brass are segregated and recycled through specialised channels. Throughout the process, safety supervision and environmental controls are maintained.

Waste Segregation and Final Clearance

Hazardous wastes are segregated at source and sent exclusively to authorised downstream facilities, such as Treatment, Storage and Disposal Facilities (TSDFs). Non-hazardous wastes are recycled or disposed of in accordance with regulatory requirements. Once dismantling is complete and all waste streams are accounted for, final clearance is issued by the authorities, formally closing the recycling process for that vessel.

2. Legal Framework Governing Ship Recycling

Ship recycling is regulated through a combination of international conventions and regional frameworks. The three most influential instruments are:

1. Basel Convention,
2. Hong Kong Convention,
3. EU Ship Recycling Regulation.

Basel Convention

Adopted in 1989, the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal aims to prevent illegal dumping of hazardous waste and ensure environmentally sound management. End-of-life ships are often classified as hazardous waste under Basel due to the presence of hazardous materials.

However, Basel was not designed specifically for ships, which are mobile assets operating under flag-state jurisdiction. Its **Prior Informed Consent (PIC)** procedure **has proven difficult to apply to vessels** that **may change ownership, flag, or recycling destination** while at sea, creating **legal uncertainty** without necessarily improving recycling standards.

Hong Kong Convention (HKC)

Recognising these limitations, the International Maritime Organization adopted the Hong Kong Convention in 2009. The HKC takes a **lifecycle approach, covering ship design,**

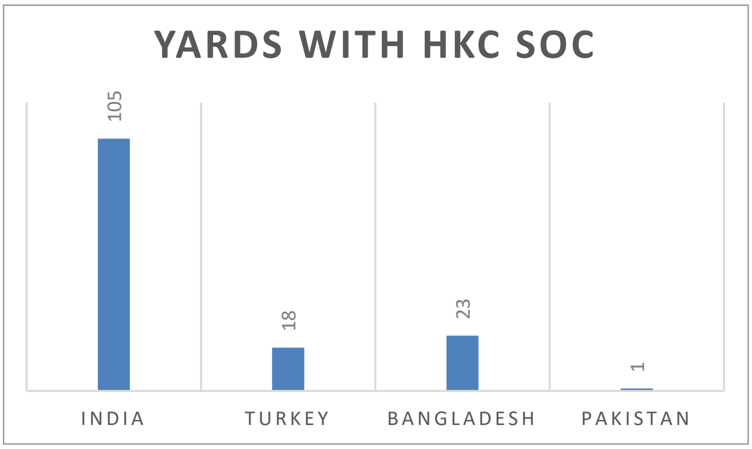


Figure 5 illustrates the number of ship recycling yards holding a Hong Kong Convention Statement of Compliance.

construction, operation and recycling. It mandates the maintenance of an **IHM**, requires **ship-specific recycling plans** and obliges recycling facilities to meet defined safety and environmental standards.

The HKC enters into force in June 26, 2025. Many **Indian recycling yards already comply with HKC requirements** through **national legislation, port authority oversight and voluntary certification**, placing them well ahead of the regulatory timeline.

India leads global preparedness with **105 HKC-compliant yards**, significantly ahead of **Bangladesh (23), Türkiye (18) and Pakistan (1)**.

EU Ship Recycling Regulation (EU SRR)

The EU SRR applies HKC principles to EU-flagged ships but **restricts recycling to EU-approved yards**. While the regulation seeks to **ensure high standards**, it also introduces **structural capacity constraints** by limiting where EU-flagged vessels can be recycled.

3. EU SRR Capacity: A Structural Limitation

A key challenge in global ship recycling is the **mismatch between EU-approved capacity and actual recycling demand**. **EU-listed yards** provide **approximately 1.5 million light displacement tonnes (LDT) of annual capacity**, whereas India, **Bangladesh, Pakistan and Türkiye together offer more than 12 million LDT per year**.

Even during periods of low recycling activity, EU yards operate close to capacity. During future peaks—expected after 2027 due to fleet ageing and regulatory pressure—EU capacity would be capable of handling only a small fraction of global demand. This structural limitation makes compliant non-EU yards indispensable to the functioning of the global ship recycling system.

4. Circular Economy: The Core of Ship Recycling

Ship recycling is one of the most effective examples of circular economy in practice. More than 90 percent of a ship's material mass is recovered and reused. While steel dominates by volume, machinery, cables, equipment and fittings also find second lives across multiple industries.

In India, recycled ship steel plays a vital role in supporting construction and infrastructure development. Producing steel from recycled material requires significantly less energy than primary steelmaking,

Materials Recovered and Removed During Ship Recycling

Category	Material / Component	Typical End Use / Destination	Environmental & Safety Notes
Ferrous Metals	Hull steel plates and sections	Re-rolling mills → construction steel (TMT bars, angles, beams)	Major contributor to circular economy; low carbon footprint compared to primary steel
	Structural members (frames, stiffeners)	Construction and fabrication industries	Requires controlled cutting and handling
Non-Ferrous Metals	Copper (cables, windings, pipes)	Electrical and electronics recycling	High recycling value; segregation essential
	Aluminium (superstructure, fittings)	Secondary aluminium production	Lightweight, high reuse potential
	Brass & bronze (valves, pumps)	Foundries and marine spares	Often refurbished for reuse
Machinery & Equipment	Main and auxiliary engines	Reuse, refurbishment, or metal recovery	Oil draining and decontamination required
	Generators, motors, compressors	Reconditioning or material recovery	Electrical insulation managed carefully
	Pumps, heat exchangers	Marine spares market or recycling	Cleaning and testing required
Electrical & Electronics	Switchboards, panels, cabling	Metal recovery and certified e-waste recyclers	PCB and insulation handling critical
	Navigation & communication equipment	Refurbishment or regulated disposal	Data and hazardous component control
Outfitting & Furnishings	Furniture, doors, panels	Reuse markets or material recycling	Often reused locally
	Galley and accommodation equipment	Reuse or scrap	Hygiene and contamination checks
Piping & Systems	Steel and copper piping	Scrap metal recycling	De-oiling essential
	Insulation materials	Regulated disposal or recovery	HBCDD and asbestos controls
Hazardous Materials	Asbestos-containing materials	Authorised TSDF	Strict worker protection required
	PCBs (capacitors, paints)	Certified hazardous waste treatment	POPs management essential
	PFOS firefighting foams	High-temperature destruction	Persistent organic pollutant
	Oily sludge and residues	Waste oil processors	MARPOL compliance required
Consumables & Fluids	Fuel oil, lubricants	Reprocessing or energy recovery	Spill prevention critical
	Refrigerants	Certified recovery facilities	Ozone and climate protection
Miscellaneous	Lifeboats, safety gear	Reuse or recycling	Certification status checked
	Glass, plastics, rubber	Recycling or regulated disposal	Segregation improves recovery

reduces mining activity, conserves natural resources and lowers greenhouse gas emissions.

By extending the life of already-processed materials, ship recycling closes the loop between production, use and reuse—an increasingly important model as countries seek to reduce resource intensity and environmental impact.

5. Steel Recycling and Climate Change

Steel production is among the largest industrial sources of carbon emissions globally. Ship recycling offers a practical and immediate pathway to reduce this footprint. Recycled steel consumes less energy, emits less carbon dioxide and relies on fewer raw materials than primary steel production.

By supplying large volumes of secondary steel, ship recycling directly supports national and global climate goals. In this context, ship recycling should be recognised not as an environmental burden, but as a climate solution.

6. Role of ESG in Ship Recycling

Environmental, Social and Governance considerations have become central to ship recycling decisions. Shipowners, financiers and cargo owners increasingly assess recycling practices as part of their ESG commitments.

Indian yards have made significant investments in worker safety, training, medical facilities and governance systems. Dedicated trauma centres near recycling clusters provide rapid emergency care. Workers receive structured safety training, personal protective equipment and health monitoring. Governance has strengthened through audits, documentation and digital traceability.

These developments demonstrate that ESG principles in ship recycling are no longer aspirational, but operationally embedded.

7. Waste Management: Streams and Future Outlook

Ship recycling generates a range of waste streams, including asbestos, PCBs, PFOS-containing foams, HBCDD insulation (**Hexabromocyclododecane**, a **brominated flame retardant)**, oily sludge, paint residues and contaminated materials. Safe management of these wastes is central to sustainable recycling.

India has upgraded TSDF infrastructure (Treatment, Storage and Disposal Facility) to handle persistent organic pollutants in line with EU standards. Specialised facilities ensure proper treatment, neutralisation, or disposal of hazardous waste.

Importantly, future recycling is expected to involve lower hazardous waste intensity. From 2011 onwards, many hazardous materials were banned or restricted in shipbuilding. As ships built after 2011 approach end-of-life around 2030, overall hazardous waste volumes are expected to decline.

8. Policy Implications and the Way Forward

Policymakers face the challenge of aligning international and regional regulations without creating capacity shortages or legal uncertainty will be critical:

- Harmonising Basel and HKC implementation,
- Recognising compliant global yards and
- Supporting investment in recycling infrastructure.

According to BIMCO (Baltic and International Maritime Council), nearly 16,000 ships—representing approximately 700 million deadweight tonnes—are expected to be recycled over the next decade. Meeting this demand will require scalable, compliant capacity, an area where India is particularly well positioned.

Conclusion: Ship Recycling as a Sustainable End-of-Life Solution

Ship recycling has evolved into an essential component of the global shipping lifecycle. As fleets age and regulations tighten, recycling provides a responsible pathway for managing end-of-life vessels while recovering valuable materials and protecting workers and the environment.

Today's recycling practices differ fundamentally from the past. The process is planned, monitored and regulated—from IHM preparation to controlled dismantling and waste disposal. International frameworks such as the Hong Kong Convention have brought consistency and safety, while regional regulations like the EU SRR face practical limitations due to constrained capacity.

Ship recycling also plays a critical role in the circular economy and climate mitigation by supplying recycled steel and reducing emissions. Coupled with growing ESG integration, improved worker welfare and upgraded waste treatment infrastructure, ship recycling stands out as a practical, scalable and climate-aligned solution for end-of-life ships.

With increasing demand for recycled materials and green employment and with substantial compliant capacity already in place, India is positioned to play a central role in shaping the future of sustainable ship recycling.

About the Authors

Dr. Anand M. Hiremath is the Chief Sustainability Officer at SSORP, specialising in ship recycling, ESG integration and circular economy practices. With deep expertise in regulatory compliance, environmental management and sustainable industrial transformation, he works closely with industry and policymakers to advance safe, compliant and climate-aligned ship recycling practices.

Email: Anand@ssorp.net

Sangeeth P is a Green Coordinator and Naval Architect at SSORP, with professional expertise in sustainable ship recycling, regulatory compliance and green yard operations. He supports implementation of environmental controls, IHM management, waste-stream optimisation and ESG-aligned practices, bridging naval architecture principles with practical sustainability execution in ship recycling yards

Oceans fueling Cyclones -Thermodynamics approach from Bay of Bengal observations

N. Vedachalam, R. Balaji,
K. Jossia Joseph, G Vengatesan

Abstract

Understanding the changes in the intensity of tropical cyclones in the Bay of Bengal is challenging due to its unique oceanographic and atmospheric conditions, including high sea-surface temperatures, vast fresh water influx and the presence of eddies. Based on the in-situ subsurface temperature and salinity changes observed by NIOT's ocean-moored observatories in the Bay of Bengal during tropical cyclone passages, the first-of-its-kind NIOT-developed OAEE-TS algorithm reports the ocean water evaporation rates for various wind speeds. Results shall serve as inputs for statistical-dynamical models for improving the intensity prediction of the tropical cyclones in the Bay of Bengal. In the light of recent rapid ocean warming trends, integrating subsurface thermal parameters into operational forecasting shall enable reliable prediction of cyclone intensification, which is essential for advance warning and disaster preparedness.

Introduction

Over the past 25 years, moored buoy networks have been developed, deployed and operated by the Ministry of Earth Sciences-National Institute of OceanTechnology (MoES-NIOT) from coastal to the deep-oceans spanning between 63–93°E and 6–20°N. They enable collecting increased spatio-temporal meteorological, water surface, and sea subsurface parameters in near real-time, in addition to tsunami buoys that provide water level variations during a tsunamigenic earthquake **(Figure.1).** The collected meteorological and oceanographic data are used for understanding the Indian Ocean dynamics and seasonal monsoons and tropical cyclones (TC) in the Northern Indian Ocean (NIO), as well as enable timely and precise weather forecast.

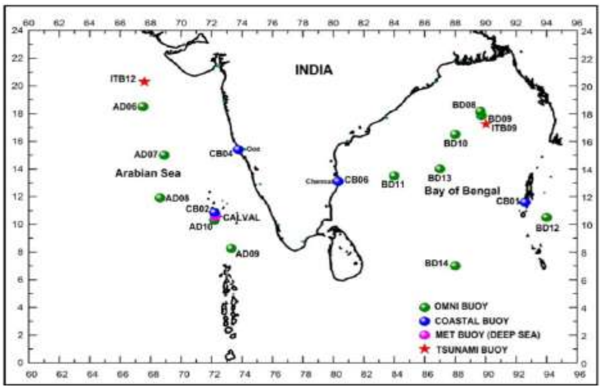


Figure.1. Location of MSB deployed in Indian waters.

Since its inception, these Moored Surface Buoys (MSB) have clocked >12 million instrument-hours, including 8.5 million meteorological instrument-hours (air pressure, temperature, humidity, wind, solar radiation and precipitation) and 3.7 million surface and subsurface oceanographic instrument-hours (temperature and conductivity). The Ocean Moored Buoy Network for Northern Indian Ocean (OMNI) buoy **(Figure.2)** transmits ~108 parameters to the Mission Control Center located at NIOT, through satellite telemetry. The well maintained water temperature and conductivity sensors have an accuracy of 0.002ºC and 0.003ms/cm, and resolution of 0.0001ºC and 0.0001ms/cm, respectively.

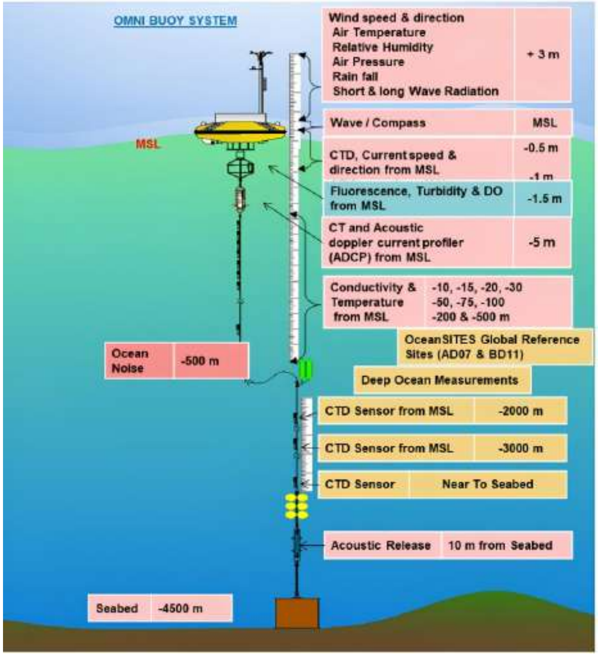


Figure.2. OMNI buoy configuration with real-time sensors

Taking into consideration the weather window available for upkeeping the MSB in the Bay of Bengal (BoB) and Arabian Sea, the annual 4-slot MSB maintenance program which is in place since 2010, ensures maintenance vessel availability for 4 slots of 15 days/slot, totalling 60 days/year. During the maintenance activity, the MSB are off-anchored, and shifted to the maintenance vessel; complete visual and performance checks are carried out and then redeployed. With this maintenance program, the cyclone tracking sensor-suite has an annual data return of ~98%.

Tropical Cyclone Genesis & Intensification

Tropical Cyclones (TC) form over warm ocean waters (>26°C) where moist air rises, creating a low-pressure area that draws in more air. This rising air cools and condenses, forming clouds and releasing latent heat that "fuels" the TC by convection, causing it to intensify. The Earth's rotation, by Coriolis Effect causes the incoming air to spiral, giving characteristic spinning. The travel speed, trajectory and strength of a TC thus depend on various internal and external factors, including TC internal dynamics, atmospheric and ocean factors, and the earth rotation **(Figure.3).**

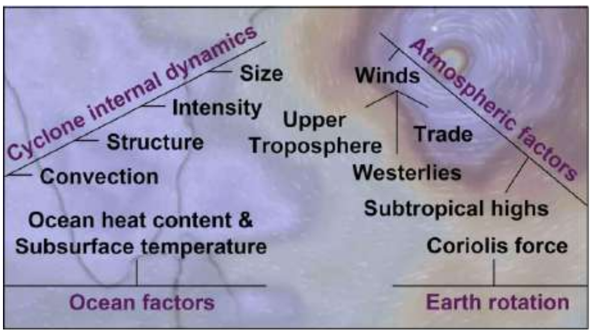


Figure.3. Factors governing the trajectory and intensification of TC

The ocean factors include sea surface temperature (SST), sub-surface temperature, stratification and the presence of eddies. However, the sustainability and intensification of TC are determined by the magnitude of moisture (latent heat), sensible heat (directly transfers the heat from the warm surface waters to the air, creating buoyancy and upward motion) and momentum exchanged at the ocean-atmosphere interface, with fluxes peaking in the eyewall, where winds are strongest. However, when the intense winds churn the ocean, the upwelling deep cold water, cools the sea surface, limiting intensification, creating negative feedback. This sea surface cooling is usually biased to the right side of TC track in the northern hemisphere, and to left of TC track in the southern hemisphere, and the amplitude of the sea surface cooling are usually in the range 1-6°C. The sea surface cooling is quasi-symmetric for slow-moving TC (with speeds <6m/s) and becomes asymmetric for fast-moving TCs.

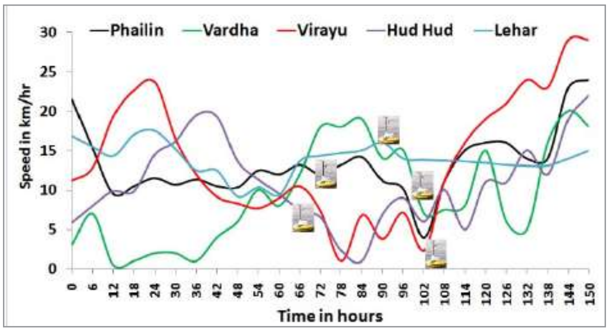
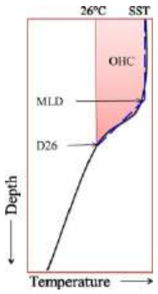


Figure.4. Averaged progressing speeds of TCs

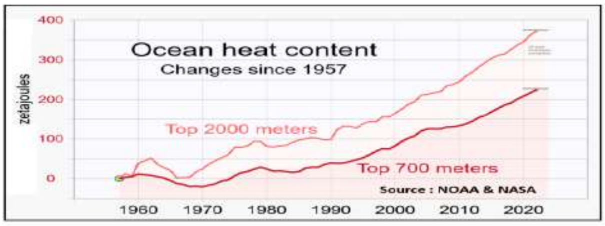
The influence of various processes involved when a TC progress is evident from the 6-h averaged progressing speeds of five severe TCs when they were approaching the OMNI buoys from a distance of 1000km, and when moving away from the buoy **(Figure.4).** The average speeds of severe TC Phailin, Vardha and Viyaru were 13, 9 and 14 km/hr, respectively, while their speed varied in the range 0-30km/h. Hence understanding ocean-atmosphere interaction processes is essential for predicting the speed, trajectory and more importantly, intensification of TC.

Oceans Fueling Tropical Cyclone Intensification

The thermo-dynamic coupling between the ocean and the atmosphere due to winds depends mainly on the degree of ocean stratification (stratification is the natural layering of ocean water into distinct horizontal layers based on density, determined by temperature and salinity). The Ocean Mixed Layer (OML) is the uppermost layer of the ocean where the density is nearly invariant with depth due to the combined effects of the convection and turbulent mixing. Slow winds interact with the ocean through interfacial drag resulting in Ekman pumping. During high winds, the atmosphere interacts with the ocean through spray drag involving two-phase components in the breaking and cresting wave zones, as well as the Ekman layers that can penetrate below shallow convection and extend down into the OML.



Integrating subsurface thermal parameters into operational forecasting shall enable reliable prediction of cyclone intensification



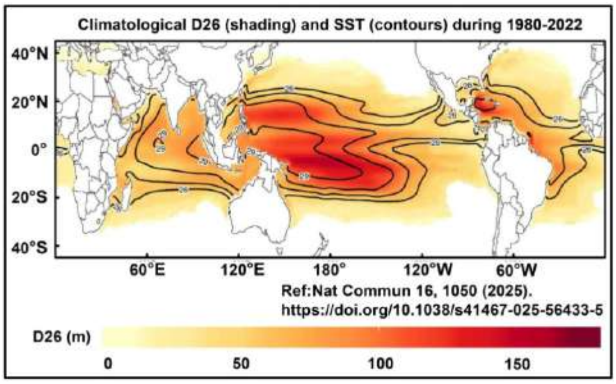


Figure.5, 6 & 7. D26 representation, OHC increase & climatology

Calculating the energy and momentum transfer between the ocean surface and the atmosphere is quite complicated, as it requires precise physical parameterisation of the sea surface waves, roughness length, sea roughness-wind stress relationship, heat transfer coefficients, convective gustiness, influence of salinity in controlling the sea surface humidity and the sea-air boundary surface temperature. The recent statistical-dynamical TC intensity prediction models and the simulation studies indicate that the dynamic changes in the sea sub-surface temperature is an important parameter for predicting the TC intensity changes, in addition to the traditional sea surface temperature (SST) and D26- referenced Cyclone Heat Potential (CHP). The D26 is the depth in the ocean where the water temperature is 26°C and the mixed layer depth **(Figure.5).** The climatological ocean surface and subsurface data (D26 in shaded, and SST in contour) during the period 1980-2022 is shown in **Figure.7.** The multi-fold increase in the Ocean Heat Content (OHC) over the past 5 decades is shown in **Figure.6.**

Figure.8 (Top) shows the trajectory of the Amphan cyclone and the wind speed recorded by the MSB that were along its track. The bottom Figure shows the temperature and salinity changes observed during various wind by the OMNI buoy subsurface sensors, that is moored in 3000m water depth at location 14 ◦ 02′ 01″ N- 87◦00′02″ E in the BoB. It could be seen that the winds of 25m/s increase the OML to depths till 80m, which is confirmed from the salinity change till the same depth. Due to the wind stresses and the subsequent evaporation of the water from the ocean surface, changes in the local buoyancy led to convection. The cool water turns denser, and the salt that is left behind sinks to the base of the OML. The rain and shallow riverine inflows of fresh water have the opposite effect of making the surface water less dense. Both processes lead to a vertical density gradient at the base of the OML **(Figure.8).**

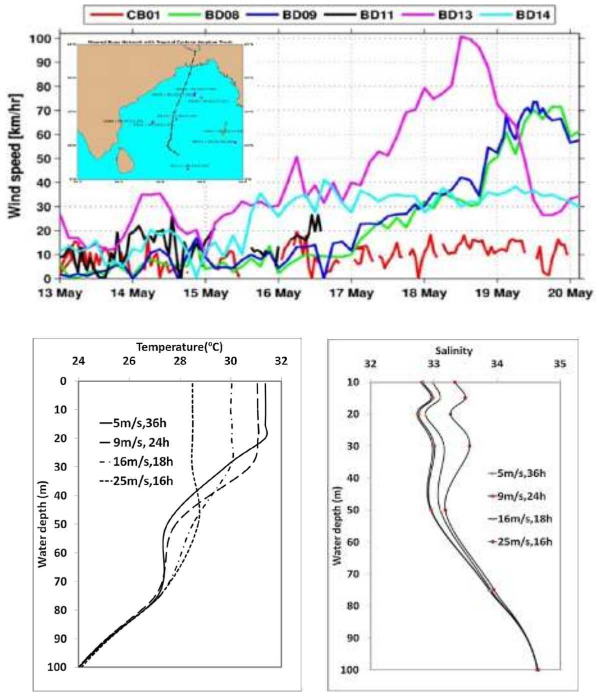


Figure.8. Temperature and salinity variation during TC passage

The TCHP is a measure of the total heat content in a column of the upper ocean, integrated from the sea surface down to the depth of 26°C isotherm (D26), and it governs the intensification of a TC. The TCHP computed for the MSB locations **(Figure.1)** in the BoB is shown in **Figure.9.** It is clear that the steep increase (> 4 times, till 80 kJ/cm^2) is during Mar-June, which is summer/ pre-monsoon season. The TCHP increase is the highest near the B10 location, where rivers Krishna and Godavari discharges into the BoB, totally >5000 m^3/s and ~200 billion m^3(BCM), annually. To note, the BoB receives ~1500BCM of water annually through river discharge, which is comparatively higher than in the Arabian Sea.

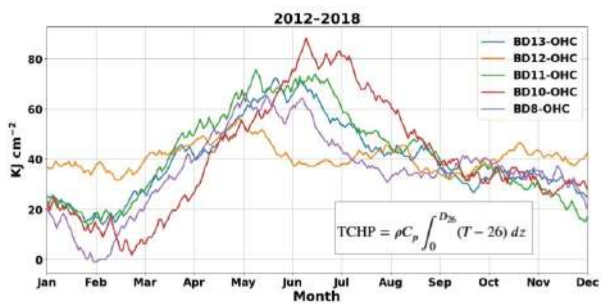


Figure.9.TCHP potential for the Bay of Bengal locations

TCHP-induced Rigorously-Intensified TCs

A TC is considered to undergo Rigorous Intensification (RI) when the maximum sustained wind speed increases by ≥15 m/s within 24h. The concept of energy transfer from the underlying warm ocean surface to developing cyclones based on the principle of the Carnot heat engine was initially propounded by Palmen in 1948 and subsequently used by Leipper and Volgenau to analyse the intensification of the TC in the Gulf of Mexico (GoM). The role of TCHP in the RI of TC was first understood in 1995, from the behavior of Hurricane Opal in the GoM, which intensified from Cat-1 to Cat-4 in 14h as it went over a warm-core ring with TCHP of 113kJ/cm^2, compared to outside which as 63 kJ/cm^2. Subsequently, NOAA recognised regions with TCHP above 90 kJ/cm^2 are most likely to cause RI. During Hurricane Katrina, TCHP was critically high in the GoM, particularly over the loop current and its warm ring (>120 kJ/cm^2), enabling the hurricane's RI to a Cat-5 storm before landfall **(Figure.10).** It was an extremely powerful and catastrophic TC that resulted in ~1400 casualties, and caused damage worth US$ 125 billion.

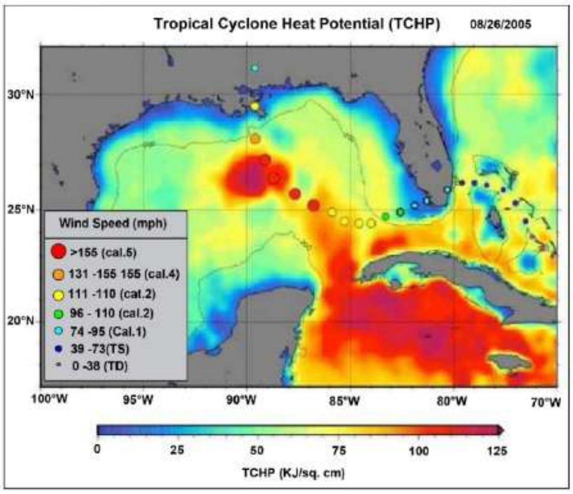


Figure.10. Hurricane Katrina intensified by TCHP

Subsequent classical examples for OHC/TCHP-induced RI, especially in recent warming trends, include Hurricane John (2024) in the Pacific; Hurricanes Katrina (2005), Irma (2017), Micheal (2017) in the Atlantic, and TC Phailin (2013), Fani (2019), and Amphan (2020) in the BoB. Based on the conductivity and temperature data collected during 1993–1996 pre-monsoon and post-monsoon seasons in the BoB, Sadhuram estimated the OHC using the Levitus climatology. Results revealed good association between OHC and TC intensification.

The RI of TC Amphan as a Super Cyclone Storm (SCS) was among the fastest-recorded TC in the BoB in the recent decades, in which wind speeds exceeded 70 m/s within 36h. The OHC in the surrounding waters remained close to 100 kJ/cm^2 threshold, required to sustain RI. The Argo float profiles deployed in the southern BoB, prior to Amphan's formation revealed that the D26 was situated unusually deep at ~100 m, compared to the climatological mean of ~75m during May, which clearly indicates role of TCHP in RI of Amphan. From the TC events during 2000–2023 **(Table.1),** it is evident that high OHC values, often exceeding the climatological threshold of 100 kJ/cm^2, provided the critical subsurface energy necessary to sustain and amplify convection during intensification phases. This establishes a consistent linkage between OHC anomalies and the increased probability of RI events in the BoB.

Table.1. Major BoB TCs intensified by TCHP

BoB TC	TCHP	Wind speed after RI in 24h
Titli	80 kJ/cm^2	23 m/s
Giri	85 kJ/cm^2	28 m/s
Fani	110 kJ/cm^2	31 m/s
Sidr	90 kJ/cm^2	33 m/s
Phailin	100 kJ/cm^2	33 m/s

While the forecast of the TC tracks and their landfall positions have significantly improved, the major forecasting challenge in the North Indian Ocean (NIO) is the RI of TC, especially in the BoB, where coastal communities are extremely vulnerable. The BoB is a semi-enclosed tropical ocean basin comprising about 7% of the global TC count, primarily in the months of Oct–Dec (post-monsoon) and Apr–Jun (pre-monsoon). It is estimated that in the NIO, every 4th cyclone during the pre-monsoon season intensifies to a severe cyclone of Cat-3 or more (wind speed >48 m/s) and every 7th cyclone in post-monsoon season intensifies to a severe cyclone of Cat-3 or more.

The BoB is also known for its high OHC pockets due to fresh water influx from large river systems, strong stratification, and seasonal monsoon processes, that create variable mixed-layer depths and barrier layers, and as a result the Bay exhibits unique thermodynamic and dynamical features that influence RI. In addition, mesoscale warm-core eddies locally enhance TCHP, often aligning with cyclone tracks. Although global studies have highlighted the role of TCHP in RI, relatively fewer investigations have systematically quantified its impact in the BoB using long-term datasets.

Measuring the OAEE in BoB using OAEE-TS approach

Estimating the Ocean Atmosphere Energy Exchange (OAEE) during TC helps to understand the changes in intensity. Analytically modelling the OAEE and estimating the atmospheric moisture generated for various levels of wind speeds (latent heat) during a TC are complicated due to the combined influence of described multiple dynamic atmospheric and oceanographic processes, that act simultaneously. The first-of-its-kind, NIOT's OAEE-Temperature & Salinity (TS) algorithm, developed and used to quantify the OAEE and water vapor generated from the ocean during TC winds (based on the salinity and OHC changes) is shown in **Figure.11.**

> *The BoB is a semi-enclosed tropical ocean basin comprising about 7% of the global TC count*

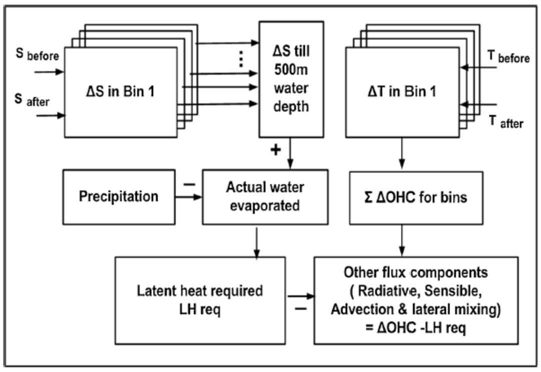


Figure.11.OAEE-TS algorithm

As described in the OAEE-TS algorithm, the quantity of the water vapor produced by the evaporation of the ocean surface water during the passage of the TC is computed by measuring the salinity change before and during its passage, considering the rate of precipitation. When the ocean surface water evaporates, it leaves the salts behind thereby increasing the salinity of the water, which sinks to lower layers due to the difference in the density, whereas, precipitation (rainfall) in the ocean decreases the salinity level. Hence the water evaporated due to the wind alone is calculated by measuring the salinity change over the entire water column and by deducting the fresh water addition due to precipitation.

The changes in the OHC during the passage of a TC are quantitatively determined based on the principles of thermodynamics by computing the difference in the OHC before and during the passage of the TC. As in the case of salinity change measurement, in-situ temperature measurements are made using the sensors in nine depth-referenced bins. The change in the heat content of the seawater in each bin is the product of the Δt (which is t_1-t_2), Cp is the specific heat capacity of sea water at that temperature, m is the mass of the water in that bin, t_1 is the bin temperature before the cyclone and t_2 is the temperature during the cyclone passage.

We analysed the subsurface parameters in the BoB during the passage of multiple TCs **(Figure.12).** From the observations, it is evident that TCs are supported by the thermal energy from water depth up to 75 m, down to the base of the pycnocline **(Figure.13).** Pycnocline is a stable density gradient that separates the upper mixed layer from the deeper water masses. It is due to the presence of fresh surface water in the BoB due to the river run-off, which helps to store the solar heat energy near the sea surface, governing the OAEE by providing instantaneous availability of heat energy during winds. At the same time, the salinity stratification also limits the depths of the ocean-atmosphere interaction up to the base of the pycnocline, which limits the energy availability to the atmosphere.

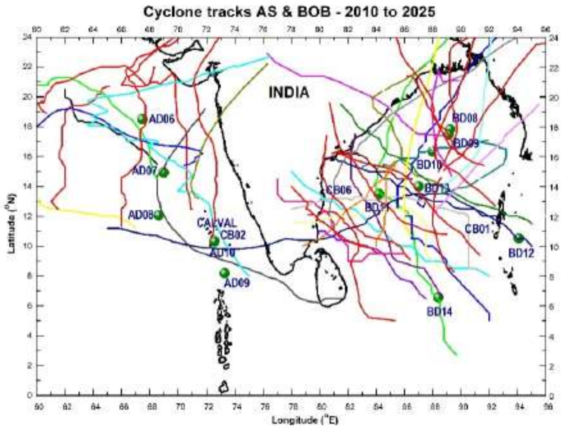


Figure.12. Trajectories of 43 cyclones in the NIO during 2010-25

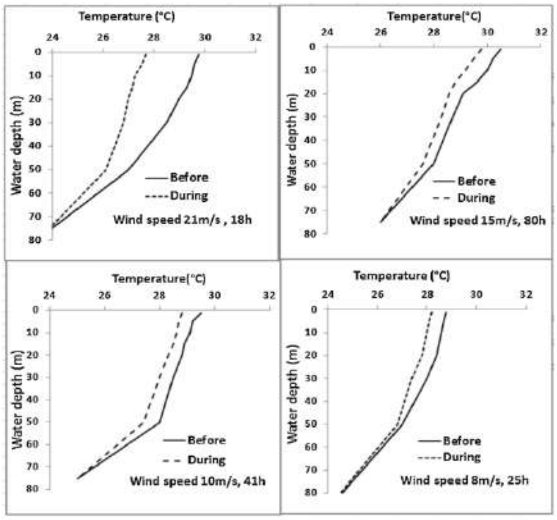


Figure.13. Thermal response during passage of severe TC in BoB

From the OAEE-TS algorithm and dynamic changes in the sea subsurface temperature, salinity and precipitation as inputs, we have calculated the water vapor generation rates for a range of wind speeds. Based on the salinity changes, the water vapor generation rates for cyclone period-averaged wind speeds of 9, 16 and 25 m/s were 0.86, 4.33 and 11.24 kg/m^2/h, respectively **(Figure.14).** For the same wind speeds, based on the OHC changes, ~76, 86 and 95 % of the changes were in the form of latent heat **(Table.2).**

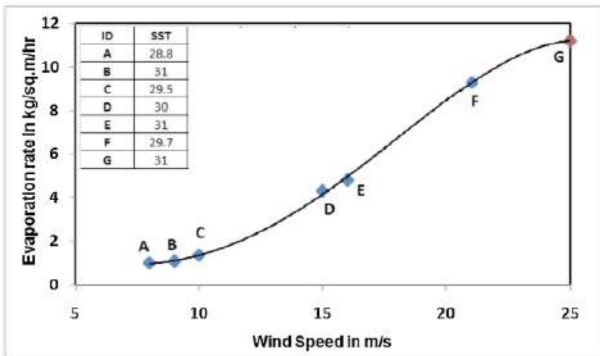


Figure.14.Evaporation rates for various wind speeds and SST

Table.2. Share of heat flux in OAEE under various wind speeds

Wind speed	% of OAEE energy	
	Latent heat	Sensible heat
9 m/s	76%	24%
16 m/s	86%	14%
25 m/s	95%	5%

Discussion and conclusion

Tropical cyclone/hurricane research is gaining momentum through our technological ability to observe the cyclone simultaneously from subsea, sea surface and atmosphere with an array of observational instruments, and to gain a comprehensive perspective of its behavior and dynamics. Over the past decades, the National Oceanic and Atmospheric Administration (NOAA)-Hurricane Research Divisions have leveraged their ability to improve cyclone forecasts by collating multi-modal observations, assimilating data and streamlining modelling and predictions sciences. Simultaneous observations using underwater glider, sail-drone, dropsondes, aircraft (Lockheed WP-3D Orion "Hurricane Hunters" that provides an MRI scan enabling to see all the different layers and internal structure from within the storm, by flying at a low altitude), and satellites significantly improved the estimate of ocean-atmosphere energy exchange, that primarily leads to intensification **(Figure.15).** Through application of physical principles of air motion, moist thermodynamics and radiation were used for developing and improving both multi-layer numerical and statistical-dynamical models that are being used in real-time cyclone track and intensity forecasting.

Since 2014, underwater glider observations have become an integral part of data gathered to improve the cyclone forecast, as well as better understand ocean-atmosphere energy exchange during tropical cyclones passages. NOAA's gliders monitor the thermal structure of the upper oceans along pre-programmed tracks in the Caribbean Sea and tropical northern Atlantic regions, where hurricane typically pass. Through 61 glider missions (4900 glider-days at sea) NOAA carried out >72,000 profiles of temperature, salinity and dissolved oxygen, and surveyed subsea conditions during 21 TCs, which had thrown enough light on the process associated with the cyclones, right from genesis, intensification, till landfall.

In the Indian context, the major forecasting challenge is in reliable assessment of the intensification of the tropical cyclones in the North Indian Ocean, especially in the BoB, where coastal communities are extremely vulnerable. Although global studies have highlighted the role of Ocean Heat Potential/ Tropical Cyclone Heat Potential in rigorous intensification of cyclones, relatively fewer investigations have systematically quantified its impact in the bay using long-term datasets. Presently, for prediction of rigorous intensification, regional meteorological agencies still rely predominantly on atmospheric indicators such as vertical wind shear, mid-tropospheric humidity, and potential intensity. Hence it is high-time to incorporating oceanic metrics into intensification indices so that predictive capabilities could be improved.

As described in this article, the identified evaporation rate parameters including the contribution of the latent heat and sensible heat could be used as inputs to the statistical-dynamical and dynamical models for improving the intensity prediction of the tropical cyclones in the Bay of Bengal. The described OAEE-TS approach could also be an applied to locations of interest, based on reliable heat content and salinity change data acquired during tropical cyclone passage. While the oceanographic systems for cyclone observation including remote sensing and in-situ platforms (floats, drifters, gliders and buoys) to measure ocean-atmosphere interactions is to be increased, at the same time, detailed studies on the combined roles of mixed-layer depth, barrier layer thickness, and mesoscale eddies in modulating cyclone–ocean interactions, and developing a probabilistic intensification prediction framework that integrates Indian ocean and atmospheric parameters could be beneficial to improve our prediction capabilities.

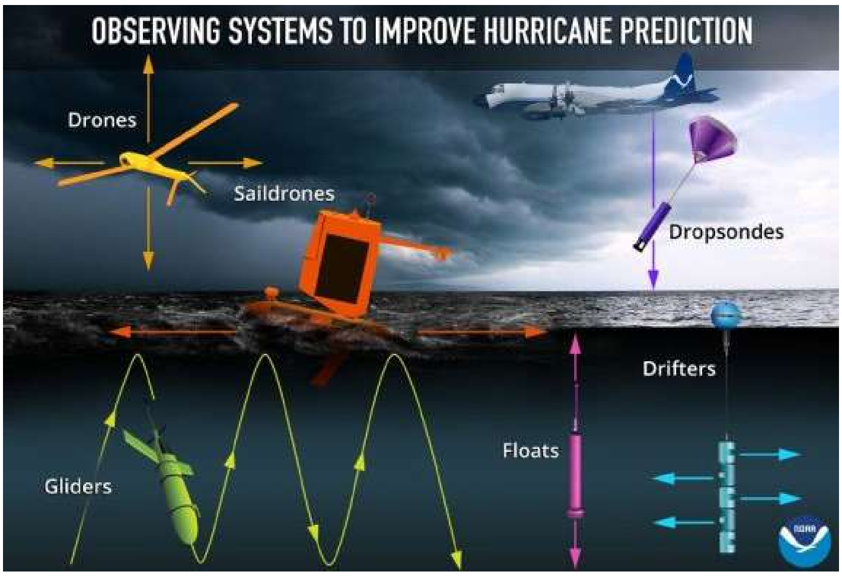


Figure.15.Observing systems used by NOAA

Acknowledgements

We thank the Ministry of Earth Sciences, Govt. of India for motivating this study.

Abbreviations

BCM	Billion Cubic Meters
BoB	Bay of Bengal
Cat	Category
CHP	Cyclone Heat Potential
GoM	Gulf of Mexico
MoES	Ministry of Earth Sciences
MSB	Moored Surface Buoys

NIO	Northern Indian Ocean
NIOT	National Institute of Ocean Technology
NOAA	National Oceanic & Atmospheric Administration
OAEE-TS	Ocean Atmosphere Energy Exchange - Temperature & Salinity
OHC	Ocean Heat Content
OML	Ocean Mixed Layer
OMNI	Ocean Moored Buoy Network for Northern Indian Ocean
kJ	Kilo Joules
RI	Rigorous Intensification
SCS	Super Cyclonic Storm
SST	Sea Surface Temperature
TC	Tropical Cyclones
TCHP	Tropical Cyclone Heat Potential

References and further reading

1. On the use of ocean dynamic temperature for hurricane intensity forecasting. 2018, Weather Forecast. 33 (2), 411–418
2. In situ ocean subsurface time-series measurements from OMNI buoy network in Bay of Bengal. 2013, Curr. Sci.
3. Reliability assessment and integrity management of data buoy instruments used for monitoring the Indian Seas, 2016, Appl. Ocean. Res. 54, 1–11.
4. India's ocean observation network: relevance to society, 2016, MTS Journal.
5. Fuel for cyclones-Quantification of OAEE during tropical cyclones in the Bay of Bengal, using Indian Ocean moored observatories. 2020, MTSJ
6. Air-sea interaction in the Bay of Bengal. 2016, Oceanography 29 (2), 28–37.
7. Quantification of ocean-atmosphere energy exchange during super cyclone Amphan in BoB using Indian Ocean moored observatories, 2021, Dynamics of atmosphere and oceans.

About the Author

Dr. N. Vedachalam is Scientist-G and Director of Deep Sea Technologies Group in National Institute of Ocean Technology (NIOT), Ministry of Earth Sciences, India. His 30 years of experience include industrial power, process, offshore and subsea domains at Aditya Birla group, General Electric & Alstom Power Conversion in France. Technical exposure includes development of multi-megawatt subsea power and control systems, offshore renewable energy systems, unmanned and manned underwater vehicles, ocean observation technologies and industrial systems. His research interests include energy, subsea robotics and reliability. He has more than 100 publications in indexed journals, holds an international and two national patents in subsea robotics and subsea processing. His is a member of various national committees and review boards.

Email: veda1973@gmail.com

Prof. R.Balaji is the Director at National Institute of Ocean Technology, Ministry of Earth Sciences. He is on deputation from IIT Bombay, where is a Professor in Department of Civil Engineering since 2011. Prior to that, he was working as Senior Coastal/Port Engineer at Sogreah Consultants, in Dubai. He obtained his Masters and Ph.D degrees in Ocean Engineering from IIT Madras. He has authored more than 80 publications in peer reviewed journals and 82 conference papers. He has bagged multiple excellence awards, including the Professor S.P. Sukhatme Excellence in Teaching Award in 2024. Apart from teaching and research, his experience includes waterfront development projects in India and abroad. His primary area of expertise includes port, harbor, marina, coastal infrastructural design and developments. He is a member of various national committees and review boards.

Dr. K. Jossia Joseph is a senior scientist in the field of physical oceanography at National Institute of Ocean Technology. She holds masters and doctorate in marine science from Cochin University of Science and Technology, Kerala. Her interest is on ocean observations and is leading the work on data analysis and applications under the Ocean Observation program at NIOT that maintains the moored buoy network in Indian Ocean. She has developed an algorithm for triggering high frequency real-time data transmission during cyclone passages which is implemented in moored buoys. The algorithm appreciated by WMO, NOAA and IMD, is patented transferred to industry. She has also participated in many cruises including the Indo-US collaborative cruise onboard RV Thompson in Jun-2018 and in Jun-23 in Northern Indian Ocean. She has published > 30 papers in peer reviewed journals, developed data products such as wave atlas. She is awarded with the premier professional exchange program IVLP (International Visitor Leadership Program) of U.S. Department of State in 2018. She serves as the Joint Secretary of the Ocean Society of India, which coordinates ocean related activities across India.

G Vengatesan is a Scientific Officer at the National Institute of Ocean Technology (NIOT), Chennai, with over 25 years of experience in marine instrumentation. His work focuses on the development, integration, testing, and deployment of marine data acquisition systems for data buoys and tsunami buoys. He has served as Chief Scientist for multiple buoy deployments and has accumulated over 700 sailing days and ~400 buoy operations in Indian waters. He currently oversees a high-accuracy calibration laboratory, supporting traceable calibration of oceanographic and meteorological sensors. He has authored/co-authored 14 international journal publications, holds one granted patent and three filed patents, and collaborates with PMEL, NDBC and WHOI of USA. He holds a B.E. in Electronics & Instrumentation and an M.Tech in Ocean Engineering (IIT Madras), with research on tropical cyclone heat potential.

THE INSTITUTE OF MARINE ENGINEERS (INDIA), GOA

MTI NO. - 207085

IMEI House, House No.11, Plot No.- D-27, Ranghavi Estate, Post Office, Dabolim, Goa 403 801
Tel: 0832- 2538500, Mobile: 9923102071, E-mail: traininggoa@imare.com

DG APPROVED MODULAR COURSES				
Sr. No.	Course Name	Course Fee	Course Duration	Course Schedule
1	Basic Training for Oil and Chemical Tanker Cargo Operations (OCTF)	₹6,950/-	6 Days	17th February, 2026 09th March, 2026
2	Basic Training for Liquefied Gas Tanker Cargo Operations (LGTF)	₹6,950/-	5 Days	24th February, 2026 17th March, 2026
3	Basic Training for Ships using Fuels covered within IGF Code (IGFB)	₹12,550/-	5 Days	04rd February, 2026 03rd March, 2026
4	Security Training for Seafarers with Designated Security Duties (STSDSD)	₹4,050/-	2 Days	09th February, 2026 23rd March, 2026
5	Ship Security Officer (SSO)	₹4,950/-	3 Days	11th February, 2026 25th March, 2026

- **Course Fee includes** lunch, two tea breaks, and one examination fee**.**
- 5% discount **on group bookings of more than 6 candidates.**
- 7% discount **on group bookings for** combo courses **(OCTF + LGTF) with more than 6 candidates.**
- *Note:* ***Course dates are subject to change.***

Shop Trials & Sea Trials of LNG Carriers

– TECHNICAL PROCEDURES, PERFORMANCE BENCHMARKS & OPERATIONAL VALIDATION – Part 1

Dhivakar Duraikkannu

ABSTRACT:

Shop trials carried out for all critical machineries prior to installation onboard, also known as Factory Acceptance Tests (FATs), to verify compliance with design specifications, safety standards and operational reliability. Sea trials for LNG carriers represent one of the most comprehensive performance verification processes in the maritime industry. Unlike conventional tankers, LNG carriers integrate dual-fuel propulsion, advanced boil-off gas (BOG) systems, complex automation platforms, and stringent safety frameworks under the IGC Code. Conducted typically over seven days, sea trials validate the vessel's hydrodynamic behaviour, propulsion efficiency, manoeuvring capability, vibration/noise thresholds, endurance performance, steering redundancy, electrical system resilience and overall safety integrity.

This article provides a full-scale technical guide—covering preparation, trial sequences, measurement techniques, acceptance criteria, Class requirements and typical operational findings. All photos from the original submission are embedded in their respective sections. The content ensures that marine engineers, superintendents, surveyors and LNG-operations professionals can use it as a practical reference, classroom training resource or commissioning handbook.

KEYWORDS: LNG Carrier, Shop Trials, Sea Trials, Hydrodynamic Performance, Dual-Fuel Engines, Progressive Speed Trial, Manoeuvring Trials, Vibration Measurement, Noise Mapping, NCR/MCR Endurance, UMS Testing, Steering Gear Trials, Class Requirements, IGC Code, Shipyard Trials, Propulsion Systems, LNG Technology.

INTRODUCTION

The shop trials are conducted by manufacturers for performance verification. Type Approval Test (TAT) & Factory Acceptance Test (FAT) Carried out during Shop Trials. The sea trials of an LNG carrier represent the first time the vessel is tested as a fully integrated, floating engineering system. While shipyard workshops individually confirm the functionality of propulsion components, electrical equipment, automation hardware, and deck systems, only sea trials unify these systems under actual dynamic loads. For LNG carriers—equipped with dual-fuel engines (X-DF, ME-GI), sophisticated BOG management systems, advanced reliquefication technologies, redundant steering systems, and high-precision control automation—the sea trial stage plays an even more critical role.

Modern LNG carriers are expected to meet stringent benchmarks not only for propulsion performance and manoeuvrability but also for EEDI/EEXI energy efficiency, emissions compliance, environmental footprint and long-term operational safety. As a result, sea trials follow a structured, data-intensive programme that includes progressive speed runs, hydrodynamic manoeuvring assessments, torsional and global vibration mapping, steering gear endurance, power management system (PMS) functionality, UMS automation trials and ship-wide noise measurements in accordance with IMO Code MSC.337(91).

More than 100 specialists from the shipyard, Class, OEM providers, automation vendors, cargo system designers and the vessel's future operating company embark for the full duration of trials. Their combined findings determine the adjustments made before the vessel's final delivery and certification for gas trials.

1. Purpose & Engineering Philosophy of Shop Trials (Beyond Compliance)

Shop trials on LNG vessels are **not merely compliance events** but represent the **first system-level validation** of machinery behaviour before integration complexity multiplies onboard.

Key engineering intent:

- Detect **design–control mismatches** early (engine ↔ FGSS ↔ IAS)
- Establish **baseline performance fingerprints** for future condition monitoring
- Validate **transient behaviour**, not just steady-state operation
- Reduce **yard commissioning rework**, which is costly and schedule-critical

For LNG vessels, shop trials must be viewed as **risk removal stages**, not box-ticking FATs.

1.2. Dual-Fuel Engine Shop Trials – What Truly Matters

Critical Test Aspects (Often Under-emphasised)

a) Load Acceptance & Rejection

- Sudden step changes (±20–30% load). **Hydraulic Dynamometer -** Used for testing engines at various loads during shop trials.
- Governor response time
- Turbocharger surge margin
- Combustion stability during transient gas admission

Hydraulic Dynamometer

b) Gas Mode Stability Envelope

- Minimum stable gas load
- Lean-burn misfire margins
- Knock detection logic sensitivity
- Cylinder-to-cylinder Pmax balancing

c) Methane Slip Control & Environmental Emission Validation

- iCER/EGR response during low-load gas mode
- Gas admission valve timing accuracy
- Slip trend vs load curve (baseline for ESG reporting)
- EEDI Verification & Emission Validation as per Class, IMO Conventions

d) Safety-Driven Fail Scenarios

- Gas trip → seamless FO fallback
- GVU isolation time verification
- Double block & bleed confirmation
- False positive immunity testing (nuisance trips)

Insight: Engines that pass steady-state FAT but show marginal transient stability often become chronic nuisance-trip units during early service.

1.3. FGSS FAT – Dynamic, Not Static Testing

Essential FAT Enhancements

- **Simulated engine gas demand curves**, not constant flow
- Compressor surge margin verification under fluctuating suction
- Valve hysteresis and response lag testing
- Fail-safe behaviour during PLC communication loss

Redundancy & Recovery Tests

- Hot changeover between compressors
- ESD reset logic integrity
- Restart permissive after emergency trips
- Nitrogen purging effectiveness verification

FGSS FAT should reproduce **real sea load dynamics**, not idealised lab conditions.

1.4. Cryogenic Pump FAT – Lessons from LNG Newbuilds

Key failure modes detected during shop trials:

- Cold-shrink misalignment of bearings
- Motor insulation degradation at cryogenic cycling
- Vibration amplification at partial load
- Cavitation onset during low NPSH conditions

Recommended Enhancements

- Multiple cold–warm cycles, not single run
- Extended endurance at partial flow
- Start–stop sequencing under cryogenic temperature
- Power factor and harmonic measurement for VFD-driven pumps

1.5. Electrical & Automation FAT – Integration Is the Real Test

IAS / PMS / ESD FAT Must Include:

- FMEA TEST – Failure Mode & Effects Analysis
- Cross-vendor communication testing
- Time-delay coordination (engine ↔ FGSS ↔ ESD)
- Alarm prioritisation under cascading faults
- Blackout recovery logic under gas-mode operation

Virtual FAT v/s (FAT) using digital twins is increasingly critical to:

- Validate logic under rare failure modes
- Reduce commissioning disputes onboard
- Accelerate class acceptance

1.6. Safety System FAT – Proving Independence & Integrity

Critical verification points:

- Gas detection sensor response time at ppm levels
- Voting logic validation (2oo3 / 1oo2)
- Fail-safe closure time for pneumatically actuated valves
- Independence of safety PLC from IAS logic

A system that trips correctly is not enough—it must trip **for the right reason, at the right time, and only when required**.

1.7. Documentation – Why FAT Records Matter for Life

Shop trial documentation is the **reference DNA** of the vessel:

- Baseline vibration & combustion data
- Control tuning parameters
- Trip thresholds and response times
- Performance curves at known ambient conditions
- Emission data at various load.

These records support:

- Warranty claims
- Condition-based maintenance
- ESG performance audits
- Incident investigations
- Environmental Compliance

Class-endorsed FAT reports form the **technical backbone** of LNG asset reliability.

1.8. Common Shop Trial Challenges (Observed in LNG Programs)

- Cryogenic contraction underestimated in piping supports
- Compressor vibration tuning delayed to sea trials
- Alarm floods due to poor prioritisation
- Vendor boundary gaps (engine vs FGSS vs IAS)
- Insufficient simulation of real operational transients

Early correction at shop level prevents **months of post-delivery tuning**.

2. Pre-Trial Preparation & Scope

2.1 Planning & Documentation

Weeks before sea trials, the shipyard distributes:

- Sea trial programme
- Safety management plan
- Passage plan
- Crew & engineer cabin arrangements
- System-wise test sheets
- Class acceptance criteria
- Data logging templates
- Emergency procedures

Class (ABS, DNV, LR, BV, KR) reviews the trial programme to ensure alignment with:

- IGC Code
- SOLAS / MARPOL
- Class Rules
- IMO noise Code (MSC.337(91))
- IMO manoeuvring criteria
- ISO 6954 guidelines for vibration

> *Shop trials are not merely compliance events but represent the first system-level validation of machinery behaviour*

3. Ship's Principal Particulars

- Length Overall: 291 m
- Breadth (Moulded): 43 m
- Design Draft: 11.8 m
- Sea Trial Draft: 9.4 m
- Service Speed: 18.5 knots at 85% MCR, 21% SM
- Main Engine: Twin WinGD 6X72DF-2.1 with iCER
- Propulsion: Twin fixed-pitch propellers

These dimensions directly determine the progressive speed trial matrix and the hydrodynamic load envelope under which engines and auxiliaries are evaluated.

4. Categories of Sea Trial Tests

Sea trials are structured into the following major groups:

1. **General Part** – regulatory compliance checks
2. **Hull Part** – hydrodynamics, vibration, noise
3. **Machinery Part** – main engine, pumps, boilers, generators
4. **Electrical Part** – UMS, blackouts, navigation systems
5. **Hull Outfitting Part** – fire systems, lifeboats, ballast, anchors
6. **Steering Gear Trials** – normal & emergency modes

5. General Tests

Class inspectors verify:

- Sea trial instrumentation calibration
- Load cells, torque meters and shaft power meters
- GPS, Doppler log accuracy
- Noise/vibration analyser certification
- Weather & sea state conditions
- Water depth adequacy (> 5× vessel draft)

Only after verification does the vessel proceed to the progressive speed track.

6. Hull Part

6.1 Progressive Speed Trials

Performed at:

- 30% MCR
- 65% MCR
- 75% MCR
- 85% MCR
- 100% MCR

Each run lasts 30 minutes with:

- Constant RPM
- Steady course
- Rudder ≤ 2°
- Depth > 5× draft

The trial determines:

- Attained speed
- Shaft power
- EEDI verification
- Propeller–hull interaction efficiency
- Sea margin validation

6.2 Manoeuvring Trials

Crash Stop Astern

Full ahead → full astern. Measures:

- Crash stop track
- Time to stop
- Head reach
- Lateral deviation

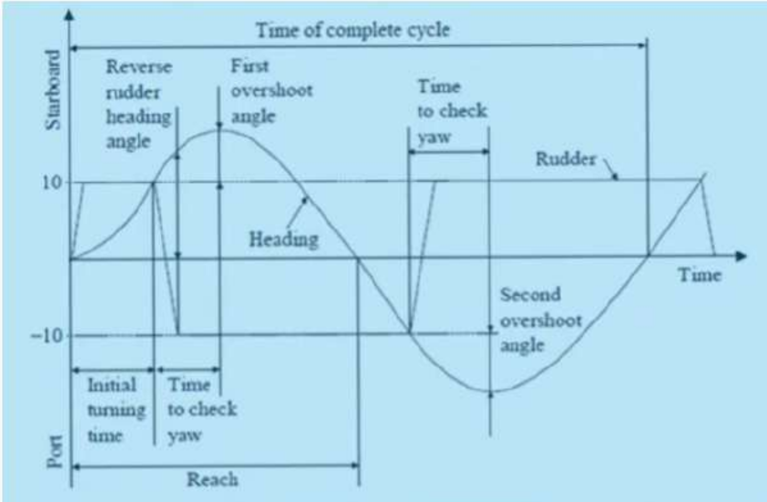
Turning Circle Test

35° rudder → full circle. Confirms IMO/MSC hydrodynamic criteria.

Zig-Zag Test

10°/10° and 20°/20° zig-zag manoeuvres quantify:

- Overshoot angle
- Yaw response
- Rudder effectiveness



Minimum Revolutions Test

Determines the lowest steady RPM enabling steerage.

7. Vibration Measurement Programme

Vibration measurements are critical due to dual-fuel engine dynamics and propeller excitation.

7.1 Global Vibration

Conducted at RPM:

30, 35, 40, 45, 50, 55, 60, 65, 70, 71, 75 (10 minutes at each RPM)

Instrumentation: accelerometers and triaxial analysers.

Criteria: ISO 6954:2000(E).

CONDITION	RPM STEP	Normal Condition	*QPTD	Remark
Steady State	5 RPM	From minimum revolution to 30 RPM	-	TV
	2 RPM	From 30 RPM to 40 RPM	OFF	TV
	5 RPM	From 40 RPM to 75.6 RPM	-	TV
Transient (Ahead)	30→41 RPM	Raising	ON	Time
	41→30 RPM	Lowering		
Transient (Astern)	30→41 RPM	Raising		
	41→30 RPM	Lowering		

RPM Setting up Interval for Torsional Measurement

7.2 Local Vibration

Performed during NCR endurance test using portable analysers.

Covers:

- Engine top plates
- Reduction gearbox foundations
- Ballast pump room
- Accommodation blocks
- Bridge wings

Typical findings include resonance bands near barred speeds or excitation from cargo compressors running.

8. Noise Measurement Programme

Noise measurements ensure compliance with the IMO Code on Noise Levels on Board Ships (MSC.337(91)).

Noise Measurement Device

8.1 Conditions

- Rudder ≤ 2°
- NCR RPM
- 5× draft depth

> *FGSS FAT should reproduce real sea load dynamics, not idealised lab conditions*

8.2 Locations

- Engine Room: 110 dB(A) limit
- Workshops: < 85 dB(A)
- Accommodation: 55 dB(A)
- Bridge: 60 dB(A)

Noise maps are generated and hotspots identified (usually cargo compressor rooms or deck machinery areas).

9. Machinery Part

This is the most extensive segment of the sea trials.

9.1 Main Engine Endurance Tests

NCR Endurance: 4 hours **MCR Endurance:** 8 hours (includes 4 hours UMS)

Parameters logged:

- Shaft RPM & shaft power
- Load index
- Turbocharger speed
- Cylinder pressures (Pmax, Pcomp)
- Fuel rack position
- Jacket water/LO temperatures
- iCER system performance
- BOG interaction (simulation only during sea trial)

9.2 Astern Endurance Test

Main engines run astern for 10 minutes. Ensures astern sealing, bearing lubrication, and complete reversibility.

9.3 Fresh Water Generator Capacity Test

Measured at NCR — confirms production rates aligned with maker's load curves.

9.4 Exhaust Gas Economiser Test

Verifies steam generation from waste heat under NCR/MCR.

9.5 Boiler Tests

Accumulation Test

Verifies safety valves can handle maximum steam production, ensuring pressure doesn't exceed safe limits, when all steam outlets are shut and the boiler fires at full rate.

Popping Test

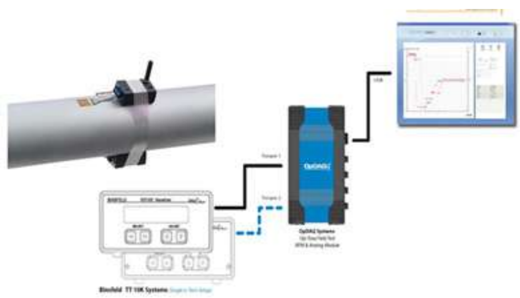
Verifies operation of safety valves at set pressure.

9.6 Starting Air System Capacity

Engines must be capable of **16 consecutive starts** with reservoirs charged to **30 bar**.

9.7 Torsional Vibration Analysis

Used to establish final **barred speed ranges**. Test involves ramping up from minimum RPM to MCR and validating against calculation models.



10. Steering Gear Trials

Steering gear trials follow SOLAS Ch. II-1 requirements.

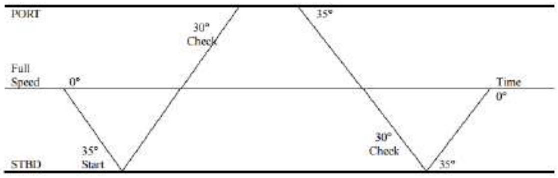
10.1 Normal Steering Trial

Performed at MCR.

Steps:

1. Midship → 35° Stbd
2. 35° Stbd → 35° Port
3. 35° Port → 35° Stbd
4. 35° Stbd → Midship

Test confirms pump capacity, ram travel time (< 28 sec), and hydraulic integrity.



Steering Test

10.2 Emergency Steering Trial

- Conducted at <7 knots or half service speed
- ESBD (Emergency Switchboard) power supply used
- Auxiliary steering unit engaged

Sequence mirrors the normal steering test but with reduced angles (±15°).

11. Fuel Oil Consumption Measurement

During progressive speed trials, fuel oil consumption at each load point is captured using:

- Mass flow meters
- Ship Performance Monitoring System
- Engine's fuel index

Results are compared against:

- Shop test curves
- Contractual guarantees
- EEDI/EEXI compliance tables

12. Shaft Alignment & Bearing Load Measurement

Measurements taken under hot running condition include:

- Forward sterntube bearing load
- Intermediate shaft bearing loads
- Aftmost engine bearing loads
- Crankshaft deflections

Misalignment corrections are applied at the yard if deviations exceed allowable tolerances.

13. Single-Engine Operation Test

With one shaft locked, the other engine must propel the vessel safely. Assesses:

- Redundancy
- Steering capability
- Load impact on running engine
- Propeller asymmetry handling

14. Centrifugal Pump & Cooler Tests

Pump run/stop tests performed include:

- Ballast pumps
- Fire/GS pumps
- Cooling water pumps
- Fuel oil & Lube oil pumps

Parameters monitored:

- Vibration
- Bearing temperature
- Suction/discharge pressures
- Seal leakage

15. Electrical Part

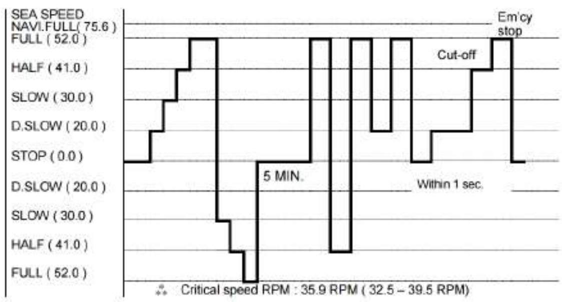
15.1 UMS (Unmanned Machinery Space) Test

Conducted during NCR endurance. Verifies:

- Alarm delays
- AutoStart logic
- ESD supervision
- Remote control readiness

15.2 Bridge Control & Safety Test

All ME commands must be executable from the bridge without local assistance.



Bridge Control Test

15.3 Main Engine Safety Test

Simulation of all slow-down trips:

- High jacket water temp
- High exhaust temp
- LO low pressure
- Overspeed
- Scavenge fire alarms

15.4 Blackout Tests

Performed for all generator running combinations. Test verifies:

- Fast bus transfer
- Dead bus recovery
- Load shedding
- Sequential restarting

> *Early correction at shop level prevents months of post-delivery tuning*

15.5 Navigation Equipment Trials

Includes:

- Gyro compass
- Magnetic compass
- Radar/ARPA
- GPS & DGPS
- Echo sounder
- Speed log
- AIS
- Communication equipment

All signals must integrate with the voyage data recorder (VDR).

15.6 Fire Detection & Extinguishing System Tests

Includes:

- Detector location verification
- Loop integrity
- CO_2/NOVEC release alarm simulation
- Manual call point sampling

16. Hull Outfitting Trials

16.1 Fire & Deck Wash

- Fire pumps
- Emergency fire pump
- Water curtain system
- Water spray tests for manifold, tank areas, accommodation façade, lifeboat stations

ITEM : WATER SPRAY SYSTEM	LOCATION ON-BOARD ( )
KIND OF INSP. : FUNCTION TEST	DATE:

Area	Result
- Cargo manifold (P&S)	
- Liquid dome area	
- Gas dome area	
- Cargo valves	
- FWD life raft	
- Accommodation front wall	
- Life boat / Life raft area (P&S)	
- Muster station / Embarkation area (P&S)	
- Cargo Machinery & Elec. motor room wall	

Pump	Pressure (Bar g)	Remark
Water spray pump		
SW supply pump for High expansion Foam system		Only Accom. & Life-raft area (P&S at upper DK)

Water Spray System Test

16.2 Ballast System

- Ballast pumps
- Stripping system
- BWTS operation

16.3 Anchor Trials

Performed at depth ≥ 110 m. Checks:

- Brake holding capacity
- Windlass torque
- Free-fall performance (if applicable)

ITEM	WINDLASS	LOCATION	SEA TRIAL
KIND OF INSP.	ANCHORING TEST	DATE :	

MAKER :

TRIAL DRAFT (FWD/AFT)	WATER DEPTH	WIND DIRECTION	WIND VELOCITY	OIL TEMP. IN POWER UNIT.	
				BEFORE TEST	AFTER TEST
/ m	m		m / sec.	℃	℃

NO.	DESCRIPTION		RESULT		REMARK
			PORT	STB'D	
1	LOWERING & BRAKE CONDITION				
2	TIME TO HOIST EACH ANCHOR SEPARATELY	3-4 SHOT	sec m / min	sec m / min	
		3-2 SHOT	sec. m / min.	sec. m / min.	
		2-1 SHOT	sec m / min	sec. m / min.	
	AVERAGE HOISTING SPEED IN TWO(2) PUMPS OPERATION *TO BE CHECKED TWO(2) PUMPS OPERATION FOR W1(STB'D) & W2(PORT) AS SHOWN BELOW. (PORT – W2 : NO.3 & 4 PUMPS) (STB'D – W1 : NO.1 & 2 PUMPS)		m / min.	m / min.	12 m / min.
3	ANCHOR STORAGE CONDITION				
4	ELECTRIC MOTOR	MAX. VOLTAGE	V	V	
		MAX. CURRENT	A	A	
5	MAX. HYDRAULIC OIL PRESSURE AT POWER UNIT			Bar	BELOW 64 BAR
6	ANCHOR CHAIN WASHING CONDITION				
7	ANCHOR SPEED LIMITER (LOWERING)				

Anchor Test

16.4 Life/Rescue Boats

- Launch with crew
- Recovery operations
- Davit & winch brake tests

17. Key Observations & Challenges During Sea Trials

Common issues encountered:

- Turbocharger tuning deviations
- Slight mismatches in manoeuvring handle vs load index
- Excess vibration near certain RPM bands
- Localised noise hotspots
- PMS logic fine-tuning
- Steering pump flow reduction under high load

- FWG performance variation due to seawater temperature
- Boiler accumulation test adjustments

Each issue is logged and rectified at the yard before delivery.

18. Conclusion

Sea trials serve as the definitive validation of LNG carriers' performance, integrating propulsion efficiency, hydrodynamic behaviour, automation robustness, and safety integrity. For LNG carriers—given their complex dual-fuel machinery and demanding cargo systems—sea trials provide essential assurance that the vessel can safely advance to full-scale **gas trials** and later enter commercial service.

Successful sea trials require flawless coordination between shipyard teams, OEM specialists, Class surveyors, and ship staff. The reliability demonstrated during these trials directly influences vessel performance, energy efficiency, EEDI/EEXI compliance, and long-term operational safety.

Acknowledgements

I would like to thank MMS – Technical, Operations & Manning Departments for giving me an opportunity to attend LNG Vessel Sea & Gas Trials.

References:

1. SIGTTO Guidance for Gas Trials on LNG Carriers
2. LGHP SIGTTO
3. LNG Vessel Cargo Operating Manual
4. Yard SEA & GAS Trail procedures.

About the Author

Dhivakar Duraikkannu currently serving as Chief Engineer on LNG carriers with MMSI, with prior experience as Gas Fleet Technical Superintendent at Anglo Eastern Ship Management, Singapore. Visiting Faculty at the Hindustan Institute of Maritime Training (HIMT), Chennai. Holds a B.S. in Marine Engineering and an MBA in Shipping & Port Management; Fellow of IME(I). Specialises in cryogenic containment, FGSS, BOG management and LNG dual-fuel machinery operations.

Email: dhiva100@yahoo.com

TECHNICAL NOTES

Marine Engineering Accident Investigation Series

When the Engine Room Goes Dark - Root Cause Investigation of Blackouts on Modern Bulk Carriers

Gajanan Karanjikar

"Most ship blackouts do not begin with a generator failure. They begin with an assumption—that automation will take care of itself, and that engineers no longer need to fully understand the logic governing the ship's electrical heartbeat."

Abstract

Blackouts on modern bulk carriers are no longer simple machinery failures or isolated generator trips. They are increasingly complex, system-level events involving automation logic, electrical protection, software configuration, and human–machine interaction. A total loss of power can rapidly escalate into groundings, collisions, or bridge allisions, exposing shipowners and operators to severe financial, legal, and reputational consequences.

Using the framework of power management systems (PMS), load-shedding logic, automation data analysis, and human factors, this paper presents a practical, investigation-oriented approach to identifying root causes of shipboard blackouts. The article also outlines the relevant international conventions and the evolving liability landscape confronting owners and managers when the engine room goes dark.

Keywords: Blackout investigation; Power Management System (PMS); Load shedding; Marine electrical systems; Automation failure; Switchboard protection; Human–machine interface (HMI); SOLAS compliance; ISM Code; Root cause analysis; Bulk carrier safety; Engine room automation

Introduction: Power Is Safety

On a modern ship, a blackout is never merely a relay opening or a diesel engine stalling. It is a systemic failure that exposes how power, automation, and human control are truly understood on board. Electrical power today is not a support function; it is the ship's nervous system. It sustains propulsion and steering control, navigation and communication systems, automation and alarms, ballast and cargo operations, and critical safety equipment.

When the main bus goes dead, the ship experiences a form of neurological collapse. In that moment, a large bulk carrier becomes a drifting, powerless mass—effectively blind and unresponsive—often in confined or congested waters. If we genuinely accept that electrical power is safety-critical, then every decision relating to its design, operation, and maintenance must be driven first by resilience and redundancy, and only then by efficiency or convenience.

At the centre of this discussion lies the Power Management System. Conceived as a loyal servant, the PMS was designed to quietly balance generator loads, start and stop sets, share kilowatts, and shed non-essential consumers to prevent overloads. Over time, however, it often becomes an unseen master. Acting faster than any human operator, the PMS mediates every critical decision between generators and consumers.

When parameters are incorrectly tuned, when sensors drift into marginal accuracy, or when software logic creates unintended interactions, the PMS can generate the very blackout it was designed to prevent. Engineers frequently adjust setpoints in good faith to reduce nuisance alarms or trips, gradually eroding the conservative margins established during commissioning. The erosion is subtle and often undocumented—until a heavy manoeuvring load, a bow thruster starts, or a crane lift pushes the system beyond its limits.

In that moment, a software layer governs the fate of the ship's electrical heartbeat, while operators watch events unfold rather than confidently directing them.

1. Why Blackouts Matter More Than Ever

For a loaded bulk carrier approaching a narrow channel or port entrance, a total loss of electrical power is not a technical inconvenience—it is an immediate navigational emergency. Steering and propulsion are lost simultaneously. Navigation and communication systems fail. Situational awareness collapses within seconds. In confined waters, a 90,000-tonne vessel can become uncontrollable in minutes.

A recent casualty involving a large cargo ship that experienced repeated power losses immediately before striking a central road bridge in a busy port channel has starkly demonstrated the consequences. The incident resulted in multiple fatalities, catastrophic infrastructure collapse, prolonged closure of a major trade artery, and claims likely to run into billions of dollars. These claims extend well beyond hull damage to include loss of life, environmental exposure, and cascading economic disruption.

In many such cases, the initiating sequence lies deep within the engine room: generator instability, PMS logic failures, switchboard protection maloperation, or delayed human response to escalating alarms. The blackout itself is rarely a single failure; it is the final manifestation of multiple weaknesses aligning at precisely the wrong moment.

For marine engineers, technical managers, and casualty investigators, understanding exactly how and why the engine room "went dark" is therefore central—not only to assigning responsibility, but to preventing recurrence.

2. Anatomy of a Blackout on a Bulk Carrier

A modern bulk carrier electrical system typically comprises multiple diesel generators connected to a central switchboard, often supplemented by shaft generators or harbour auxiliaries. A Power Management

System controls generator start/stop sequences, load sharing, and load shedding. Essential services are supplied via the main switchboard and backed by an independently driven emergency generator. All of this is integrated through automation and alarm systems linking engines, auxiliaries, boilers, and cargo machinery.

In practice, blackouts arise from a combination of three interacting categories:

1. **Prime mover issues** such as fuel system faults, air ingress, governor instability, overspeed trips, low lubricating-oil pressure, or scavenge fires.
2. **Electrical faults** including short circuits, earth faults, protection relay maloperation, or switchboard component failure.
3. **Automation, PMS, or human failures**, such as incorrect load sharing, failure to auto-start standby generators, defective load-shedding logic, or delayed or incorrect operator response.

The critical investigative mistake is to treat a blackout as a single equipment failure. In reality, it is a system event. A generator trip may be the final trigger, but the true causes usually lie upstream—in configuration, maintenance practices, automation logic, or human-machine interaction.

3. Power Management Systems: Protection or Risk?

Although designed to prevent blackouts, the PMS frequently becomes central to blackout investigations. A structured review should include recovery of PMS logs, reconstruction of event sequences, verification of parameter settings, and examination of interfaces with propulsion control and shaft-generator systems.

A typical sequence reconstructed during investigations is depressingly familiar: a sudden large load step causes a frequency dip; the PMS attempts to start an additional generator; the start fails or is delayed; load shedding is insufficient or misconfigured; generators overload and trip; and the vessel blacks out completely.

Common findings include PMS configurations with inadequate safety margins, disabled auto-functions left unreinstated after maintenance, incorrect load-priority lists, and undocumented software or parameter changes. In several cases, safety features were technically present but rendered ineffective by progressive "tuning" to avoid nuisance alarms.

Where incidents are complex or contested, shore-based simulation of PMS logic—often with manufacturer support—has proven invaluable in confirming or disproving investigative hypotheses.

4. Load Shedding: The Last Barrier

Load shedding represents the final safety net against a total blackout. When correctly configured, it is often the difference between a brief brownout and complete loss of power.

Investigations must examine load-priority lists, shedding speed, and the effectiveness of interlocks protecting essential consumers such as steering gear. Frequent weaknesses include high-demand consumers operating without generator-availability interlocks, manual overrides left in place after testing, and gradual erosion of conservative settings in service.

In many cases, the load-shedding system did not fail—it was quietly neutralised long before the casualty occurred.

5. Automation Data: Making the Invisible Visible

Beyond PMS logs, modern ships generate extensive forensic data across multiple automation platforms. Alarm and event logs from engine, boiler, propulsion, and auxiliary systems must be correlated with VDR data, including speed, heading, telegraph commands, and bus voltage and frequency.

Accurate time synchronisation across systems is essential. Investigators frequently identify repeated partial power losses or unstable electrical conditions minutes—or even days—before the final blackout. These warning signs are often logged, acknowledged, and then forgotten.

In hindsight, the blackout was not sudden. It was merely the point at which an unresolved problem could no longer be contained.

6. Human–Machine Interface and Crew Response

No blackout investigation is complete without examining how watchkeepers interacted with the system. Alarm overload, poor interface design, inadequate training in digital PMS logic, and the absence of realistic blackout recovery drills are recurring contributors.

Interviews should focus on what engineers actually perceived during the event, which alarms were routinely ignored, and whether clear recovery procedures existed and were understood. Increasingly, investigators and courts ask not only what the engineer did, but whether the system enabled them to do the right thing under stress.

7. Regulatory and Compliance Context

Blackout investigations are framed by SOLAS Chapters II-1 and V, the ISM Code, the IMO Casualty Investigation Code, and classification society rules governing electrical installations and automation. Failure to demonstrate compliance—or effective implementation—can significantly increase exposure to detention, insurance disputes, and liability claims.

8. Legal and Financial Consequences

Blackout-related casualties can generate extreme financial exposure, including hull and machinery damage, third-party infrastructure claims, personal injury or fatality claims, cargo losses, salvage, pollution liability, and prolonged off-hire. Legal scrutiny typically focuses on seaworthiness, due diligence, and whether defects were known—or should reasonably have been known—before the voyage.

A documented history of proper investigations and corrective action can be a powerful defence. A culture of normalising repeated trips and "quick fixes" can be devastating.

9. From Investigation to Prevention

The true value of a blackout investigation lies in prevention. Effective outcomes include fleet-wide PMS reviews, stronger change-management procedures, enhanced training and drills, and closer collaboration with manufacturers and class.

Recent investigations into a major bridge allision in the United States have renewed attention on degraded electrical connections and abnormal heating in main power systems. Thermal imaging surveys conducted under realistic load conditions are increasingly recognised as a powerful preventive tool, capable of identifying incipient failures long before they escalate into catastrophic blackouts.

Blackouts may never be eliminated entirely, but their frequency and severity can be drastically reduced when each incident is treated as a source of engineering, operational, and organisational learning.

Closing Perspective

In an era of advanced automation and data-rich systems, the engine room going dark should no longer be a mystery. With disciplined, system-level investigation grounded in electrical engineering, automation logic, and human-factors analysis, the industry can ensure that the next blackout alarm leads not to disaster, but to understanding—and to a safer fleet.

About the Author

Capt. Gajanan Karanjikar is a Master Mariner, marine surveyor, and US-based casualty investigator with decades of experience at sea and ashore. His work spans ship command, technical surveys, flag-state and class compliance, and post-casualty investigations. He combines traditional seamanship with modern forensic methods to help the industry learn from its most challenging incidents.

Email: captgajanan@gmail.com

Going Astern into MER Archives…

The March – April 1986 starts with an Important Notice: Due to rising costs and financial strain, the Governing Council reviewed options and decided to increase subscription rates. Advertising income was a uncertain, and reducing or discontinuing MER was rejected because of its importance to members. Revised subscription and entrance fees take effect from 1 October 1985, and members are requested to comply promptly to support the Institute Members are requested to pay the revised rates promptly to support the Institute's finances.

The editorial welcomes the government's late initiatives to revive a struggling shipping industry, noting a pragmatic shift by the transport ministry in linking debt rescheduling to the remaining life of ships, rather than a narrow financial approach. It emphasises that shipping is strategically vital to national trade, commerce, and defence, and calls for coordinated action by government, ports, and shipping companies.

There are a series Energy efficiency technologies discussed almost 40 years ago which are being considered for implementation today due to decarbonization requirements commonly under energy efficiency technologies (EET's). How prophetic these articles are! Some sample article which can read by the readers and stoke their interest include the following:

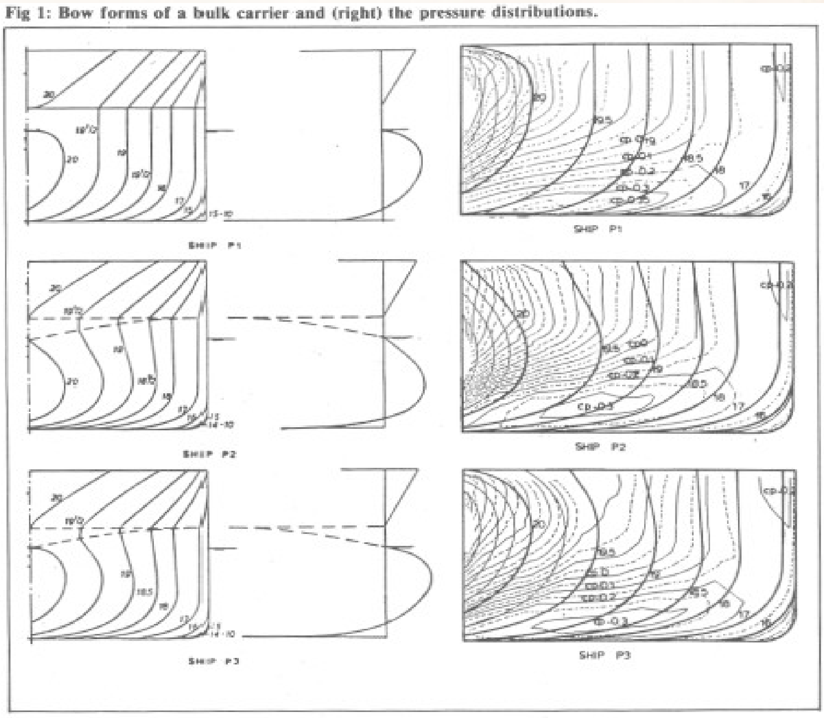
Energy saving hulls: Are fins & ducts necessary by M Jonk from Marine Engineering Research Institute Netherlands, MARIN (pages 7 to 8)

The article argues that **hull-form optimisation is more important than add-on devices** for energy savings. Properly designed hulls can reduce resistance and power demand so effectively that fins, ducts, or energy-saving devices add little benefit. Using MARIN studies, it shows how optimised bow forms and flow characteristics lower required power, while devices should only be considered when hull optimisation is constrained by design limits.

Table 1: Smaller resistance, hence lower power requirement for ships P2 and P3.

Speed in knots	Ship P1		Ship P2		Ship P3	
	P_E%	P_D%	P_E%	P_D%	P_E%	P_D%
12	100	100	90.2	84.6	92.1	84.1
13	100	100	92.3	86.5	93.2	86.7
14	100	100	93.4	88.3	94.1	87.1
15	100	100	92.1	85.8	92.6	85.5
16	100	100	91.9	85.7	92.8	85.1
17	100	100	95.7	90.3	95.9	90.9

Fig 1: Bow forms of a bulk carrier and (right) the pressure distributions.



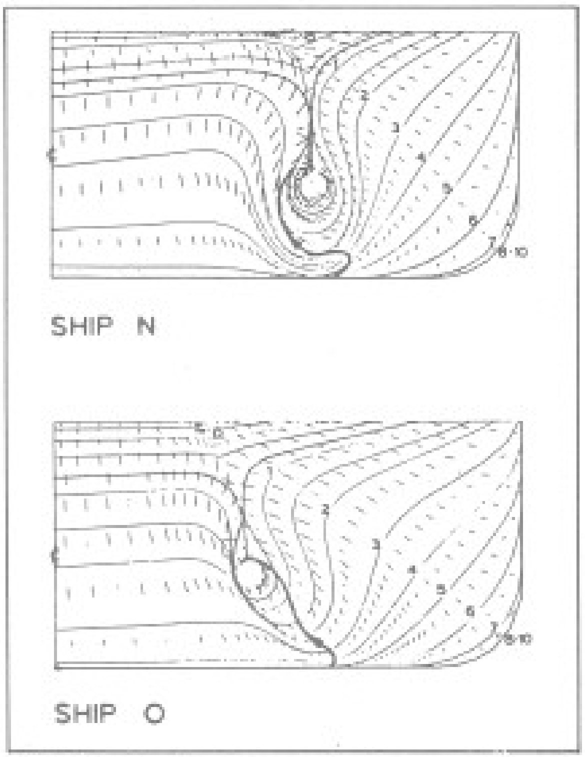


Fig 2: Body plans for a twin-skeg vessel.

Ship	*N*		
Speed in knots	P_E %	P_D inw %	P_D outw %
15	100	100	108.7
16	100	100	108.8
17	100	100	109.0
18	100	100	109.2
19	100	100	109.3
20	100	100	110.3
Ship	*O*		
15	71.4	85.2	87.0
16	71.0	84.8	86.7
17	74.7	83.9	85.3
18	75.7	83.1	83.9
19	77.6	84.5	84.2
20	82.2	91.9	88.9

Table 2: Model test figures.

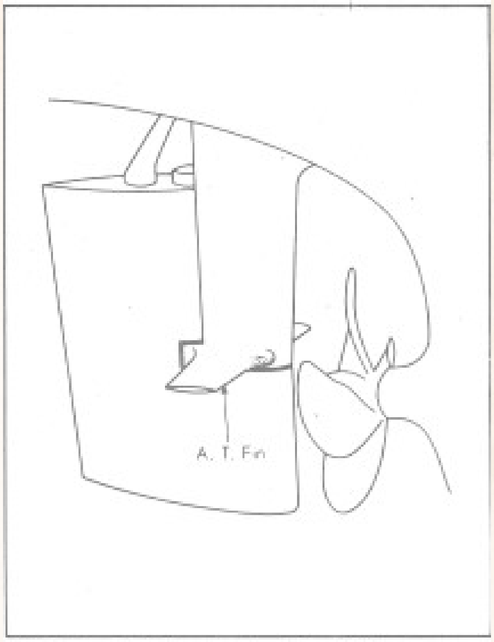
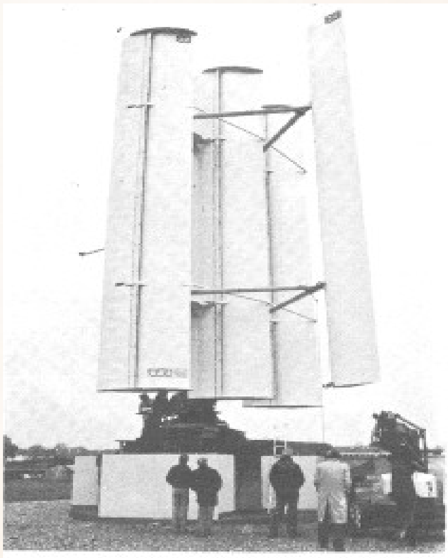


Fig 3: The AT fin developed by IHI

New Style sailors slash fuel costs by Arther Convey (page 11)

The article reports that **wind-assisted propulsion using new-style rigid sails (wing sails)** can significantly reduce fuel consumption and operating costs for ships. Backed by the British Wind Energy Association, it argues that modern, computer-controlled sails can deliver **20–30% fuel savings**, pay back their cost within a few years, and be applied to both newbuilds and retrofits. Early trials and installations show promising results, suggesting that wind assistance could cut emissions, lower costs, and revive idle or marginal vessels, making wind a practical supplementary propulsion option for commercial shipping rather than a niche experiment.



The advantages are not only fuel savings.

More efficient turbocharging offers greater fuel saving potential (pages 12-13)

The article explains that **greater fuel savings can be achieved by improving turbocharger efficiency and adopting turbocompound (power turbine) systems** on diesel engines. While conventional engine improvements offer limited further gains, recovering surplus exhaust energy through a power turbine can reduce fuel consumption by up to **4%**, and even more at optimal operating points. Trials show benefits across part-load operation as well, with improved scavenging efficiency and reduced need for auxiliary blowers. As engine builders validate these results, turbocompounding is increasingly seen as a practical, integrated solution for improving overall propulsion efficiency and lowering fuel costs.

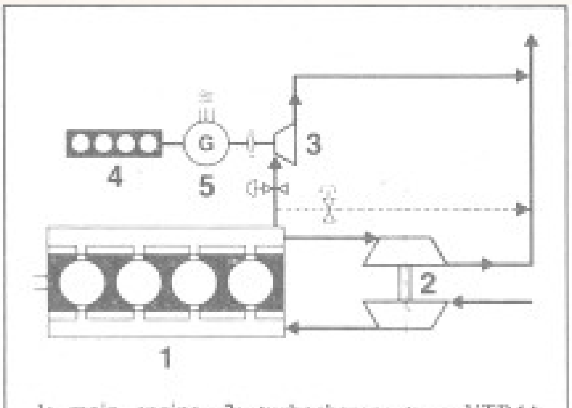


Fig 1: BBC integrated power system.

Power turbine on a test rig: the optimum exhaust gas flow to the turbine was 10%.

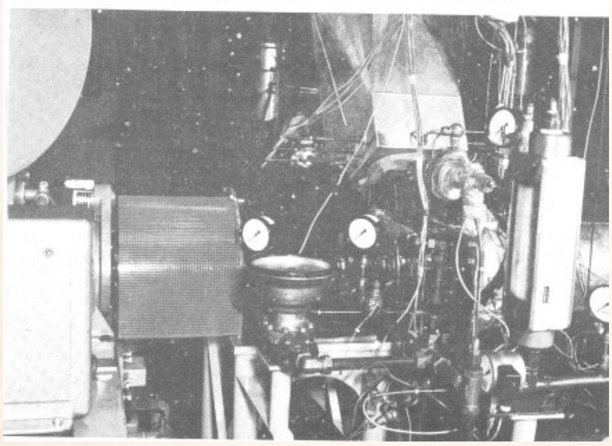
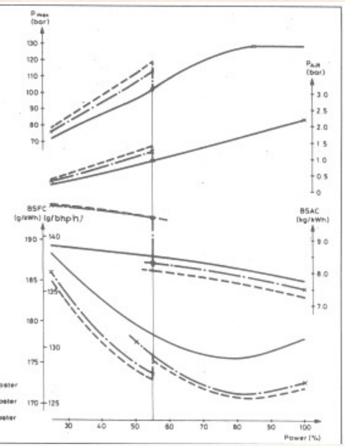


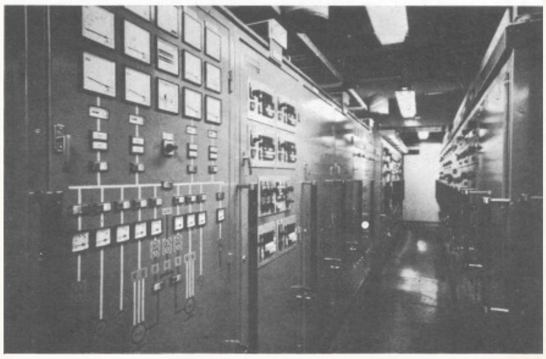
Fig 2: Results from a 6RTA58 diesel with and without a power turbine. Both apply to the engine's R1 rating. The power turbine switch on/off point is at 55% power.

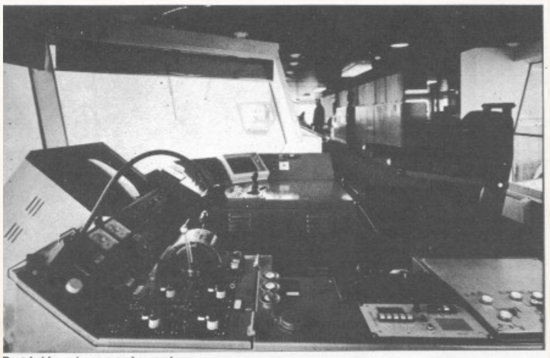


Cycloconverters for AC/AC propulsion for new Finnish icebreakers (page: 26 28)

The article describes a **new-generation Finnish icebreaker**, *Otso*, featuring **cycloconverter-based AC/AC diesel-electric propulsion** supplied by Wärtsilä. The Karhu II class combines twin-screw propulsion, advanced AC motors, a power-turbine bubbling system, and stainless steel in exposed hull areas to improve efficiency, manoeuvrability, and icebreaking performance. Designed for higher power economy and versatility, the vessel represents a technological step forward in Baltic icebreakers, supporting both severe ice operations and assistance to large merchant ships.

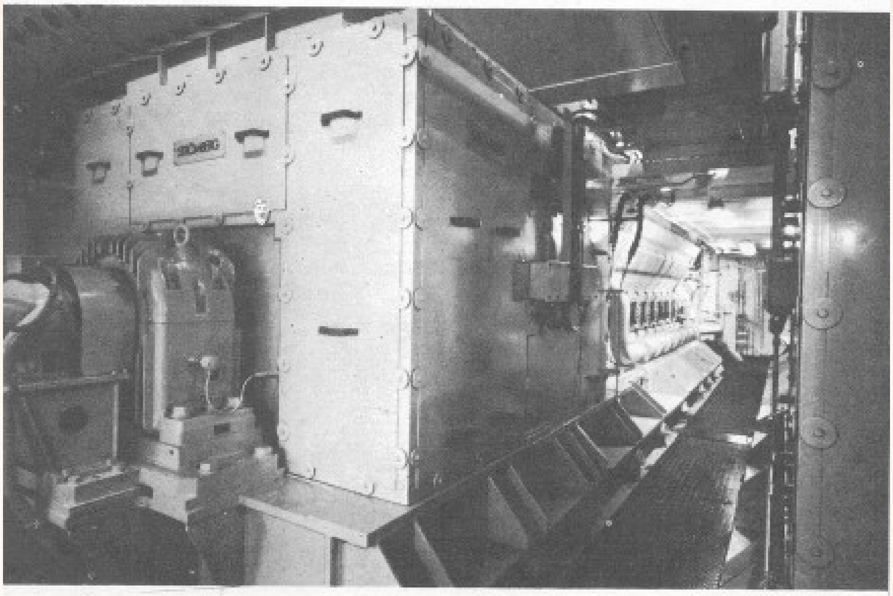
Main switchboard

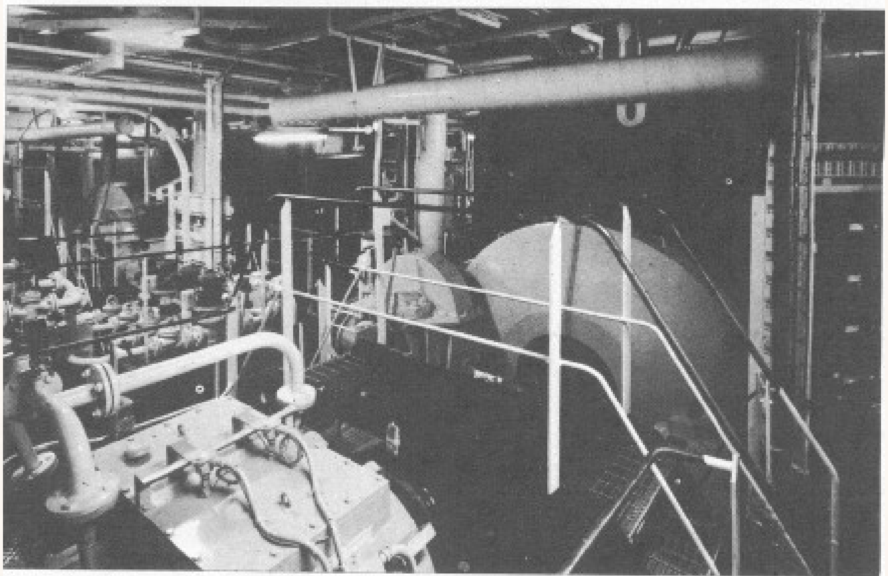




Port bridge wing control console

Stromberg generator





Propeller motor and thrust bearing

We invite observations, discussion threads from readers, taking cues from these sepia-soaked MER pages. – Hon.Ed

THE INSTITUTE OF MARINE ENGINEERS (INDIA)

KOLKATA BRANCH

MTI NO. 307030
31/3, Sahapur Colony, Flat No. A-1/2, New Alipore, Kolkata-700053
Tel. (M) : +91 8697430058/9831636004
E-mail: principalkolkata@imare.in/ enquirymetckol@imare.in

Course Fee & Schedule for DGS Approved Courses at IMEI, Kolkata Branch

Sr. No.	Name of the course	Course Fee	Course Duration	Schedule
1.	Basic Training for Ships using Fuels covered within IGF Code (IGFB)	Rs.10,000 /- (including lunch & one-time Exit Examination fees)	5 days	2nd March- 6th March, 2026
2.	Crisis Management & Human Behaviour	Rs. 8,000 /- (including lunch & one-time Exit Examination fees)	5 days	9th February-13th February, 2026/ 9th March -13th March, 2026
3.	Crowd management, Passenger Safety and Safety Training	Rs. 3,500 /- (including lunch & one-time Exit Examination fees)	3 days	16th February-18th February, 2026 / 16th March -18th March, 2026
4.	Security Training for Seafarer with Designated Security Duties (STSDSD)	Rs. 2,000 /- (including lunch & one-time Exit Examination fees)	2 days	19th February-20th February, 2026/ 19th March -20th March, 2026
5.	Ship Security Officer (SSO)	Rs. 2,500 /- (including lunch & one-time Exit Examination fees)	3 days	23rd February-25th February, 2026 / 23rd March-25th March, 2026

- **Rs. 50/- for DGS Fee for issuance of certificate**
- **If more candidates are available, we can schedule a special batch as and when required.**
- **Special Discount may be available for block booking.**

Note: Dates are subject to change

"Reg. No. MCS/090/2018-20"
RNI No. MAHENG/2006/19917
W.P.P. Licence No.:
MR/Tech/WPP-336/ South/2018-20

IME(I) House, Nerul, Navi Mumbai