ISSN 2250-1967

MARINE ENGINEERS REVIEW INDIA

JOURNAL OF THE INSTITUTE OF MARINE ENGINEERS (INDIA)

Volume : 20 | Issue : 8 | July 2026 | ₹ 90/-

The Great Maritime Reset

Redefining Ships, Fuels and Operations

09 3D Technology for Shipbuilding, Ship Repair and Marine Manufacturing

17 Dry Gas Sealing Systems for Centrifugal Compressors

27 Fundamentals of Fuels and Emissions

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) - Commencing Soon
- Assessment, Examination and Certification of Seafarers ***Course Id – 1062*** (OFFLINE) – (12 Days) - 13th July 2026/ 21st Sep 2026/ 16th Nov 2026
- Advanced Training for Ships using Fuels covered within IGF code ***Course Id – 5312*** (OFFLINE) – (5 Days) - Commencing Soon
- MEO Cl. I (FG) : 2- months course (OFFLINE) - 1st July 2026 / 1st Sep 2026 / 2nd Nov 2026 (followed by Simulator course) **Discount on combined bookings of Class I Course with Simulator**
- MEO (CEO – NCV) – STCW 2010: 2 month course (OFFLINE) – 01st July 2026 / 02nd November 2026
- MEO (SEO – NCV) Part-A - STCW 2010: 2-month course (OFFLINE) – 01st August 2026
- MEO (SEO – NCV) Part-B - STCW 2010: 4-month course (OFFLINE) – 2nd Nov 2026
- MEO Cl. IV (NCV) - STCW 2010 - 4 months course (OFFLINE) – 01st July 2026
- MEO (CEO – NCV) BRIDGING COURSE: 15 Days (OFFLINE) – 03rd Aug 2026 / 01st Oct 2026 / 01st Dec 2026
- MEO (NCV – SEO) BRIDGING COURSE: 1 Month (OFFLINE) – 01st July 2026
- MEO CL. II (FG): 4-month Course (OFFLINE) – 01st July 2026/ 01st Aug 2026/ 01st Sep 2026/ 01st Oct 2026 / 01st Nov 2026/ 01st Dec 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) – 07th July 2026 / 14th July 2026 / 22nd July 2026 / 03rd Aug 2026 / 10th Aug 2026 / 19th Aug 2026
- ENGINE ROOM SIMULATOR MANAGEMENT LEVEL (3 DAYS) COURSE FOR MEO CLASS I (OFFLINE) – 27th June 2026 / 01st July 2026 / 28th Aug 2026 / 01st Sept 2026 / 29th Oct 2026 / 02nd Nov / 29th Dec 2026
- ENGINE ROOM SIMULATOR MANAGEMENT LEVEL (5 DAYS) COURSE FOR MEO CLASS II (OFFLINE) – 25th June 2026 / 01st July / 27th July 2026/ 01st Aug 2026/ 26th Aug 2026/ 01st Sep 2026 / 25th Sep 2026 / 01st Oct 2026/ 27th Oct 2026/ 02nd Nov 2026/ 25th Nov 2026 / 01st Dec 2026/ 26th Dec 2026
- ENGINE ROOM SIMULATOR OPERATIONAL LEVEL (3 DAYS) COURSE (OFFLINE) - 8th July 2026/ 20th July 2026/ 10th Aug 2026/ 20th Aug 2026 / 21st Sep 2026/ 22nd Oct 2026/ 21st Dec 2026
- 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

VIZAG HIMT

YOUR TRUSTED MARITIME TRAINING PARTNER

LEADING THE WAY IN MARITIME EXCELLENCE

TRAIN TODAY
SAIL TOMORROW!

ALL COURSES OFFERED

EMPOWERING CAREERS.
SHAPING FUTURES.

Duration as per DG Shipping guidelines.

- Approved Courses
- Experienced Faculty
- Modern Infrastructure
- Industry Oriented Training
- 100% Compliance with DG Shipping Norms

OUR COURSES

COURSE	DURATION (DAYS)
Basic Safety Training + Security Training for Seafarers with Designated Security Duties - (STCW) (BST + STSDSD)	13
Refresher Training for Proficiency In PST - (RPST)	1
Refresher Training for Proficiency in FPFF - (RFPFF)	1
Refresher Training for Advanced Fire Fighting - (RAFF)	1
Refresher Training for Proficiency In PSCRB - (RPSCRB)	1
Basic Training for Oil And Chemical Tanker Cargo Operations (TFC-COM) - (OCTCO)	6
Engine Room Simulators Operational Level - MEO Class IV - (ERS)	3
MEO Class II Preparatory Course - (PCT)	4 mths
Proficiency In Survival Craft & Rescue Boats - (PSCRB)	5

COURSE	DURATION (DAYS)
Advanced Fire Fighting - (AFF)	5
Medical First Aid - (MFA)	4
Engine Room Simulators - Management Level - MEO Class II - (ERSM)	5
Diesel Engine Combustion Gas Simulator-MEO CLASS-I - (DECGS)	3
Refresher and Updating Training Course for all Engineers - (REO)	4
Refresher Training for Medical Care - (RMC)	1
Refresher Training for Medical First Aid - (RMFA)	1
Passenger Ship Familiarization - (PSF)	3
Basic Liquified Gas Tanker Cargo Operations - (LGTF)	5

GOOD NEWS

MEO CLASS II
MMD EXAMS
Now at Vizag

Upgrade to Management Level with D.G. SHIPPING APPROVED

MEO CLASS II

Limited Period Discount Available

MEO Class II (PCT) + ERSM

Actual Amount : ~~44,800/-~~

Discounted Package Amount: 42,900/-

Vizag HIMT

Phone: 98404 00000 | Email: help@himtmarine.com

Online Booking at www.himt.co.in

Book your Course through our App

Available on the App Store

GET IT ON Google Play

HIMT Booking

SCAN TO LEAN MORE

INMARCO 2026
INTERNATIONAL MARITIME
CONFERENCE & EXHIBITION
REGISTER
NOW
27–29
OCTOBER 2026
MUMBAI
Maritime Technology Leadership
Worldwide Industry Engagement
Maritime Legacy Since 1982
SECURE YOUR SPOT
2026.inmarco.in
Scan To Register

Editorial

"The pessimist complains about the wind; the optimist expects it to change; the realist adjusts the sails." — William Arthur Ward

Navigating a World of Contradictions

The maritime industry today stands at the crossroads of rapid technological progress and growing geopolitical uncertainty. While governments, industries, and international organisations pursue ambitious decarbonisation goals, conflicts and shifting alliances continue to disrupt trade, supply chains, and energy markets, reminding us that sustainability must coexist with security, resilience, and practical decision-making.

The wars in Ukraine-Russia and West Asia also raise an important environmental question. While shipping, ports, and industries report emissions, the greenhouse gases and ecological damage caused by military operations, infrastructure destruction, fires, and reconstruction remain largely unmeasured. Establishing an international framework to quantify, report, and review war-related environmental impacts would strengthen transparency, accountability, and global climate governance.

Amid these challenges, India has strengthened maritime resilience through the Bharat Maritime Insurance Fund, enhancing domestic insurance capacity against war-related risks. Simultaneously, expanding cooperation between the Directorate General of Shipping and South Korean shipbuilding organisations promotes technology transfer, workforce development, innovation, and industrial modernisation supporting Maritime Amrit Kaal Vision 2047.

India's energy security has received a boost through offshore gas discoveries in the Andaman region and renewed hydrocarbon exploration in West Bengal, reinforcing the value of indigenous resources for long-term economic growth and strategic resilience.

Meanwhile the adoption of the MASS Code at MSC 111 marks a historic milestone in regulating autonomous shipping. Together with advances in artificial intelligence, digital twins, additive manufacturing, alternative fuels, and evolving environmental regulations, it signals a transformative era for global maritime operations and governance.

The articles in this issue explore these developments through practical case studies, engineering innovations, operational experience, and regulatory perspectives. They encourage readers to question assumptions, embrace continuous learning, and prepare for an industry where resilience, collaboration, and informed leadership will determine long-term success. As maritime professionals, we must continue adapting with purpose, curiosity, integrity, and confidence, ensuring every challenge becomes an opportunity to innovate, collaborate, and lead the global maritime community toward a safer, cleaner, and more resilient future for generations to come with shared responsibility.

The July 2026 issue presents a diverse collection of articles highlighting technological innovation, operational excellence, and the maritime industry's transition towards a sustainable future.

Dr. Shibbu John explores how 3D printing and visualisation technologies are transforming maritime manufacturing through on-demand spare parts, predictive maintenance, digital inventories, and sustainable shipbuilding, improving efficiency while reducing costs, waste, and emissions.

Mr. Venkat examines tandem dry gas sealing systems for centrifugal compressors, focusing on API 692 best practices, gas conditioning, performance monitoring, and maintenance strategies that enhance reliability, safety, and environmental compliance.

Mr. Vikrant Rai explains the science behind greenhouse gases, carbon cycles, hydrogen pathways, Global Warming Potential, and lifecycle emissions, providing the scientific foundation for maritime decarbonisation and the transition to net-zero shipping.

Dr. Shantanu Paul reviews ammonia's regulatory readiness as a marine fuel, discussing evolving IGC and IGF Code requirements, safety frameworks, crew competency, and the importance of regulatory clarity in driving future adoption.

Capt. Gajanan Karanjikar analyses the causes of marine engine overheating, highlighting the importance of thermal-history analysis, root-cause investigation, and proactive cooling-water management to prevent machinery failures.

The NIOT team, in Part D of its Digital Twin series, introduces **"Chaitanya,"** an AI-powered Cognitive Digital Twin for Matsya 6000 that delivers real-time decision support, predicts emergencies, and optimizes battery and oxygen management during deep-ocean missions.

We hope this issue informs, inspires, and stimulates thoughtful discussion as the maritime industry navigates an era of rapid technological change and sustainable transformation. Happy reading!

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

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)	₹7,250/-	6 Days	16th July, 2026, 6th August, 2026
2	Basic Training for Liquefied Gas Tanker Cargo Operations (LGTF)	₹7,525/-	5 Days	09th July, 2026, 13th August, 2026
3	Basic Training for Ships using Fuels covered within IGF Code (IGFB)	₹13,250/-	5 Days	16th July, 2026, 19th August, 2026
4	Security Training for Seafarers with Designated Security Duties (STSDSD)	₹4,050/-	2 Days	01st July, 2026, 3rd August, 2026
5	Ship Security Officer (SSO)	₹5,525/-	3 Days	27th July, 2026 27th August, 2026

- **Course Fee includes** lunch, two tea breaks, and one examination fee**.**
- 5% discount **on group bookings of more than 6 candidates.**
- 10% discount **on group bookings for** combo courses **(OCTF + LGTF) with more than 6 candidates.**
- *Note:* ***Course dates are subject to change.***

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/

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

Cover Credits: **Kryon**

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

RANKED A1 (OUTSTANDING)

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

Sl. 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	6th July -10th July, 2026/ 3rd August- 7th August, 2026
2.	Crowd management, Passenger Safety and Safety Training	Rs. 3,500 /- (including lunch & one-time Exit Examination fees)	3 days	13th July - 15th July, 2026/ 10th August- 12th August, 2026
3.	Crisis Management & Human Behaviour	Rs. 8,000 /- (including lunch & one-time Exit Examination fees)	5 days	20th July -24th July, 2026/ 17th August- 21st August, 2026
4.	Security Training for Seafarer with Designated Security Duties (STSDSD)	Rs. 2,000 /- (including lunch & one-time Exit Examination fees)	2 days	27th July -28th July, 2026/ 24th August - 25th August, 2026
5.	Ship Security Officer (SSO)	Rs. 2,500 /- (including lunch & one-time Exit Examination fees)	3 days	29th July -31st July, 2026/ 26th August - 28th August, 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

3D Technology for Shipbuilding, Ship Repair and Marine Manufacturing

Shibu John

ABSTRACT

The maritime sector, covering shipbuilding, ship repair, offshore engineering, boat construction and marine asset management, is experiencing a significant technological evolution driven by digital transformation, sustainability requirements, supply-chain resilience and the need for enhanced operational efficiency. Conventional manufacturing and maintenance practices remain heavily dependent on extensive physical inventories, lengthy procurement cycles, labor-intensive documentation processes and subtractive manufacturing techniques that often result in material wastage, higher operating costs and increased environmental impact. As the industry seeks innovative solutions to improve competitiveness while complying with increasingly stringent environmental regulations, advanced digital technologies are emerging as critical enablers of change.

This paper explores the transformative impact of 3D Printing (Additive Manufacturing) and 3D Visualisation technologies on modern maritime operations. It examines the integration of 3D Scanning, Computer-Aided Design (CAD), Simulation, Digital Twin technology and Artificial Intelligence (AI) in creating a digitally connected maritime manufacturing ecosystem. The study highlights practical applications in ship repair and component reclamation, reverse engineering of obsolete parts, production of polymer and metal marine-grade components, large-scale boat manufacturing and digital inventory management.

Additive Manufacturing enables rapid, on-demand production of spare parts, reducing lead times, inventory expenses and vessel downtime while offering greater design flexibility and material efficiency. At the same time, 3D Visualisation technologies provide accurate digital representations of vessels and equipment, supporting predictive maintenance, lifecycle asset management, condition monitoring and virtual inventory systems. Together, these technologies facilitate a transition from conventional inventory-driven operations to a data-centric manufacturing model that improves operational resilience and resource utilisation.

Furthermore, the adoption of these technologies contributes significantly to maritime decarbonisation through reduced material consumption, lower transportation requirements, minimised waste generation and support for circular economy principles. By aligning with Industry 4.0 initiatives and emerging sustainability frameworks, 3D Printing and 3D Visualisation are redefining how maritime assets are designed, produced, maintained and managed throughout their operational lifecycle.

This paper presents a strategic roadmap for implementing these technologies across shipyards, naval organisations, offshore operators and marine original equipment manufacturers (OEMs), demonstrating their ability to deliver substantial economic, operational, environmental and competitive advantages within the future maritime ecosystem.

Keywords : 3D Printing; Additive Manufacturing; 3D Visualisation; Shipbuilding; Ship Repair; Marine Manufacturing; 3D Scanning; Digital Twin; Artificial Intelligence; Reverse Engineering; On-Demand

Rebuild, Reuse, Reclaim: The Future of Ship Repair

Manufacturing; Digital Inventory; Wire Arc Additive Manufacturing (WAAM); Direct Energy Deposition (DED); Predictive Maintenance; Industry 4.0; Sustainable Shipping; Circular Economy; Maritime Decarbonisation; Lifecycle Asset Management.

1. INTRODUCTION

Shipbuilding and marine engineering rank among the most capital-intensive and resource-demanding industries worldwide. Whether constructing large commercial vessels, naval ships, fishing vessels, leisure craft, or offshore structures, the sector faces a wide range of operational and economic challenges. These include extended manufacturing and repair lead times, dependence on global supply chains, scarcity of obsolete spare parts, excessive inventory holding, material wastage, environmental concerns and growing regulatory demands for sustainability and emissions reduction.

Traditionally, maritime manufacturing and maintenance have relied on centralised production systems and extensive physical inventories to ensure the availability of critical spare parts. While effective in supporting operational continuity, these practices often result in substantial capital blockage, warehousing expenses and inefficiencies arising from unused or obsolete inventory. Furthermore, conventional manufacturing methods typically involve material removal processes that generate significant waste and consume considerable energy.

The emergence of advanced 3D Technologies, particularly 3D Printing and 3D Visualisation, represents a paradigm shift in how maritime assets are designed, manufactured, repaired and maintained. Rather than producing and storing large quantities of components in advance, maritime stakeholders can now digitise assets, maintain virtual inventories and manufacture parts only when required, either at the point of use or close to operational locations.

This approach not only enhances responsiveness and flexibility but also strengthens supply-chain resilience, reduces inventory costs and supports sustainability objectives. Through the integration of additive manufacturing, digital visualisation, simulation technologies and artificial intelligence, a new digital maritime manufacturing ecosystem is emerging.

3D GRAPHY envisions this transformation as a fully connected Digital Maritime Manufacturing Ecosystem, where digital design, virtual asset management, on-demand production and intelligent analytics combine to optimise the entire lifecycle of maritime assets.

2. OVERVIEW OF 3D TECHNOLOGY IN THE MARITIME SECTOR

2.1 3D Printing (Additive Manufacturing)

3D Printing, commonly referred to as Additive Manufacturing (AM), is a production process that creates components layer by layer directly from digital models. Unlike conventional subtractive manufacturing techniques that remove material from a larger workpiece, additive manufacturing uses only the material necessary to build the component. This significantly reduces waste, enables complex geometries and supports decentralised production capabilities.

The maritime sector is increasingly adopting a range of additive manufacturing technologies to meet diverse operational requirements. Key technologies include:

Polymer-Based Technologies

- Fused Deposition Modelling (FDM)
- Stereolithography (SLA)
- Selective Laser Sintering (SLS)
- Digital Light Processing (DLP)

Metal-Based Technologies

- Direct Energy Deposition (DED)
- Wire Arc Additive Manufacturing (WAAM)
- Powder Bed Fusion (PBF)

Large-Format Additive Manufacturing

- Boat hull fabrication
- Structural marine components
- Large moulds and tooling systems

These technologies enable shipyards and marine operators to manufacture complex components with reduced lead times, lower tooling requirements and improved production flexibility.

2.2 3D Visualisation Technologies

While additive manufacturing provides the capability to fabricate physical components, 3D Visualisation technologies form the digital foundation that supports the entire process. They enable accurate capture, analysis, simulation and management of maritime assets throughout their lifecycle.

Major 3D Visualisation technologies include:

- 3D Scanning for reverse engineering and as-built documentation
- 3D CAD modelling for design creation and optimisation
- Simulation tools for structural validation and performance analysis
- Digital Twin technology for real-time asset monitoring and lifecycle management
- AI-powered analytics for predictive maintenance and operational optimisation

Together, these technologies create a digital-first framework that improves decision-making, enhances maintenance planning and supports efficient shipbuilding and repair operations. By combining virtual asset representation with advanced manufacturing capabilities, maritime organisations can achieve higher levels of efficiency, reliability and sustainability.

3. 3D PRINTING FOR SHIP REPAIR AND RECLAMATION

3.1 Challenges in Conventional Ship Repair

Ship repair operations are often constrained by the urgent requirement for replacement components and spare parts. Many vessels continue to operate for decades, resulting in frequent demand for parts that are either obsolete, discontinued, or no longer supported by original equipment manufacturers (OEMs). In many cases, these components must be sourced internationally, leading to extended lead times, high transportation expenses and increased vessel downtime.

Shipyards and repair facilities are therefore faced with significant challenges, including:

- Unavailability of legacy or discontinued components
- Dependence on foreign suppliers and complex supply chains
- High procurement and logistics costs
- Critical time constraints during repair periods
- Increased downtime affecting operational efficiency and profitability

Traditional repair methods often involve machining replacement parts from solid metal stock. While effective, these methods typically generate considerable material waste, require specialised tooling and extend repair schedules.

3.2 Additive Manufacturing for Repair Parts

Additive Manufacturing offers a transformative solution to these challenges by enabling rapid, localised and on-demand production of replacement components. Through advanced 3D scanning technologies, damaged or obsolete parts can be digitally captured and reverse engineered to create accurate replacement models.

Key applications include:

- Reverse engineering of worn or obsolete components
- On-demand production of spare parts within shipyards

“ ***Less Waste, Lower Emissions, Greater Operational Efficiency*** ”

- Fabrication of replacement parts near operational locations
- Repair and restoration of damaged assemblies
- Manufacture of customised components with improved performance

Common maritime repair applications include:

- Pumps and pump casings
- Valves and valve components
- Impellers and rotating equipment
- Ducting systems
- Brackets and structural supports
- Housings and protective enclosures
- Cable trays and routing systems
- Clamps, connectors, seals and gaskets

Advanced metal additive manufacturing technologies such as Direct Energy Deposition (DED) and Wire Arc Additive Manufacturing (WAAM) provide additional opportunities for component reclamation. Instead of replacing entire assemblies, worn surfaces can be rebuilt and restored through material deposition techniques, extending component life while significantly reducing maintenance costs and material consumption.

This approach improves repair turnaround times, enhances asset availability and strengthens supply-chain resilience for maritime operators.

4. POLYMER-BASED PARTS IN SHIPBUILDING AND MARINE APPLICATIONS

4.1 Advantages of Polymer 3D Printing

Polymer-based additive manufacturing has emerged as one of the most accessible and versatile applications of 3D printing within the maritime industry. Modern marine-grade polymers provide excellent resistance to harsh operating environments and can be engineered to withstand a variety of mechanical and environmental stresses.

These materials offer resistance to:

- Corrosion and saltwater exposure
- Chemical attack from fuels and lubricants
- Ultraviolet radiation
- Moisture absorption
- Temperature fluctuations

Polymer additive manufacturing also provides several operational advantages, including:

- Lightweight components that reduce vessel weight
- Enhanced design flexibility and geometric freedom
- Integrated channels and complex internal structures
- Rapid design modifications and customisation
- Elimination of expensive tooling requirements

These benefits make polymer-based manufacturing particularly suitable for both prototype development and end-use maritime applications.

4.2 Applications in Shipbuilding

Shipyards are increasingly incorporating polymer-based additive manufacturing into daily operations. Components can be produced quickly and cost-effectively while meeting specific functional requirements.

Typical applications include:

- Ventilation ducts and airflow management systems
- Protective covers and equipment housings
- Electrical enclosures and cable protection units
- Interior fittings and furniture components
- Instrument and sensor mounting systems
- Protective casings for electronic equipment
- Manufacturing jigs and assembly fixtures
- Custom maintenance tools and support devices

Virtual Inventories, Real Savings, Immediate Availability

"Transform Physical Inventories into Digital Asset Libraries"

For shipbuilders, polymer 3D printing enhances productivity by reducing fabrication time, simplifying installation procedures and improving maintenance accessibility. The technology also enables rapid prototyping, allowing design teams to evaluate and optimise components before final production.

- Improved production efficiency
- Lightweight yet structurally efficient designs

These capabilities are particularly valuable for patrol vessels, leisure craft, workboats, autonomous marine systems and small commercial vessels where rapid production and customisation are essential.

5. BOAT MANUFACTURING AND LARGE-SCALE 3D PRINTING

5.1 3D Printed Boats: A New Manufacturing Paradigm

Large-scale additive manufacturing is revolutionising boat construction by enabling direct fabrication of sizeable marine structures. Unlike traditional boatbuilding methods that depend heavily on moulds, plugs and specialised tooling, large-format 3D printing allows components to be manufactured directly from digital designs.

Applications include:

- Boat hull sections
- Deck structures
- Internal support frameworks
- Composite moulds and plugs
- Customised marine structures

The reduction in tooling requirements significantly decreases development costs while accelerating production schedules. Designers also gain greater freedom to optimise hull forms and structural geometries without being constrained by traditional manufacturing limitations.

5.2 Benefits for Boat Builders

The adoption of large-scale additive manufacturing offers several advantages to boat manufacturers:

- Faster development and prototyping cycles
- Reduced tooling investment
- Greater design flexibility
- Customisation for specialised applications
- Lower material wastage

6. DIGITAL INVENTORY MANAGEMENT THROUGH 3D VISUALISATION

6.1 Challenges of Physical Inventory Management

The maritime industry traditionally relies on maintaining extensive inventories of spare parts to ensure operational continuity. While this approach provides security, it also introduces significant inefficiencies.

Common challenges include:

- Large amounts of capital tied up in inventory
- Obsolescence of stored components
- High warehousing and storage expenses
- Logistics and transportation complexities
- Accumulation of unused material and scrap

For fleet operators managing multiple vessels, these challenges can represent a substantial financial burden.

6.2 The Digital Inventory Concept

The integration of 3D Visualisation and Additive Manufacturing introduces a fundamentally different approach to spare-parts management. Instead of storing physical components, organisations can maintain certified digital inventories consisting of validated 3D models.

Under this model:

- Physical inventories are replaced by digital libraries
- Components are stored as secure digital files

- Parts can be produced on demand when required
- Manufacturing can occur near the point of use
- Inventory costs and storage requirements are significantly reduced

Digital inventory systems improve flexibility, reduce waste and ensure faster access to critical components throughout a vessel's operational lifecycle.

7. ENVIRONMENTAL AND SUSTAINABILITY IMPACT

7.1 Reduction in Material Waste

One of the most significant advantages of additive manufacturing is its efficient use of materials. Unlike conventional machining processes, which remove material to create components, additive manufacturing uses only the material necessary for production.

This results in reductions in:

- Metal scrap generation
- Polymer waste
- Material losses during fabrication
- Energy-intensive machining operations

The outcome is a more resource-efficient manufacturing process with lower environmental impact.

7.2 Lower Carbon Footprint

3D Printing contributes to maritime decarbonisation efforts through several mechanisms:

- Reduced transportation of spare parts
- Localised manufacturing near shipyards and ports
- Lower logistics-related emissions
- Reduced material consumption
- Lighter vessel components that improve fuel efficiency

Collectively, these benefits support global initiatives aimed at reducing greenhouse-gas emissions within the maritime sector.

7.3 Supporting the Circular Economy

Additive Manufacturing aligns closely with circular economy principles by prioritising repair, refurbishment and reuse over replacement.

Key contributions include:

- Extending equipment service life
- Reclaiming damaged components
- Supporting remanufacturing strategies
- Recycling polymers and metals
- Minimising waste generation

These practices support the sustainability objectives of the International Maritime Organization (IMO) and broader Environmental, Social and Governance (ESG) frameworks.

8. OVERALL BENEFITS OF 3D PRINTING AND 3D VISUALISATION IN MARITIME

Operational Benefits

- Reduced vessel downtime
- Faster repair and maintenance cycles
- Enhanced supply-chain resilience
- Improved operational flexibility

Economic Benefits

- Lower inventory holding costs
- Reduced capital blockage
- Improved asset utilisation
- Lower lifecycle operating expenses

Technical Benefits

- Greater design freedom
- Enhanced engineering innovation
- Improved simulation-based optimisation
- Cost-effective customisation

Digital Twins Enable Smarter Maritime Asset Management

> **3D Technologies Drive Sustainable Maritime Innovation**

of modern maritime operations. Their ability to support digital inventory systems, on-demand manufacturing, predictive maintenance, component reclamation and lifecycle optimisation is fundamentally changing how ships and marine assets are designed, constructed, repaired and maintained.

By reducing dependence on extensive physical inventories, minimising material waste, lowering carbon emissions and improving operational efficiency, these technologies provide a practical pathway toward a more sustainable and resilient maritime industry.

As digital transformation continues to reshape global shipping and marine manufacturing, organisations that embrace 3D Technology will gain significant advantages in competitiveness, cost efficiency, innovation and environmental performance. Through its ecosystem-driven approach and technological expertise, 3D GRAPHY remains committed to advancing this transformation and helping shape the future of digital maritime manufacturing.

Environmental Benefits

- Reduced waste generation
- Lower greenhouse-gas emissions
- Sustainable manufacturing practices
- Improved compliance with environmental regulations

9. ROLE OF 3D GRAPHY

As a leading 3D Technology Consortium, 3D GRAPHY plays a vital role in supporting digital transformation within the maritime sector.

The organisation assists maritime stakeholders through:

- Technology consulting and implementation strategies
- Capability development and workforce training
- Industry–academia partnerships
- Pilot projects and proof-of-concept initiatives
- Conferences, workshops and knowledge-sharing platforms

Through initiatives such as 3D GEM, 3D GRAPHY brings together shipyards, marine engineers, researchers, technology providers and industrial stakeholders to accelerate the adoption of advanced manufacturing and visualisation technologies.

10. CONCLUSION

3D Printing and 3D Visualisation technologies have evolved from emerging innovations into strategic enablers

About the Author

Dr. Shibu John, Founder & CEO – 3D GRAPHY, A 3D Technology Consortium | India Founder Organiser, 3D GEM.

References

- Lloyd's Register. (2020). *Guidance Notes for Additive Manufacturing Framework*. London: Lloyd's Register.
- Bureau Veritas. (2021). *Guidelines for Additive Manufacturing and 3D Printed Components in Marine Applications*. Paris: Bureau Veritas.
- ISO/ASTM 52900:2021. *Additive Manufacturing—General Principles—Fundamentals and Vocabulary*. Geneva: International Organization for Standardization.
- ISO/ASTM 52910:2018. *Additive Manufacturing—Design Requirements, Guidelines and Recommendations*. Geneva: ISO.
- Gibson, I., Rosen, D. W., & Stucker, B. (2021). *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping and Direct Digital Manufacturing* (3rd ed.). New York: Springer.
- Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T. Q., & Hui, D. (2018). "Additive Manufacturing (3D Printing): A Review of Materials, Methods, Applications and Challenges." *Composites Part B: Engineering*, 143, 172–196.
- Frazier, W. E. (2014). "Metal Additive Manufacturing: A Review." *Journal of Materials Engineering and Performance*, 23(6), 1917–1928.
- DebRoy, T., Wei, H. L., Zuback, J. S., et al. (2018). "Additive Manufacturing of Metallic Components – Process, Structure and Properties." *Progress in Materials Science*, 92, 112–224.
- Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). "Digital Twin: Enabling Technologies, Challenges and Open Research." *IEEE Access*, 8, 108952–108971.
- Singh, S., Ramakrishna, S., & Gupta, M. (2017). "Towards Zero Waste Manufacturing through Additive Manufacturing." *Procedia CIRP*, 61, 353–358.

INNMARCO 2026

Global Leaders to Converge in Mumbai to Shape the Future of Sustainable Shipping

MUMBAI, INDIA – The Institute of Marine Engineers (India) – Mumbai Branch, alongside its Navi Mumbai and Gujarat chapters, has announced the return of its flagship event, **INMARCO 2026**. Taking place from **27–29 October 2026** at **The Westin, Powai, Mumbai**, this premier quadrennial international maritime conference and exhibition has served as a cornerstone of maritime dialogue and technological advancement for over four decades.

Organised in association with the **Ministry of Ports, Shipping and Waterways, Government of India**, and the **Directorate General of Shipping**, with the **Indian Register of Shipping (IRS)** as the Platinum Sponsor, INMARCO 2026 serves as a powerful global platform. It unites national and international maritime stakeholders, policymakers, and industry pioneers to drive conversations that shape future policy frameworks and future-ready strategies.

Event at a Glance

- **Event Name:** INMARCO 2026 – International Maritime Conference & Exhibition
- **Dates:** 27–29 October 2026
- **Venue:** The Westin, Powai, Mumbai, Maharashtra, India
- **Frequency:** Quadrennial (Every four years)
- **Organiser:** The Institute of Marine Engineers (India) – Mumbai Branch
- **Key Partners:** Ministry of Ports, Shipping and Waterways (Govt. of India) & Directorate General of Shipping
- **Platinum Sponsor:** Indian Register of Shipping (IRClass)

Media Contact & Registration

For press credentials, interview requests with keynote speakers or exhibition details, please contact:

- **Contact Name/Position:** Suraj Negi
- **Email Address: inmarco@imare.in**
- **Phone Number:** +919967481448
- **Event Website: https://2026.inmarco.in/**

Core Theme: "Maritime Landscape 2030, Opportunities and Challenges"

As the maritime sector undergoes one of its most significant historical transitions, sustainability has shifted from a corporate objective to a critical global responsibility. INMARCO 2026 will spotlight the breakthrough innovations, regulatory policies, and cross-border collaborative efforts driving the industry's journey toward aggressive decarbonization and net-zero shipping.

The next decade of maritime growth will be defined by rapid technological transformation. INMARCO 2026 is set to showcase emerging technologies and smart solutions—including digitalization, Artificial Intelligence (AI), automation, and next-generation vessel operations—that are actively reshaping efficiency and safety in the global maritime ecosystem.

About the Organiser

The Institute of Marine Engineers (India) is a premier professional body dedicated to the promotion and advancement of marine engineering science and technology. Through its extensive network of branches and chapters, the Institute facilitates continuous professional development, industry collaboration and policy advocacy to support a resilient global maritime sector.

Dry Gas Sealing Systems for Centrifugal Compressors

Venkat Krishna Soundarraja

Tandem Dry Gas Seals – Design & Maintenance Insights

Abstract:

Tandem Dry Gas Seals (DGS) have become the industry standard for centrifugal compressors due to their superior reliability and reduced maintenance compared to conventional lubricated seals.

These seals are primarily used in high-pressure, safety-critical rotating equipment such as centrifugal compressors and pumps on offshore platforms, LNG facilities, FPSOs and subsea oil & gas installations. Their role is to prevent hazardous gas leakage, ensure equipment reliability and meet stringent environmental and safety standards.

This paper outlines critical design and operational considerations to enhance seal performance and longevity. Key topics include:

- Seal Gas Supply & Conditioning: Emphasises the importance of clean, dry gas to prevent contamination and ensure seal integrity.
- Primary & Secondary Seal Monitoring: Discusses venting strategies and health diagnostics for both seal stages.
- Separation Gas Control: Details the role of inert gases (typically nitrogen) in isolating the seal from bearing housing contaminants.
- Failure Modes & Mitigation: Identifies common degradation factors such as oil migration, hydrate formation and poor filtration.
- Recommended Control Logic: Covers alarm, shutdown and permissive conditions to safeguard seal operation.

The paper advocates for adopting best practices aligned with API 692 to improve compressor reliability and reduce lifecycle costs.

Introduction:

In the realm of high-performance turbomachinery, ensuring reliable containment of process gases is paramount.

Tandem dry gas seals, as standardised by API 692, represent a critical evolution in compressor sealing technology—offering non-contacting operation, modular support systems and enhanced monitoring capabilities.

API 692 is an American Petroleum Institute (API) standard that provides guidelines for dry gas seal support systems used in compressors and expanders, particularly in the petroleum, chemical and gas industries. It focuses on ensuring the reliability and safety of these systems by outlining requirements for design, application, testing, installation and maintenance.

This article explores the design principles, functional streams, pressure dynamics and troubleshooting strategies associated with tandem dry gas seals, providing engineers and operators with a comprehensive guide to optimising seal performance and minimising downtime.

What is a dry gas seal system?

API 692 introduces definition and terminology governing dry gas seal systems.

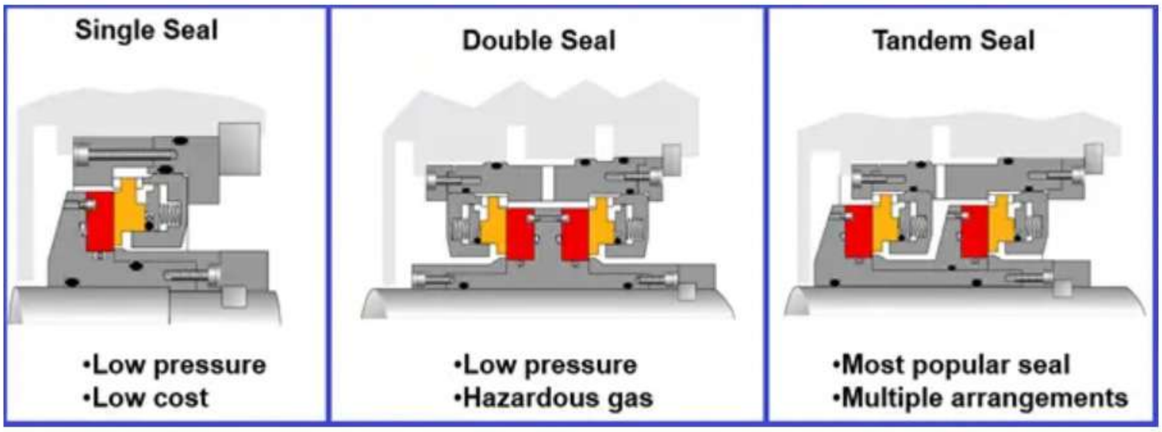


Figure.1. Types of dry gas seals

The process gas high pressure centrifugal compressors used in oil & gas industries requires highly safe and reliable operating requirement.

Main use case: Compressors handling natural gas, flare gas, or process gases.

Location: Gas export compressors, booster compressors and reinjection compressors on offshore rigs and FPSOs.

They are also found in Cryogenic pumps**,** used in LNG liquefaction and regasification plants.

The dry gas seals are used to prevent the gas leakages from the compressors and plays roles as critical component. Hence the proper design and monitoring of dry gas seals are most important.

At their core, dry gas seal systems do two main jobs:

- providing a clean and conditioned environment for the dry gas seals.
- monitoring the health of the dry gas seal.

Types of dry gas seals are as follows: (Refer to **Figure.1**)

- Single
- Tandem with intermediate labyrinth seal
- Tandem without intermediate labyrinth seal
- Double

To accomplish these goals the dry gas seal system is usually broken down in five separate independent streams for tandem seals and four streams for double seals.

These streams share some definitions and historically have been referred to by many different names.

Below are the API 692 names for the streams and a brief description, with reference to **Figure.2**.

1. **Seal Gas** (Sometimes referred to Buffer Gas):

- Seal gas flows across the primary seal (inboard stage) of the dry gas seal out towards the primary vent and across the inboard process labyrinth, back into the process (compressor suction).
- Seal gas prevents dirty, unfiltered process gas from entering the dry gas seal. This gas must be cleaned and conditioned so as to be completely dry and free of particulate contamination.

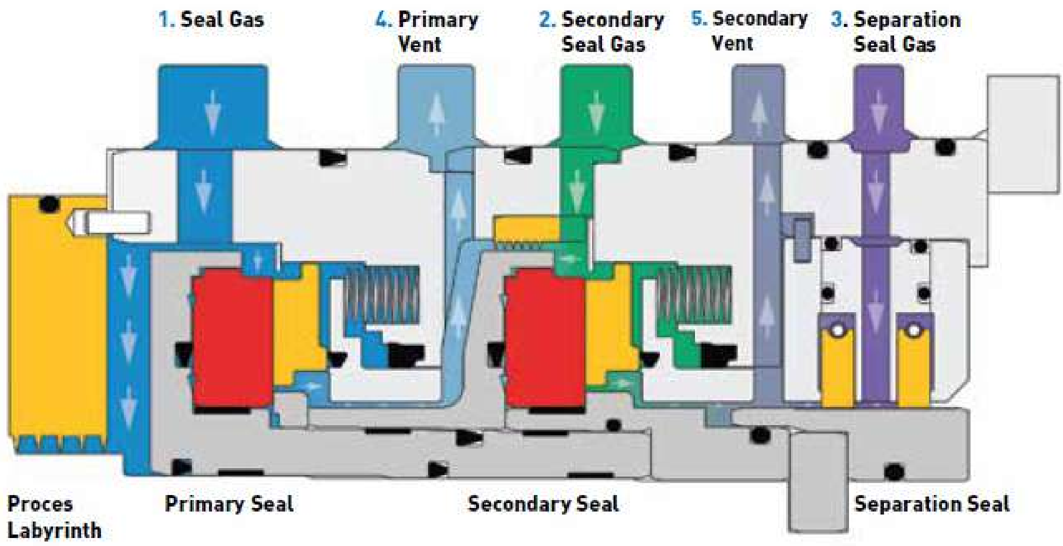


Figure.2. Tandem type dry gas seal

- The conditioning is usually accomplished via the addition of filters and a gas conditioning unit, such as separators, boosters and heaters.

2. **Secondary Seal Gas** (Only applies to tandem seals): (Sometimes referred to as Buffer Gas, Intermediate Injection or Intermediate Gas)

- This gas flows across the secondary seal (outboard stage) of a tandem dry gas seal and out the secondary vent, as well as across the intermediate labyrinth and out the primary vent.
- It is usually nitrogen and must also be cleaned and filtered to ensure the gas is dry and free from particulate matter. Not every seal will feature an intermediate labyrinth or secondary seal gas, but API 692 specifies them as standard.
- Secondary seal gas offers numerous benefits including vastly improving the ability to monitor the health of the secondary seal and improving the robustness of the secondary seal.
- This is realised by allowing back pressure to be generated quickly to achieve start permissive. The additional volume flow in the primary vent prevents spurious alarms and trips during transient operation conditions in the field, this is especially relevant for lower pressure applications where leakage rates for the inboard stage are low.
- Refer **Figure.3.** for flowchart of starting conditions for a gas compressor.

> *Precision That Prevents Disaster*

Operational Highlights:

- **Back Pressure Threshold** ensures that the secondary seal isn't dry or vulnerable when the machine starts.
- **Primary Vent Flow** acts like a stabilizer: more flow, better differentiation between actual leakage vs normal transient blips.
- **Interlocks** are logic gates or conditions that ensure safety before proceeding with compressor activation.
- This flow is especially critical in low-pressure systems where signal strength from leakage is weaker and prone to misinterpretation.

3. **Separation Seal Gas** (Sometimes referred to as Buffer Gas or Tertiary Gas):

- This gas is injected between the two separation seal elements.
- If a labyrinth is injected between the two separation labyrinth halves,
- if a carbon ring type seal (T93FR or the T83), then between a pair of carbon rings.
- Separation seal gas prevents bearing oil ingress into the sealing area. Typically, separation seal gas is nitrogen or another inert gas, but air may also be used.
- If using air, particular care must be taken to avoid creating explosive mixtures in the secondary vent.
- These can be pressure or flow controlled depending on customer preference. For clearance type seals, typically flow control is preferred due to the reduced nitrogen consumption rates.
- Flows are calculated to ensure a minimum velocity figure is achieved in all conditions to prevent oil ingress.

4. **Primary Vent**:

- The primary vent serves as a gas exit for leakage from the primary seal and sometimes secondary seal gas.

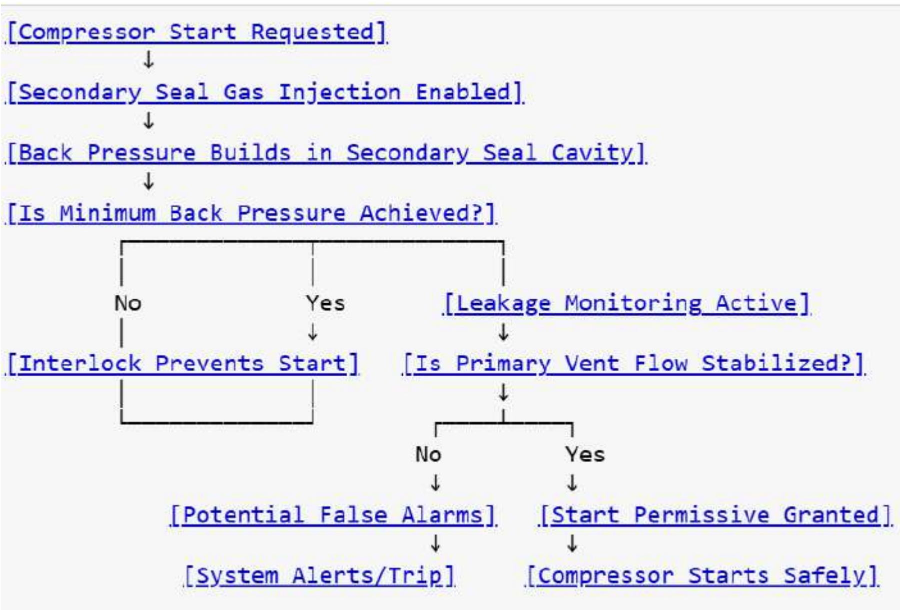


Figure.3. Conditional Flowchart: Secondary Seal Gas Impact

- It is the main monitoring point for seal health, typically equipped with flowmeters and pressure transmitters.
- Leakage levels are key indicators, with alarms often set to thresholds like 10× guaranteed leakage.
- To stabilise readings, API 692 recommends backpressure control devices (regulator or orifice) within the vent:
  - o 'They generate controlled backpressure, improving secondary seal monitoring.
  - o 'This dampens pressure noise and enhances trend clarity.

In vent studies, proper instrumentation and backpressure tuning are critical, as they influence the pressure cascade and dry gas seal system accuracy.

5. Secondary Vent:

- The secondary vent carries leakage from the outboard (secondary) seal and the inboard side of the separation seal.
- It must remain unrestricted—backpressure risks reverse pressurisation of the secondary seal due to low differential pressures.
- Pressure should be maintained near atmospheric, with very low flowrates.
- API 692 allows optional pressure and flow monitoring, though John Crane advises against it, citing minimal utility.
- Element analysers are optionally permitted for select applications but are not typical for most installations.

How Backpressure Devices in primary vent aid Secondary Seal Monitoring:

a. Creates a Defined Pressure Gradient

- By adding backpressure in the **primary vent**, the system raises the **pressure in the intermediate chamber** between the primary and secondary seals.
- This elevates the downstream pressure slightly above atmospheric, ensuring the **secondary seal is not exposed to vacuum** conditions or unstable pressure zones.
- A stable gradient allows accurate readings of **secondary seal gas flow or leakage**, improving detectability of anomalies.

b. Damps Transients and Sensor "Noise"

- Flowmeters and pressure transmitters in the primary vent can show erratic readings during startup or pressure dips.
- Backpressure acts as a hydraulic cushion, smoothing out rapid fluctuations.
- This reduces **false alarms** and helps trend lines reflect actual seal behavior instead of noise.

c. Improves Isolation Between Seal Stages

- Without controlled backpressure, leakage from the primary seal could evacuate too rapidly, **masking small but crucial leak signals** from the secondary seal.
- Controlled venting creates an environment where **both primary and secondary leakage paths are distinguishable** instrumentation can "see" them more clearly.

d. Enables Repeatable Conditions for "Vent Studies"

- Studies examining vent flow characteristics, alarm calibration and leakage trends rely on **consistent pressure staging**.
- A backpressure regulator or orifice lets you **tune and lock down those conditions**, providing reliable baselines across operating cycles.

6. Gas Conditioning unit:

- One of the leading causes of gas seal failure is improperly conditioned gas entering the seals.
- All gas must be both clean and dry before it goes across seal faces. GCUs condition the gas protecting the seal.
- GCUs are typically made up of four items: filters (coalescing and separators), heaters, boosters and coolers. The most significant change is that now these items should be considered as standard.
- Meaning that sufficient justification must be made by the system vendor not to include such feature as heaters and boosters.

Function of Dry Gas Seals:

- The key elements within a Gas Seal are the sealing faces and secondary sealing elements (**Figure.4**).
- A shaft sleeve, which is fixed with the compressor shaft, holds the rotating seat.
- The rotating seat is sealed against the shaft sleeve with a secondary sealing element, which is a special O-ring or PTFE filled sealing device.
- **The rotating seat has the gas grooves integrated to generate an aerodynamic lift off and provide gas film stiffness during operation.**

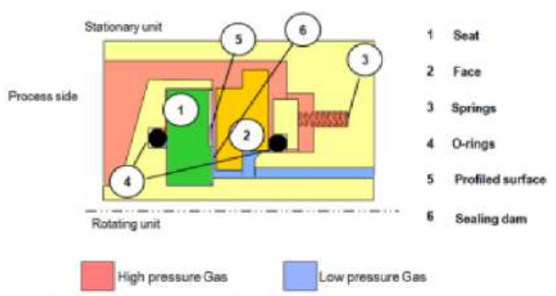


Figure 1: Core parts of Dry Gas Seals

Figure.4. Dry Gas seal components

- The non-rotating elements combine a seal housing, fixed to the compressor casing and the non-rotating seal face.

- The stationary elements are designed to compensate for axial movements of the compressor rotor in relation to the compressor case.
- The compressor shaft is exposed to axial movement caused by different loads, case expansion from heat and pressure or vibrations.
- Compensation for axial movements is achieved by allowing the non-rotating face to move along the balance sleeve (sleeve below the non-rotating face, item 2).

> *Safety Starts at The Seal*

- The nonrotating face is sealed against the balance sleeve with a dynamic sealing element (O-ring or PTFE filled sealing device), which slides on the balance sleeve.
- **When pressure is applied to the seal or the compressor is rotating, the applied forces will hold the seal faces off and maintain the appropriate gap of 3 to 5 microns between them.**
- When these conditions are not present springs are required to hold the seal faces together.
- To avoid any wear on the sealing faces, **Gas Seals are designed to lift off when operated. This means the rotating seat and stationary face have no contact in operation.**
- The seals are kept from touching by the generation of **hydro-dynamic pressure**, created by small grooves cut into the face of the rotating ring which draws gas into the seal, forcing the two surfaces apart.

• **Because the space between the seals is less than human hair, the sealing gas used must be completely dry and free from grit, dust, or moisture**. An external source of sealing gas is therefore used to ensure cleanliness.

• This separation is called **lift off**. The lift off is mainly influenced by two effects (**Figure.5**):

- Differential pressure over the faces
- Circumferential speed

- The seal can lift off at a certain differential pressure, a certain speed or a combination of speed and differential pressure.
- The lift off speed and differential pressure depends on the specific operating conditions, like gas type and detailed seal design.
- **The tandem seal system is designed so that after the failure of the primary seal, the machine can be safely shut down using the containment provided by the secondary seal without a hazardous release of gas into the atmosphere**.
- Although these dry gas seals are able to handle high levels of vibration without damage, reverse rotation of the shaft at high speeds will damage the seals as they are not able to develop the hydro-dynamic pressure

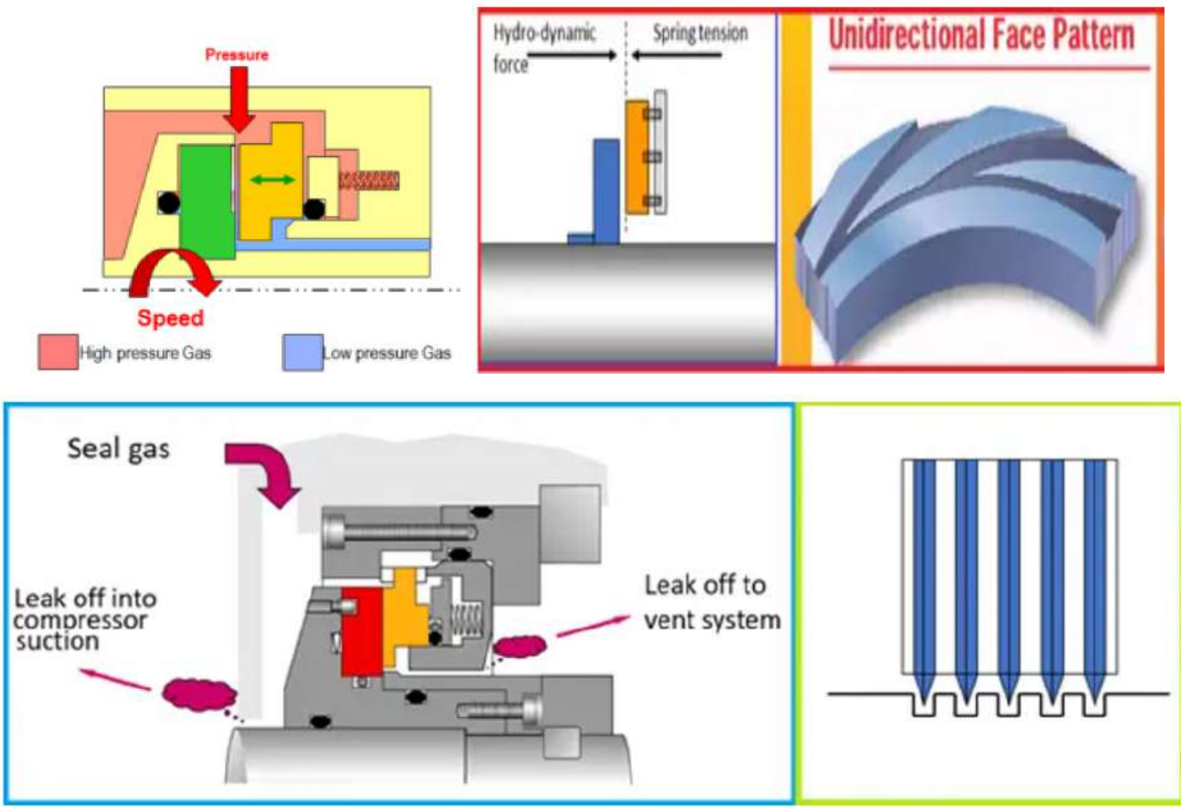


Figure.5. Seal lifts off while running

required to push the sealing faces apart. **Figure.6** shows the sealing face spiral groove arrangement.

- The most common gas seal arrangements used in the industry for compressors are:
  - tandem arrangements (**Figure.7**) or
  - tandem with intermediate labyrinth arrangements (**Figure.8**).

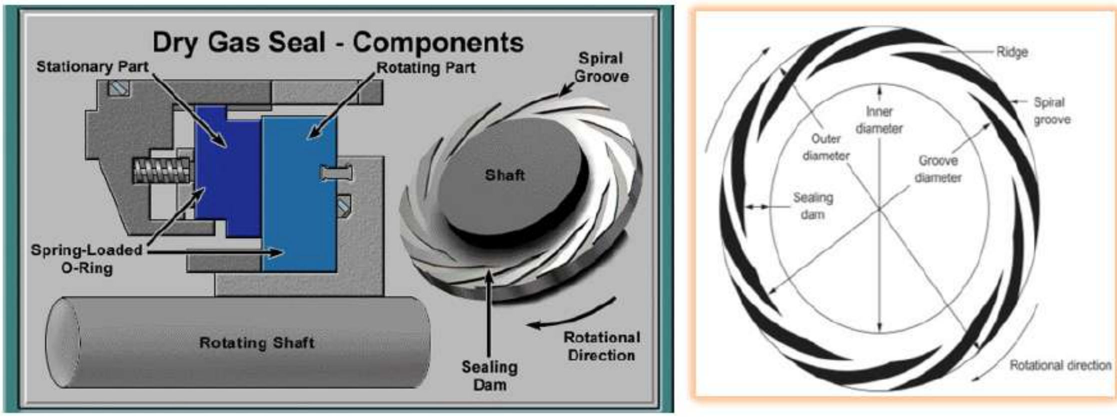


Figure.6. Dry gas seal components

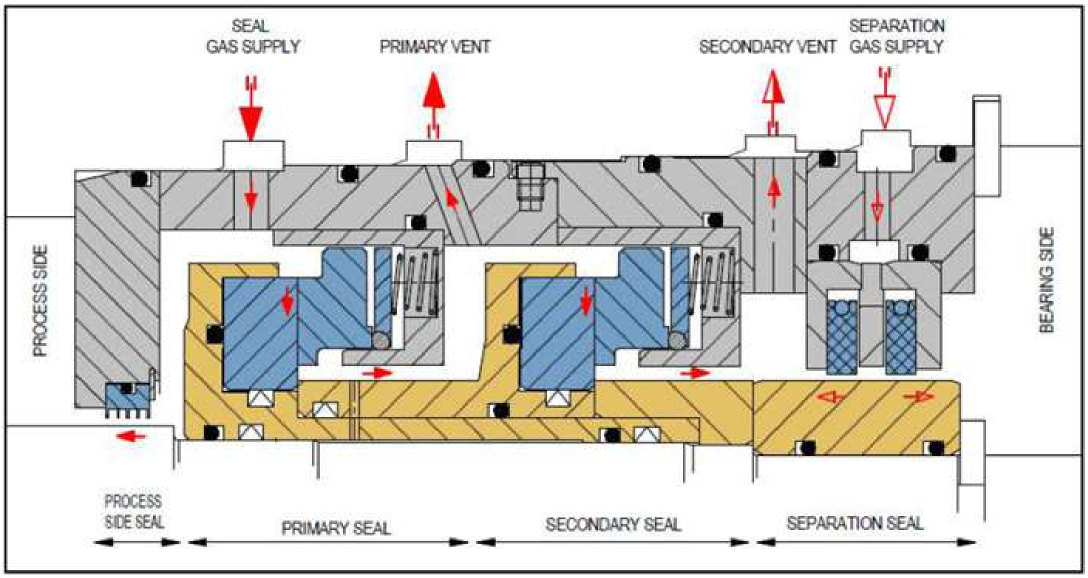


Figure.7. Tandem Seal Schematic

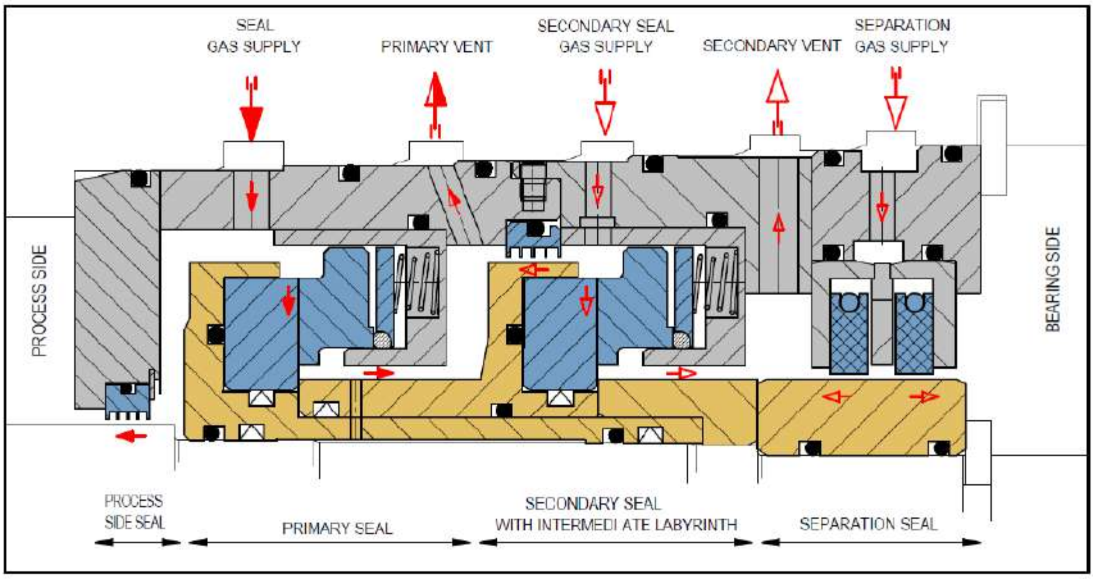


Figure.8. Tandem Seal with Intermediate Labyrinth Schematic

> *When Seals Perform, Compressors Thrive*

Dry Gas Seal control system:

- Dry Gas Seal and barrier gas control systems are specially designed to supply gas, at the correct pressure and flow, to the dry gas seals.
- These systems are panel-mounted and installed adjacent to the compressor skid.
- The DGS will have reliable operation only if the gas is clean. The seal gas filter is installed to filter the contaminants.
- Ingress of foreign material into the running gap of the seals leads to degrade sealing performance (increased gas leakage) and eventual failure of the seal.

Control system provides three main functions:

- Filtration of Seal gas & Buffer Gas
- Regulation of Seal gas & Buffer Gas
- Monitoring of seal Performance
- Design is simple to operate and user friendly with minimum maintenance requirements.

Seal Gas loop:

- Seal gas must be dry and free of particles less than 3 micron.
- Sealing gas is injected between the inner labyrinth seal and the Dry gas seal.
- The majority of this gas flows across the inner labyrinth seal and into the compressor or process side of the Compressor.
- A very small amount of the sealing gas passes through the primary seal & out of the primary vent which is normally connected to user's flare system. Refer **Figure. 9, 10, 11**.

Dry gas seal control system Layout

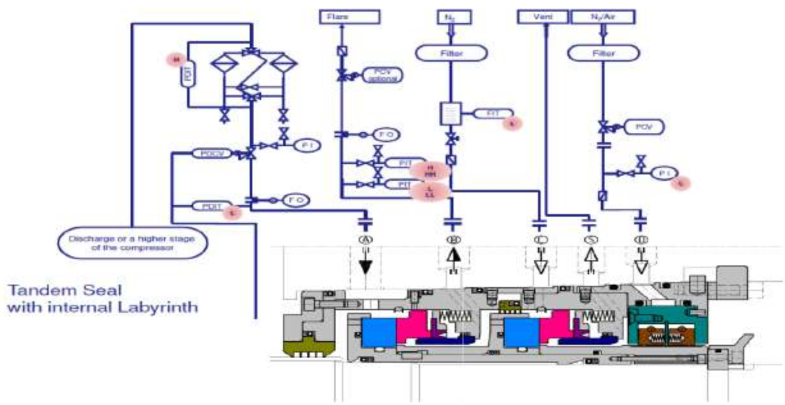


Figure.9. Dry gas seal control system layout

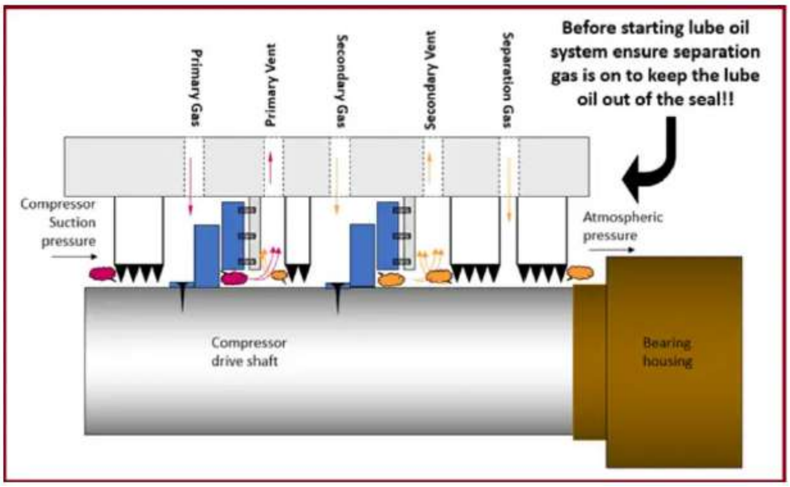


Figure.10. Dry gas seal (tandem type) arrangement

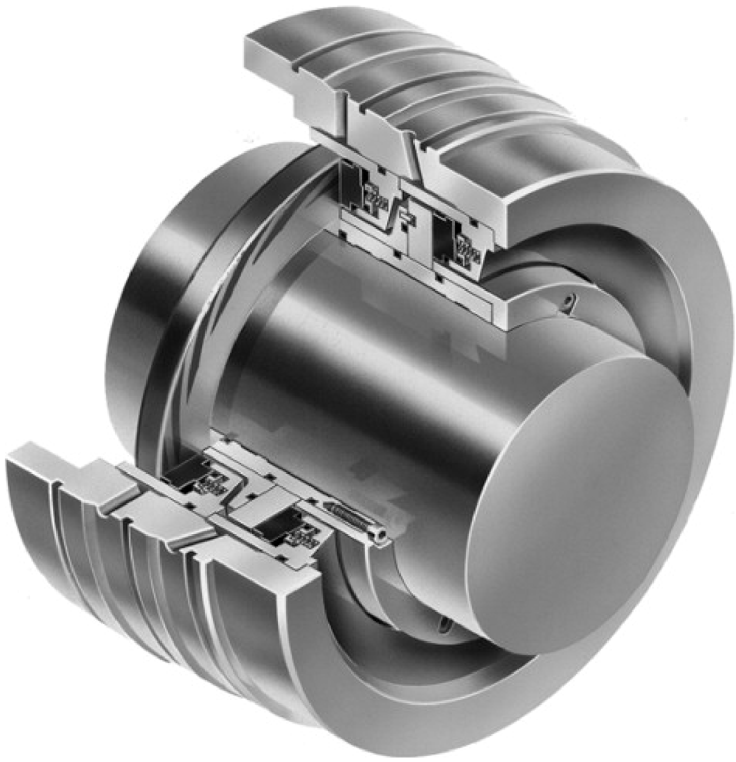


Figure.11. Dry gas Tandem type seal

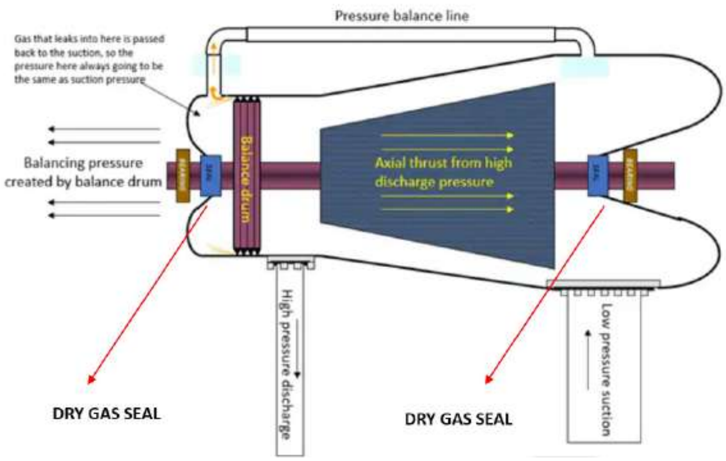


Figure.12. Dry gas seal location on compressor shafting.

Pressure Balancing:

- The thrust created by the high-pressure discharge pushing the compressor rotor back towards the suction is canceled by creating opposing thrust using a balance drum. (**Figure.12**)
- This pressure balancing system also means the compressor seals are only ever exposed to suction pressure.

Overview of Tandem Dry Gas Seals (API 692):

Tandem dry gas seals are non-contacting mechanical seals used in centrifugal compressors to prevent process gas leakage. API 692 standardises their design, support systems and monitoring requirements for enhanced reliability and safety in oil, gas and petrochemical industries.

Key Features:

- **Dual sealing stages:** Primary and secondary seals arranged in series.
- **Intermediate labyrinth:** Optional, adds a buffer zone between seals.
- **Non-contacting faces:** Grooved rotating ring and flat stationary ring maintain a micron-level gap.
- **Gas-lubricated:** Uses clean, dry gas to create a pressure barrier and lubricate seal faces.

Functional Streams (as per API 692)

Stream Type	Function	Typical Medium
Seal Gas (Primary)	Flows across the primary seal to prevent process gas ingress	Clean process gas or nitrogen
Secondary Seal Gas	Flows across the secondary seal to monitor and contain leakage	Nitrogen (inert)
Separation Seal Gas	Isolates bearing housing from seal system	Nitrogen or dry air
Primary Vent	Collects leakage from primary seal	Mixed seal/process gas
Secondary Vent	Collects leakage from secondary seal and separation seal	Should be near atmospheric

Table 1. Functions of dry gas sealing elements

Pressure Profile (Typical Ranges)

Seal Stage	Inlet Pressure (Typical)	Outlet Pressure (Typical)	Notes
Primary	~5–10 psi above process pressure	Drops to primary vent (~atmospheric or flare pressure)	Ensures positive differential
Secondary	~5 psi above primary vent	Atmospheric or slightly above	Prevents reverse pressurization
Separation	~5–10 psi above bearing housing pressure	Atmospheric	Protects against oil ingress

Table 2. Typical Operating profiles

- **Modular support systems:** API 692 mandates separate modules for filtration, conditioning and monitoring.

Key Design Advantages:

- **Dry running**: No liquid contamination, enhancing longevity.
- **Modular support systems**: Easy maintenance and standardised interfaces.
- **Non-contact operation**: Minimises wear and friction.
- **Continuous monitoring**: Vent flows, pressure diff and temperature.

These values vary based on compressor design, operating conditions and seal configuration. Always consult OEM specs for exact figures.

Common Faults & Defects:

- **Contamination**: Entry of liquid hydrocarbons, particulates, or lube oil into seal faces.
- **Improper gas conditioning**: Leads to condensation and seal face damage.
- **Seal face wear**: Due to dry running or misalignment.
- **Pressure imbalance**: Can reverse pressurise seals, causing failure.
- **Instrumentation failure**: Faulty flowmeters or transmitters can mask early warning signs.
- **High Vent flows**: Excess leakage, worn seal faces.
- **Bearing Oil Ingress**: Inadequate separation seal pressure.

Troubleshooting Tips:

- **Monitor differential pressure** across seal faces for early warnings of leakage paths.
- **Check vent flow rates** for abnormal leakage, regularly.
- **Inspect filter elements** regularly for clogging or liquid accumulation.
- **Ensure proper seal gas superheat** to avoid condensation (typically 20°F above dew point).
- **Verify separation gas supply** to prevent oil migration.
- **Verify instrumentation** and **alarm thresholds** for correct operation.

Conclusions:

On board ships, Tandem Dry Gas Seals (DGS) are not as widespread as in land-based oil & gas plants, but they are used in very specific high-value, high-pressure rotating machinery where leakage prevention and reliability are critical.

You could typically find them in Main Gas Compressors (LNG Carriers & Gas-Fueled Vessels).

o **Cargo handling compressors**: Used to compress boil-off gas (BOG) from LNG cargo tanks for reliquefaction or as fuel for propulsion.

> *Your Last Barrier Against Gas Leakage*

o **Fuel gas compressors**: On LNG carriers and dual-fuel ships, tandem DGS are used in compressors feeding gas engines/turbines.

o **Refrigerant compressors:** In LPG carriers and chemical tankers, tandem DGS are used in compressors handling volatile hydrocarbons (propane, butane, ethylene).

o **FPSOs and FSRUs (Floating Storage & Regasification Units):** Tandem DGS are used in onboard gas compression and regasification modules.

Why Ships Need Tandem DGS?

o **Safety**: Prevents flammable/toxic gas leakage into enclosed machinery spaces.

o **Environmental compliance**: Meets MARPOL Annex VI and IMO IGF Code requirements for low emissions.

o **Reliability**: Redundancy is essential in remote, offshore operations where maintenance is difficult.

o **Cargo integrity**: Ensures LNG/LPG cargoes remain uncontaminated and safely handled.

o Tandem dry gas seals are more than just mechanical barriers—they are dynamic systems that rely on precise gas staging, clean operation and vigilant monitoring.

o By adhering to API 692 guidelines and understanding the interplay of seal pressures, support streams and failure modes, operators can significantly improve compressor reliability and safety.

o Whether in design, commissioning, or maintenance, a deep grasp of these seals empowers teams to prevent costly failures and extend equipment life in demanding industrial environments.

References

- Dry Gas Sealing Systems for Axial, Centrifugal, Rotary Screw Compressors & Expanders, API STANDARD 692, FIRST EDITION, JUNE 2018.
- API 692 Seal Gas systems, Design guidelines- John Crane
- Asia Turbomachinery & pump symposium-Singapore, 22-25 Feb 2016, DRY GAS SEAL CONTAMINATION DURING OPERATION AND PRESSURIZED HOLD – BACKGROUND AND POTENTIAL SOLUTIONS.
- Asia Turbomachinery & pump symposium-Singapore, 22-25 Feb 2016, Dry gas seal failure and troubleshooting Manikandan, A GE Oil & Gas, Doha, Qatar, Moorthy Subramanian Eagle Burgmann Middle East FZE, UAE.

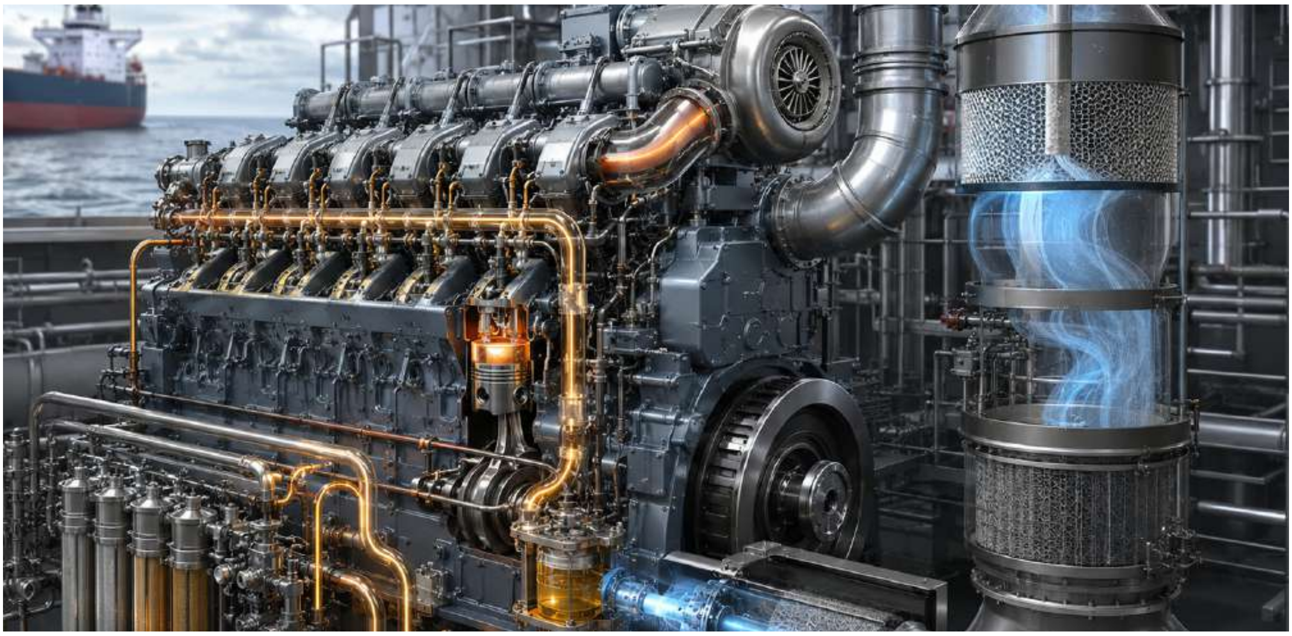
About the Author

Venkat Krishna Soundarraja, Fellow of IME(I), blends 30 years of marine engineering and data science. Former Chief Engineer turned Chief Data Officer (Volteo Maritime Pte. Ltd.), he drives digital transformation and sustainability in maritime operations. As educator, mentor and researcher, he bridges theory with practice, translating complex data into clear insights while inspiring future engineers through teaching, writing and innovation.

Email: venkatmarine158@gmail.com

Fundamentals of Fuels and Emissions

Paper 1 : Fundamental of Fuels and Emissions



Vikrant Rai

Abstract

The global maritime industry is undergoing a profound transformation as it seeks to align with international climate goals and the International Maritime Organization's (IMO) strategy for reducing greenhouse gas (GHG) emissions. A clear understanding of fuels, emissions, carbon cycles and greenhouse gas accounting is essential for evaluating the effectiveness of emerging decarbonisation pathways. This paper provides a foundational overview of the relationship between greenhouse gases, global warming, fuel production pathways and lifecycle emissions. It explains the natural carbon cycle, the causes of anthropogenic climate change and the roles of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) in global warming. The concept of Global Warming Potential (GWP) and the significance of GWP20 and GWP100 metrics are discussed in the context of maritime fuel policy.

The paper further examines the fundamental composition of fuels, sources of carbon and hydrogen and the distinction between fossil, biogenic and renewable feedstocks. Various fuel categories, including conventional fuels, alternative fuels, biofuels, e-fuels, hydrogen, methanol and ammonia, are explained along with their production pathways and associated emissions. Special emphasis is placed on lifecycle assessment (LCA), well-to-wake greenhouse gas accounting and the need to avoid merely shifting emissions from ship operations to fuel production processes. By establishing the scientific and technical principles underpinning maritime decarbonisation, the paper provides a framework for understanding IMO's Net-Zero ambitions, fuel transition strategies and future green shipping policies.

Keywords: Green Shipping; Greenhouse Gases (GHGs); Carbon Cycle; Global Warming; Anthropogenic Emissions; Global Warming Potential (GWP); GWP20; GWP100; Alternative Fuels; Biofuels; E-Fuels; Hydrogen; Ammonia; Methanol; Lifecycle Assessment (LCA); Well-to-Wake Emissions; Tank-to-Wake Emissions; Well-to-Tank Emissions; Maritime Decarbonisation; IMO Revised GHG Strategy; Net-Zero Fuels; Carbon Accounting.

Introduction

Climate change has emerged as one of the most significant global challenges of the twenty-first century, prompting governments, industries and international organisations to develop strategies aimed at reducing greenhouse gas emissions and limiting global temperature rise. The maritime sector, responsible for transporting more than 80% of global trade by volume, plays a critical role in this transition. Although shipping remains one of the most energy-efficient modes of transportation, its continued reliance on fossil fuels contributes substantially to global greenhouse gas (GHG) emissions. Consequently, the International Maritime Organization (IMO) has adopted increasingly ambitious measures to facilitate the transition towards low-carbon and ultimately net-zero shipping.

A meaningful discussion on maritime decarbonisation requires a clear understanding of the fundamental science behind fuels and emissions. Greenhouse gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) naturally regulate Earth's temperature through the greenhouse effect, making life on Earth possible. However, human activities, particularly the extraction and combustion of fossil fuels, have disturbed the natural carbon balance by releasing large quantities of carbon that had remained stored underground for millions of years. This disruption has increased atmospheric greenhouse gas concentrations and contributed significantly to global warming.

The transition toward sustainable shipping has led to the emergence of numerous fuel options, including liquefied natural gas (LNG), biofuels, hydrogen, ammonia, methanol and synthetic e-fuels. While many of these fuels offer reduced emissions during combustion, their overall environmental performance depends heavily on how they are produced, transported and utilised. Evaluating fuels solely on the basis of exhaust emissions can therefore be misleading. Modern regulatory frameworks increasingly emphasise lifecycle greenhouse gas accounting, which considers emissions from fuel production, transportation, storage and end use.

This paper forms the first part of a broader series entitled *Conceptual Analysis of Green Shipping and Consolidated List of References*. The objective of the series is to clarify the concepts associated with "green" and "green shipping," examine the evolution of international negotiations within the IMO and identify key considerations for the development of Indian Green Shipping policies.

Given the breadth and complexity of the subject, the series is divided into three interconnected papers:

Paper 1: Fundamentals of Fuels and Emissions

Paper 2: The Difference Between Short-Term and Mid-Term Measures

Paper 3: Essence of the IMO Net-Zero Framework

As the foundation of the series, this paper focuses on the scientific and technical principles governing fuels and greenhouse gas emissions. It explores the carbon cycle, greenhouse gas characteristics, global warming potential metrics, fuel feedstocks, fuel production pathways and lifecycle assessment methodologies. By establishing these fundamental concepts, the paper seeks to provide maritime professionals, policymakers, regulators and stakeholders with the knowledge necessary to understand the rationale behind current and future decarbonization measures and the transition towards sustainable shipping.

Carbon Cycle/Greenhouse Gases and Global Warming

1. **How is Earth's temperature maintained?**

   a) Earth's temperature is maintained through a **delicate balance of incoming solar radiation and outgoing heat, managed by the atmosphere acting as a blanket**.

   b) The blanket of air that surrounds the earth is called atmosphere and it contains different gases such as carbon dioxide, Nitrogen, Oxygen, Neon and others.

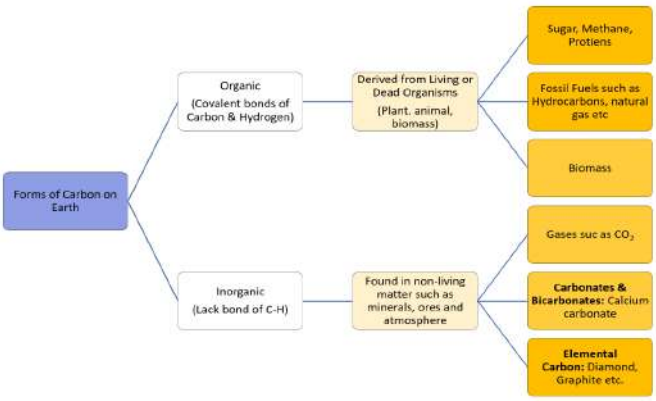
   c) Few of gases such as Methane, Ozone and Carbon Dioxide etc absorb heat radiated from earth's surface and maintain the temperature of earth. These gases are called Greenhouse gases.

   d) Greenhouse gases are important to maintain Earth's temperature for sustenance of life on earth.

2. **Then why it is said that anthropogenic emissions of Greenhouse lead to Global Warming?**

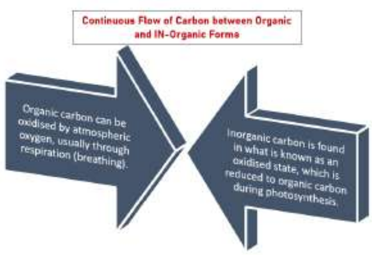
i. **Forms of Carbon on Earth and Carbon Balance**

   a) The amount of carbon we have on Earth doesn't change. It is the same as it is now as it was millions of years ago. Only one form of carbon changes to another form. The forms of carbon are:



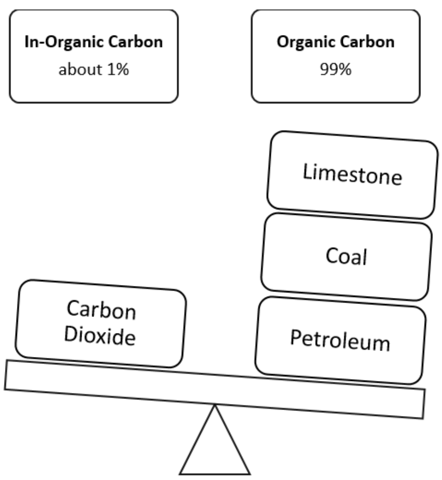
ii. **Imbalanced Carbon Cycle**

   a) Carbon is the lifeblood of Earth and is naturally regulated by the carbon cycle. IPCC defines carbon cycle as the flow of carbon (in various forms, e.g., as carbon dioxide (CO_2), carbon in biomass and carbon dissolved in the ocean as carbonate and bicarbonate) through the atmosphere, hydrosphere, terrestrial and marine biosphere and lithosphere.

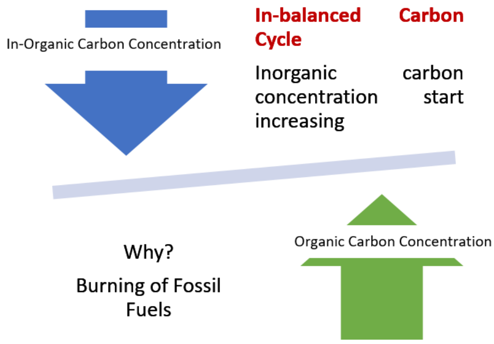


b) This balance is achieved by continual and repeated movement of carbon among the Earth's atmosphere, oceans, soil, rocks and living organisms converting one form of carbon to another. It involves photosynthesis taking from the air, respiration and decomposition returning it and geological processes storing it in fossil fuels. This balance regulates Earth's climate, maintain its temperature and supports life.

Balanced Carbon Cycle



c) However, global warming is a result of this carbon cycle going out of balance. When we say carbon cycle is out of balance, it means that the concentration of greenhouse gases specially CO2 in earth's atmosphere, is more than what it had been hundreds of years ago. This increases the average temperature of earth with resultant impact.



d) The higher-than-normal concentration of greenhouse gases in earth's atmosphere is due to Anthropogenic emissions. IPCC defines Anthropogenic emissions as emissions of greenhouse gases (GHGs), precursors of GHGs and aerosols caused by human activities. These activities include the burning of fossil fuels, deforestation, land use and land-use changes (LULUC), livestock production, fertilisation, waste management and industrial processes.

> *Not All Green Fuels Are Truly Green*

3. **What are various Greenhouse gases and which all of these are covered in IMO Revised GHG Strategy?**

a) The **UNFCCC (United Nations Framework Convention on Climate Change) convention** covers **seven primary GHGs: 1. carbon dioxide (CO_2), 2. methane (CH4), 3. nitrous oxide (N_2O), 4. hydrofluorocarbons (HFCs), 5. perfluorocarbons (PFCs), 6. sulphur hexafluoride (SF_6) and 7. nitrogen trifluoride (NF_3).** These gases, along with others like water vapor, contribute to the greenhouse effect, trapping heat in the atmosphere and causing global warming.

b) Most fuels which are used on board have a molecular structure which are bonds of carbon and hydrogen and as per combustion equation, the CO_2 is the major greenhouse gas which is emitted. However:

i. Nitrous oxide (N_2O) can be emitted during the combustion of fossil fuels, particularly coal, oil and natural gas as the nitrogen content in these fuels and specific combustion conditions can also lead to N_2O formation.

ii. Methane can be produced when the hydrocarbons in fossil fuels (like natural gas, oil and coal) are not burned completely. Factors like engine type, fuel composition and engine efficiency can influence the amount of methane released.

c) The **IMO Revised GHG Strategy** and **IMO Net Zero Framework** aims to reduce emissions of CO_2, CH_4 and N_2O only.

4. **How do we compare the impact of various Greenhouse gases on Earth's atmosphere?**

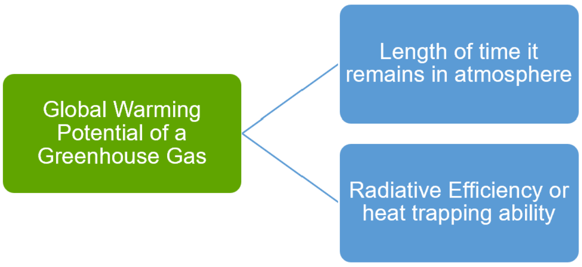
a. To know the potential climate effect of equal emissions of each of the greenhouse gases, IPCC developed, the concept of relative **Global Warming Potentials (GWP)**, which consider the differing times that gases remain in the atmosphere. This index defines the time-integrated warming effect due to an instantaneous release of unit mass (1 kg) of a given greenhouse gas in today's atmosphere, relative to that of carbon dioxide.

b. Basically, **Global Warming Potential (GWP) is a metric used** to compare the heat-trapping ability of different greenhouse gases relative to carbon dioxide over a specific timeframe, typically 100 years.

c. **GWPs provide a common unit of measure**, which allows analysts to add up emissions estimates of different gases (e.g., to compile a national GHG inventory) and allows policymakers to compare emissions reduction opportunities across sectors and gases.

d. When **comparing greenhouse gas emission from various activities**, it is easier to use equivalent amount of CO_2 emitted for easier comparison rather than comparing individual greenhouse effect of each individual greenhouse gas.

e. The **GWP is the ability of a GHG to trap heat in the atmosphere over time, relative to carbon dioxide (CO_2).** The length of time the gas remains in the atmosphere and its heat trapping ability determine its GWP.



f. **The heat trapping ability or radiative efficiency measures** how effectively the greenhouse gas absorbs radiation. Atmospheric Lifetime details as to how long a gas remains in the atmosphere before being removed.

The interplay of radiative efficiency and atmospheric life time can be understood from following facts:

i. Two GHG gases each with same radiative efficiency but one with smaller atmospheric lifetime (10-12 years) or short-lived and other having long atmospheric lifetime (100-200 years): The short-lived gas will have low GWP in long term compared to other GHG because it will not remain in atmosphere after 10-12 years and thus will absorb radiation only for 10-12 years, while the gas with long-life in atmosphere will continue absorbing radiation.

ii. Two GHG gases "A" & "B" with "A" having higher radiative efficiency than "B" but the atmospheric lifetime of "A" is only 10-12 years (short-lived), while "B" having long atmospheric lifetime (100-200 years): The $GWP_{20\text{-Years}}$ of "A" will be much higher with than that of "B"; but $GWP_{100\text{-Years}}$ of "A" may be higher than that of "B" but the difference may not be as much as that in **$GWP_{20\text{-Years.}}$**

iii. The examples of CO_2 and N_2O may be seen as below:

Greenhouse Gas	Lifetime in atmosphere	Radiative Efficiency compared to CO_2	$GWP_{20\text{-Years}}$	$GWP_{100\text{-Years}}$
CO_2	Tens of thousands of Years	NA	1	1
Methane CH_4	12 Years	Higher	82	28
Nitrous Oxide N_2O	100 Years	Higher	264	265

Table 1: Greenhouse Gases Comparative GWP and thus Climate Impact

> *Carbon Accounting Shapes Shipping's Future*

g. Assigning CO_2 as **$GWP_{20\text{-Years}}$** and **$GWP_{100\text{-Years}}$** as 1 means if in 20-Years Radiative Efficiency of CO_2 is 1 watt/m^2/ppm then in 20-Years radiative efficiency of CH_4 and N_2O are respectively 82 watt/m^2/ppm and 264 watt/m^2/ppm respectively. It provides a comparative basis with respect to Carbon Dioxide, which is the major greenhouse gas in the atmosphere.

5. **What happens when we set GHG reduction goals based on GWP20-years instead of GWP100-Years?**

i. Global warming potential (GWP) is a **method to determine the heat absorption impact of a greenhouse gas over a specific period, relative to carbon dioxide (CO_2), which has a GWP of 1 and it does not in any way details amount of greenhouse gas in the atmosphere.**

ii. The **choice of time horizon (that is GWP based on 20-years or 100-Years)** has major policy implications. As can be seen from Table 1 above, policies based on **$GWP_{20\text{-Years}}$**, that is, a 20-year time horizon raises the seen impact on climate by short-lived gases such as Methane (CH_4) by a factor of 2.92 (82/28) compared **to $GWP_{100\text{-Years}}$**, that is a time horizon of 100-years.

iii. Adopting the 20-year GWP index has immediate policy ramifications as it would influence the level of the baseline as a **GWP_{20} baseline** would be higher than a **GWP100 baseline** and thus would influence the order of how control steps are implemented, with the phase out of substances with **high GWP20** likely to be implemented first.

iv. The **IMO 2024 Guidelines on Lifecycle GHG Intensity of Marine Fuels** issued via Resolution **MEPC 391(81):**

- The **GHG emissions** are calculated as **CO2-equivalent (CO2eq)**
- It uses the global warming potential over a 100-year time-horizon (GWP100) to convert emissions of other

> ***Beyond CO_2: Methane Matters Too***

gases than CO2, as given in the fifth IPCC Assessment Report, for CO_2, CH_4 and N_2O, as follows:

$$gCO_{2\text{-equivalent-100-Years}} = (GWP\text{-}CO_2(100y) \times gCO_2) + (GWP\text{-}CH_4(100y) \times gCH_4) + (GWP\text{-}N_2O\ (100y) \times gN_2O)$$

Note taking $GWP_{100\text{-Years}}$ as $CO_2 = 1$; $CH_4 = 28$ & $N_2O = 265$, the equation becomes:

$$gCO2\text{-equivalent-100-Years} = (1 \times gCO2) + (28 \times gCH4) + (265 \times gN2O)$$

- These GWP_{100} values is used in the guidelines for the purpose of quantifying the GHG intensity. in accordance with these guidelines. A calculation using a global warming potential over a 20-year horizon (GWP_{20}) may be provided as information for comparative purposes, as follows:

$$gCO_{2\text{-Equivalent}}(20y) = (GWP\text{-}CO_2(20y) \times gCO_2) + (GWP\text{-}CH_4(20y) \times gCH_4) + (GWP\text{-}N_2O\ (20y) \times gN_2O)$$

Note taking $GWP_{20\text{-Years}}$ as $CO_2 = 1$; $CH_4 = 84$ & $N_2O = 264$, the equation becomes:

$$gCO_{2\text{-equivalent-20-Years}} = (1 \times gCO_2) + (84 \times gCH_4) + (264 \times gN_2O)$$

Fundamental of Fuels:

6. **What are fuels made up of? How do or can we produce Fuels?**

i. The fuels are fundamentally made from Carbon and/ or Hydrogen. Conventional hydrocarbon fuels or for that matter any fuel contain primarily hydrogen and/ or carbon in elemental form or in various compounds.

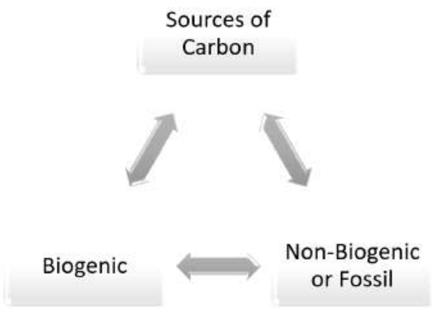
ii. To produce fuels, we need to find the sources of carbon, hydrogen or carbon & hydrogen and pass these through production processes.

7. **What are conventional fuels made up of?**

i) Both Conventional oil and natural gas are made up primarily of hydrocarbon (H), which is a chemical compound consisting entirely of carbon (C) and hydrogen (H).

8. **What are various sources of Carbon?**

a) There are basically two types of carbon as shown below:



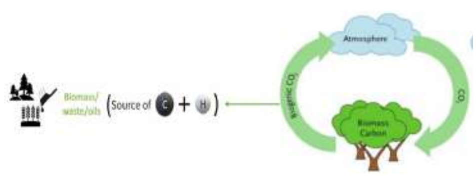
b) IPCC defines **Biogenic carbon emissions Carbon released as carbon dioxide or methane** from combustion or decomposition of biomass or biobased products.

c) Biogenic carbon is carbon stored in biological material e.g **trees, plants**, etc. and it means **carbon that is absorbed from the atmosphere through photosynthesis**. It is part of the **fast, natural biogenic carbon cycle**.

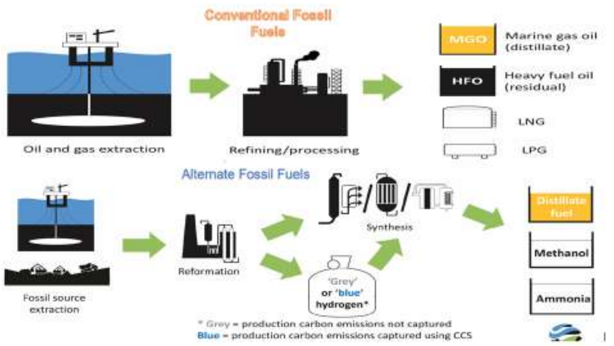
d) **Biogenic carbon cycle** is a **natural, fast-acting process** where **plants absorb atmospheric via photosynthesis** to create **biomass (cellulose),** which **is later released back into the atmosphere** through **decay, respiration, or combustion**. **This cycle spans years to decades** and **unlike fossil carbon**, it is considered renewable.

e) Fossil carbon comes from organisms that died millions of years ago, buried, transformed and stored in the form of coal, oil or natural gas. This carbon has come out of natural carbon cycle and is not meant to return to atmosphere. **Burning this carbon means introducing carbon emissions in atmosphere which have been out of carbon cycle, millions of years ago creating an unbalance in the concentration of gases in atmosphere (increasing the concentration of greenhouse gases) and thus enhancing global warming.**

f) Sources of biogenic carbon



g) Sources of Fossil Carbon



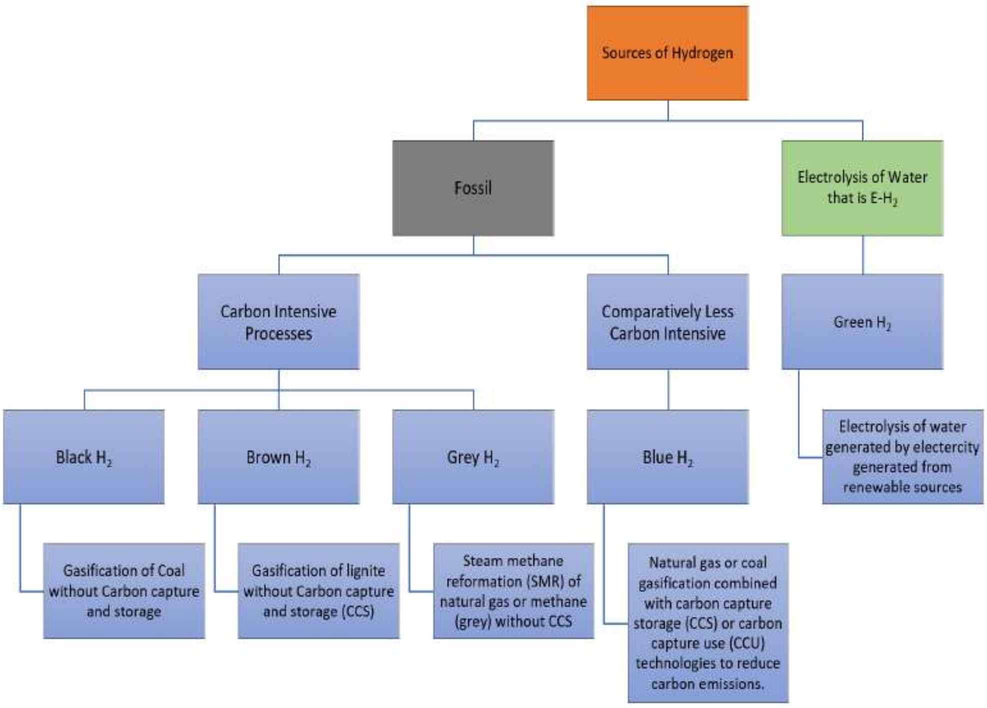
9. **What are various sources of hydrogen?**

a) We can get hydrogen from either fossil sources or through electrolysis of water.

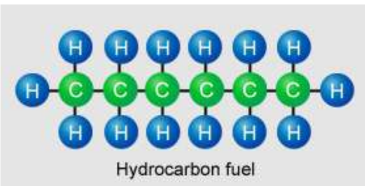
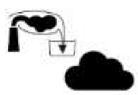
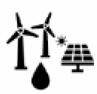
b) Note that the green hydrogen is produced using electrolysis of water with electricity generated by renewable energy. The carbon intensity ultimately depends on the carbon neutrality of the source of electricity (i.e., the more renewable energy there is in the electricity fuel mix, the "greener" the hydrogen produced).

c) Fossil fuels are the dominant source for global hydrogen production, accounting for over 90% of supply, primarily through reforming natural gas (Gray/Blue hydrogen) or gasifying coal (brown/black hydrogen).

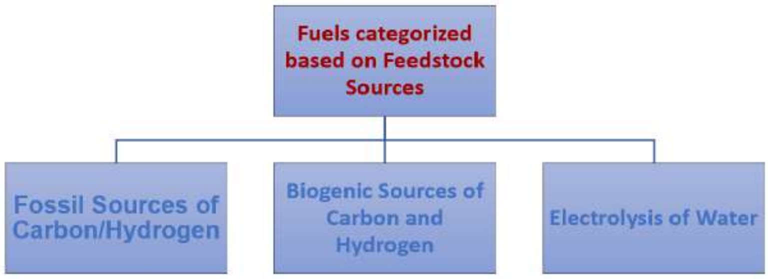
d) Black or brown hydrogen refers to hydrogen produced by coal gasification. The black and brown colours sometimes indicate the coal type: bituminous (black) and lignite (brown). This process generates significant CO2 emissions.

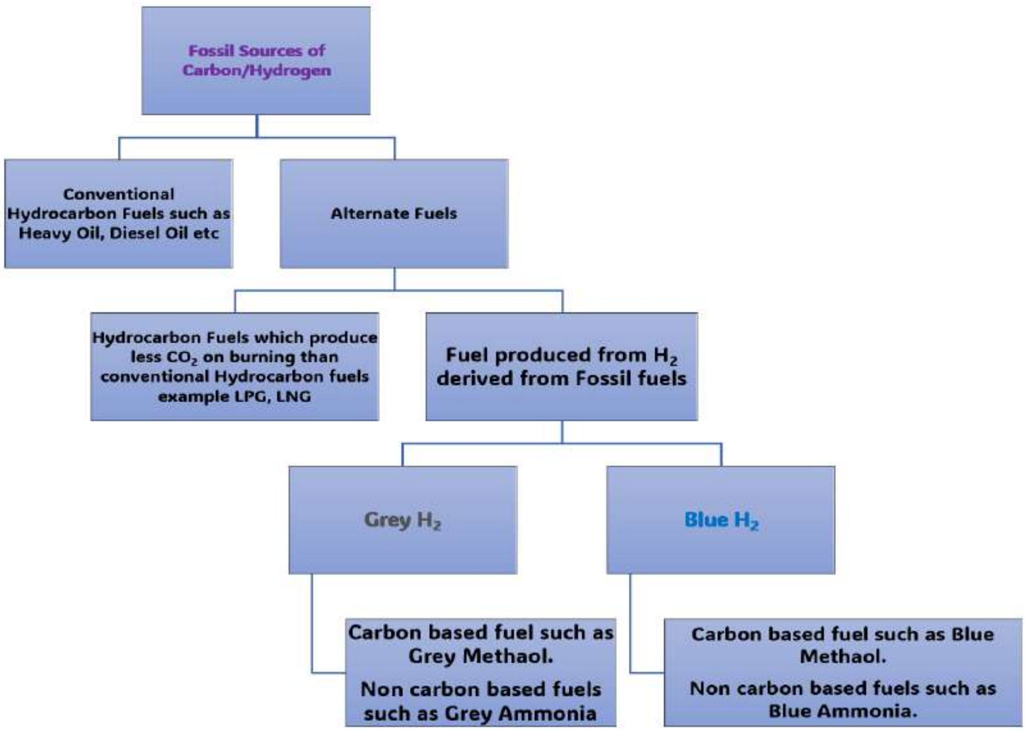


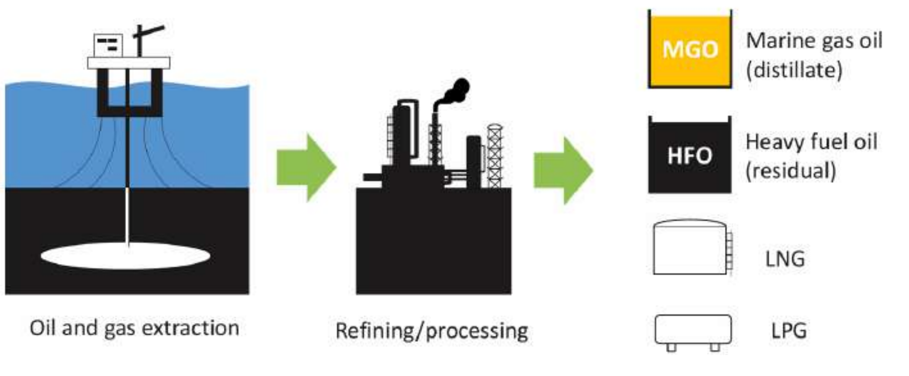
10. **Show feedstocks for carbon and hydrogen**

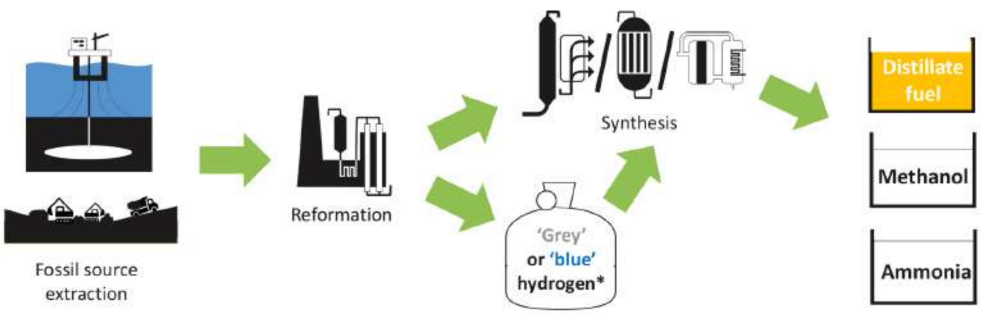
Feedstock	Source of	Feedstock	Source of
Fossil sources 	Carbon and hydrogen	Point source, atmospheric CO_2, 	Renewable Carbon
Biomass/Waste Oil 	Biogenic source of Carbon and hydrogen	Electercity and Water 	Renewable Hydrogen provided renewable electricity used for electrolysis

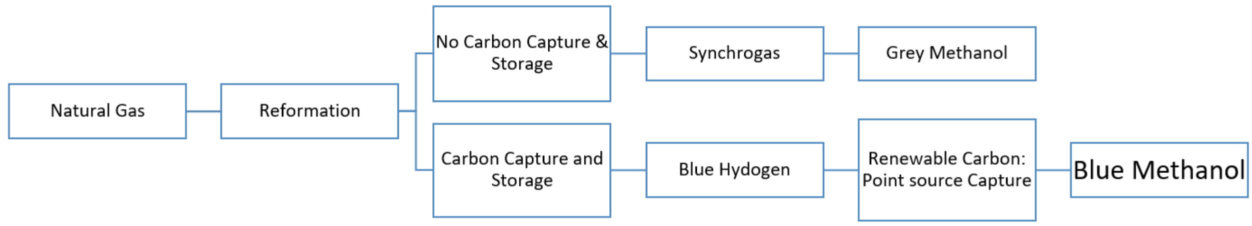
11. **We keep on hearing various terms such as alternate fuels, green fuels zero/near zero fuels etc. Explain what these means?**





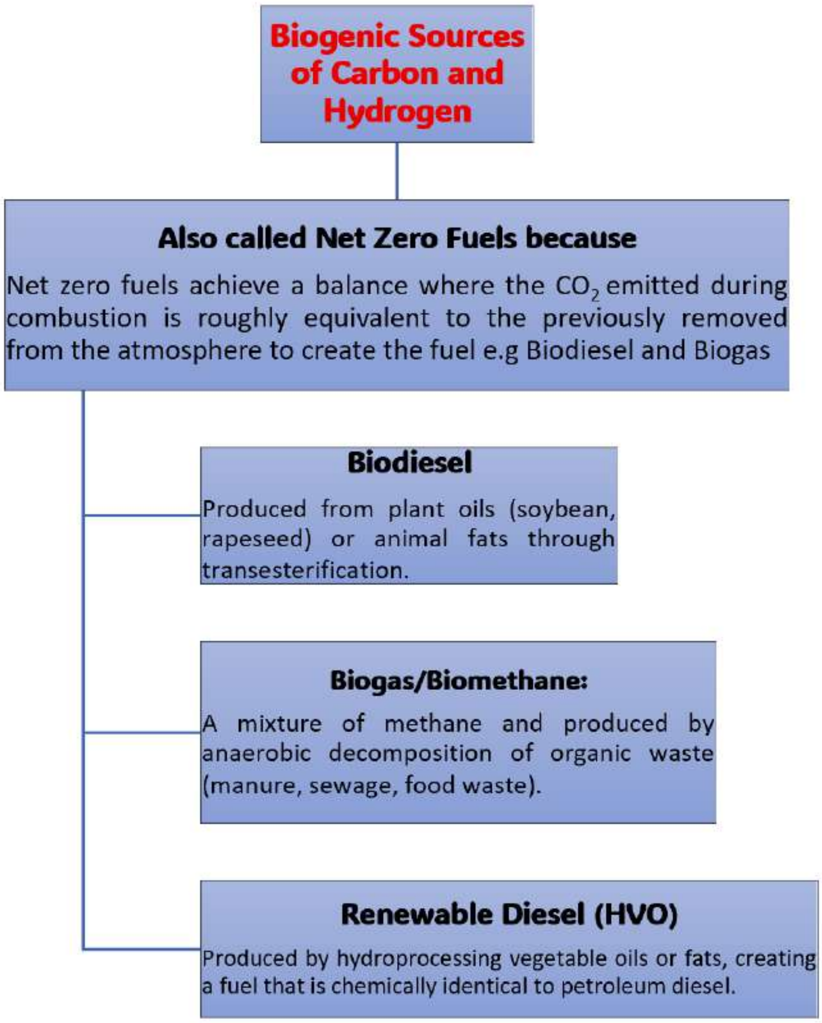


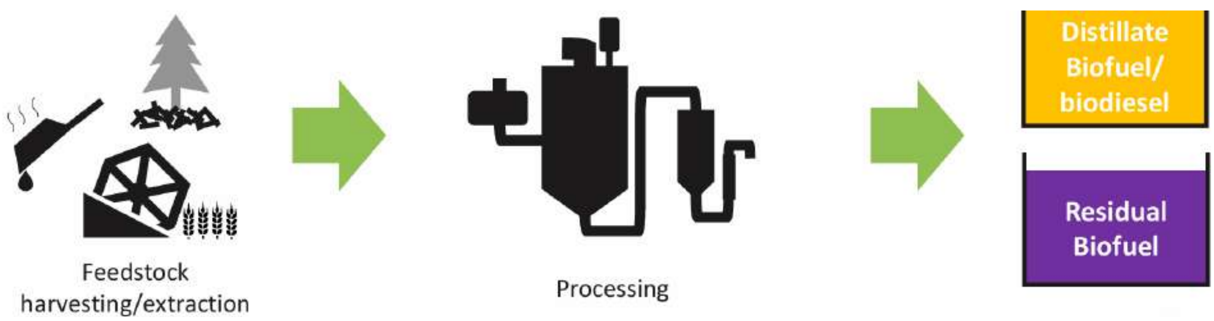




NB: Blue hydrogen is produced mainly from natural gas, using a process called steam reforming, with carbon dioxide produced as a by-product. This CO_2 is captured and stored {carbon capture and storage (CCS)} making this Blue H_2 to be called Low Carbon Hydrogen.

Grey hydrogen is created from natural gas, or methane, using steam methane reformation but without capturing the greenhouse gases made in the process. Grey hydrogen is essentially the same as blue hydrogen, but without the use of carbon capture and storage.





Electrolysis of Water to produce E-Hydrogen

E-Fuels

These fuels are also called ZNZ (Zero/Near Zero Emission Fuels)

Zero Emission Fuels or Green Fuels:

Here first Green hydrogen is produced through the electrolysis of water, where electrolysis is powered by renewable energy.

Green Fuels Without Carbon

Green hydrogen and Nitrogen captured from air through Haber-Bosch

Green Fuels with Carbon

Green H_2 + Point Source Atmospheric Carbon or Biomass

Near Zero Emission Fuels

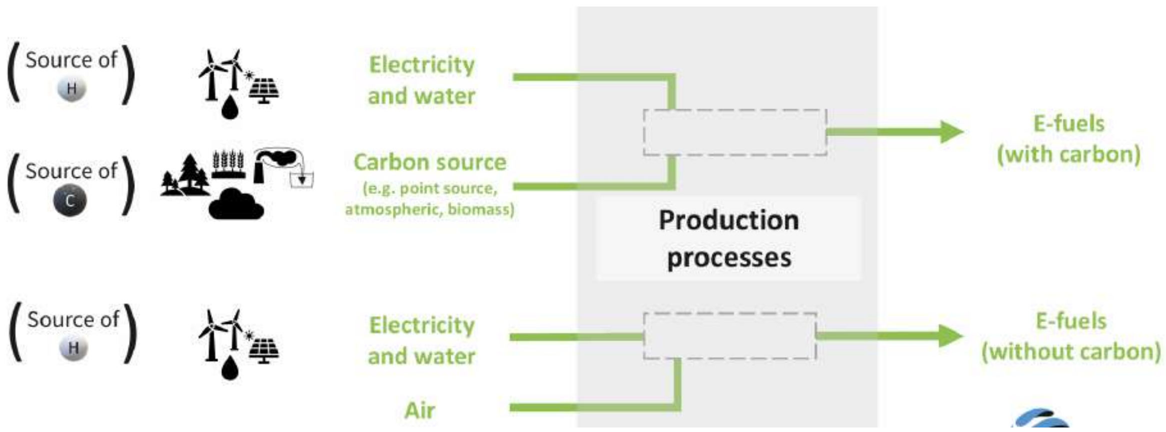
Though H_2 is produced from electrolysis of water, 100% renewable electercity is not used for H_2 production.

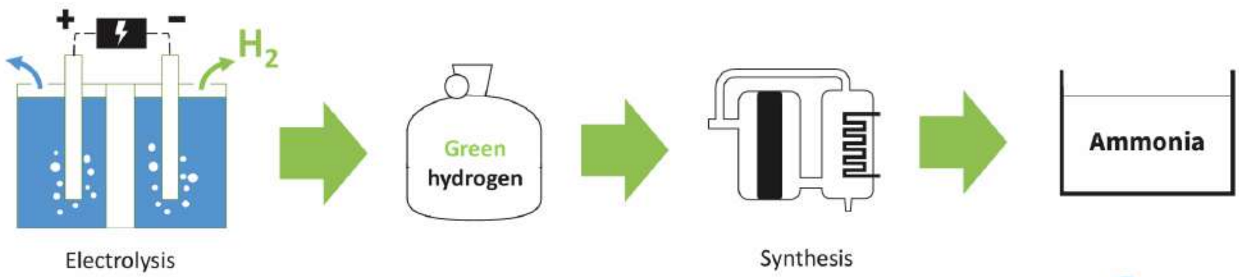
Near Zero Emission Fuels without Carbon

Near Zero Emission hydrogen and Nitrogen captured from air through Haber-Bosch

Near Zero Emission Fuels with Carbon

Near Zero Emission H_2 + Point Source Atmospheric Carbon or Biomass





> *Lifecycle Emissions Tell The Real Story*

12) How do we compare different fuel with respect to their greenhouse gas emission potential?

Different fuels are compared basically through what we call Greenhouse Gas Accounting. Carbon accounting involves the quantification of carbon dioxide, methane and other greenhouse gases emitted during various activities or operations.

For understanding GHG accounting we need to understand following terms:

1) Emission Factors

a) **IPCC defines Emission factor** as a coefficient that quantifies the emissions of a greenhouse gas per unit activity. In terms of fuels used on ships, the activity can be production of fuel or burning/combustion of fuel or both production + Combustion of fuel.

b) **Common emission factors** can be:

- Mass-Based Emission factor in kilograms of CO2 equivalent per Kg per Kg of activity if the activity can be defined in terms of Mass: Specific industrial processes that are highly carbon-intensive, often measured in Kg-CO_2-Equivalent per Kg of material produced e.g. steel, cement, HFO etc.
- Energy based Emission factors in kilograms of CO2 equivalent per megajoule (Kg-$CO_{2\text{-}e}$/MJ) is used for direct comparison of the carbon intensity of different energy sources based on their energy heat content.

When comparing the greenhouse gas (GHG) intensity of different fuels, energy-based emission factor Kg-$CO_{2\text{-}}$Equivalent/MJ is the preferred standard over mass-based emission factor Kg-CO_2-Equivalent/Kg. This is because different fuels have vastly different energy densities (heating values). Comparing them by mass is misleading because one kilogram of LNG (48,000 KJ/Kg) provides significantly more energy than one kilogram of Diesel or Gas Oil (42,700 KJ/Kg).

c) **Other types of emission factors**

The other types of emission factors used in Shipping are Energy efficiency: Design Indices & Operational Indices. Operational indices like **Energy Efficiency Operational Indicator (EEOI)** and **Annual Efficiency Ratio (AER)** are parameters that refer to the actual carbon intensity of a vessel which are the prime concern of the **CII.** This is the Summation of each fuel consumed and its **Carbon Factor C_f.** The Carbon Factor represents the **conversion factor between fuel consumption and CO_2 emissions**. It is the specific mass of CO_2 emitted in grams when created per unit mass (in grams) of a specific marine fuel is burned. Note, it only gives amount of one greenhouse gas emitted (that is carbon dioxide) on burning fuel (and not during production and transportation) and only what we call from tank to wake CO_2 emissions and not tank to wake **$CO_{2\text{-equivalent}}$ emissions.**

$$\text{EEOI} = \frac{\sum_i \sum_j FC_j \times C_{Fj}}{\sum_i M_{cargo} \times D}$$

$$\text{AER} = \frac{\sum_j FC_j \times C_{Fj}}{DWT \times D}$$

$$\underline{\sum_i \sum_j FC_j \times C_{Fj}} \quad \text{or} \quad \underline{\sum_i \sum_j FC_j \times C_{Fj}}$$

Type of fuel	Reference	Lower calorific value (kJ/kg)	Carbon content	C_F (t-CO_2/t-Fuel)
1 Diesel/Gas Oil	ISO 8217 Grades DMX through DMB	42,700	0.8744	3.206
2 Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	41,200	0.8594	3.151
3 Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	40,200	0.8493	3.114
4 Liquefied Petroleum Gas (LPG)	Propane	46,300	0.8182	3.000
	Butane	45,700	0.8264	3.030
5 Ethane		46,400	0.7989	2.927

Type of fuel	Reference	Lower calorific value (kJ/kg)	Carbon content	C_F (t-CO_2/t-Fuel)
6 Liquefied Natural Gas (LNG)		48,000	0.7500	2.750
7 Methanol		19,900	0.3750	1.375
8 Ethanol		26,800	0.5217	1.913

Resolution MEPC.364(79) 2022 Guidelines on the Method of Calculation of the Attained EEDI for New Ships.

These emission factors, that is, EEOI and AER are basically to measure and compare operational energy efficiency, while considering that all ships are using same type/s of fuel (that is conventional fossil fuels) with minor differences in their Carbon Factor as can be seen above.

With thrust on carbon emissions, many new fuels are entering marked with wide variation in Carbon factor C_f and thus comparing operational energy efficiency may become difficult and thus IMO is deliberating on changing these factors to as below:

$$\text{EEOI} = \frac{\text{Energy used in GJ (fuel used x Calorific value in MJ/KG)}}{\text{Mass of Cargo Carried x Distance Travelled}}$$

$$\text{AER} = \frac{\text{Energy used in GJ (fuel used x Calorific value in MJ/KG)}}{\text{DWT x Distance Travelled}}$$

2) Lifecycle Greenhouse Gas Emissions to prevent shifting of GHG emissions from downstream to upstream:

a) The low carbon and zero-carbon fuels as seen above have different/diverse production pathways. Some fuels like ammonia and hydrogen on combustion does not produce any greenhouse gas because they do not contain carbon in their molecular structure, yet depending upon production pathway, these fuels can emit large amount of greenhouse during production and transportation.

b) Grey Hydrogen during production emits 132 gm-CO_{2e}/MJ of energy, while on combustion it does not emit any greenhouse gas. However, HFO (Heavy Fuel Oil) emits 13.5 gm-CO_{2e}/MJ during production and 78.1 gm-CO_{2e}/MJ, that is a total of 91.6 gm-CO_{2e}/MJ from production and combustion. When we compare the two fuels, we find that combining both ghg emission during production and combustion makes HFO a better choice to use, while when we compare ghg emitted during combustion only hydrogen is a better choice.

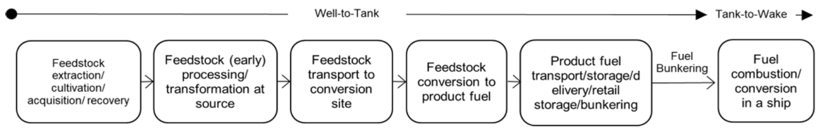
c) If we now intend to replace HFO with Grey Hydrogen, the ghg emissions can be said to shift from combustion to production, that is from downstream to upstream and it may not have any positive impact with respect to global warming. Hence, IMO has decided to use/transit to fuels, with Zero/ Near Zero Lifecycle Emissions and not tank to wake emissions only, that emissions of greenhouse gas from burning fuels.

d) **The life cycle assessment (LCA) methodology refers to answering following two questions**:

- How much greenhouse gas is emitted during production and transportation of this particular fuel to ships tank?
- How much greenhouse gas is emitted when the fuel is combusted? This will depend upon the molecular structure of fuel and amount of carbon present.

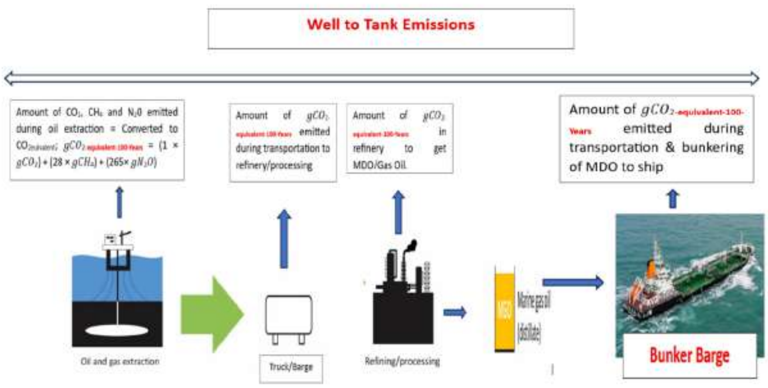
e) LCA is basically assessment of greenhouse gas emissions from the fuel production to the end-use by a ship (well to wake); it results from the combination of a "Well-to-Tank" part (from primary production to carriage of the fuel in a ships tank, also known as upstream emissions) and a "Tank-to-Wake" (also called "Tank to Propeller") part (from the ships fuel tank to exhaust also known as down stream emission).

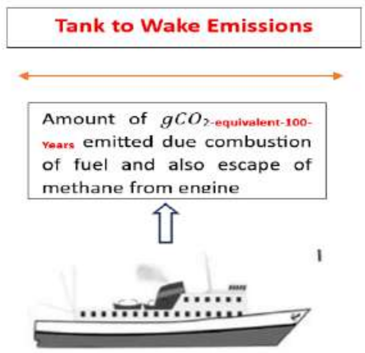
> **Carbon In, Carbon Out, Climate Impact**

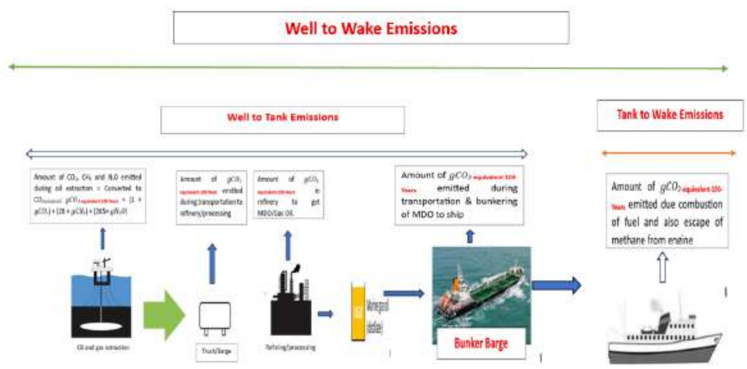


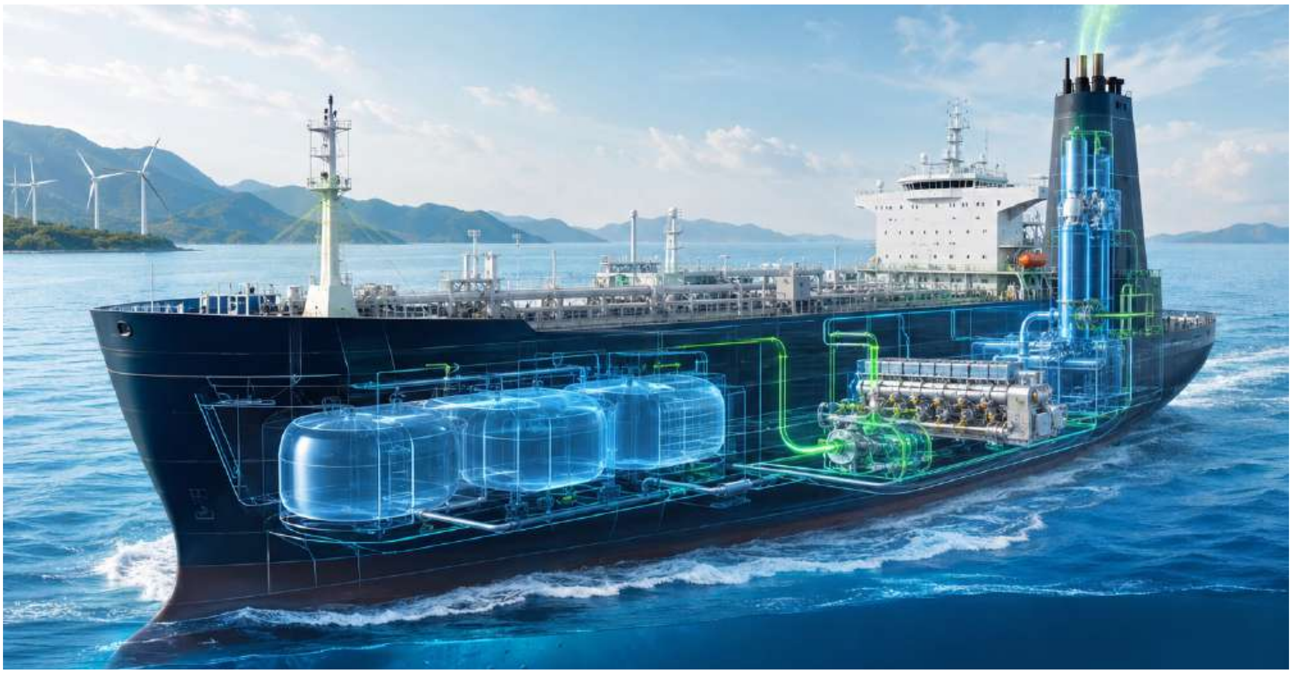
f) As per **OECD {Life-Cycle Assessment of Passenger Transport:** An Indian Case Study; World Bank; Downloaded on 20 May 2026 **Life-cycle assessment of passenger transport (EN)}, the life-cycle assessment (LCA)**, considers not only the carbon emissions from a vehicle's use, but also from its manufacturing, delivery and infrastructure needs. LCAs provide an effective means of understanding the impact of alternative policy choices on greenhouse gas (GHG) emissions.

3) **Explanatory Diagrams Lifecycle Emissions of MDO**









Conclusion

The transition toward green shipping is fundamentally a transition toward a more balanced and sustainable carbon cycle. Understanding the scientific principles governing greenhouse gases, carbon flows, fuel chemistry and lifecycle emissions is essential for evaluating the effectiveness of decarbonisation strategies within the maritime industry. While carbon dioxide remains the dominant greenhouse gas associated with shipping, methane and nitrous oxide can also contribute significantly to climate change and must be considered through appropriate Global Warming Potential metrics.

The analysis demonstrates that fuels cannot be assessed solely based on emissions generated during combustion. Alternative fuels such as hydrogen, ammonia, methanol, biofuels and synthetic fuels may exhibit very different environmental performances depending on their feedstocks and production pathways. A fuel that appears emission-free during ship operation may still possess a high greenhouse gas footprint if produced using carbon-intensive processes. Consequently, lifecycle assessment and well-to-wake greenhouse gas accounting have become indispensable tools for comparing fuels and preventing the transfer of emissions from downstream ship operations to upstream fuel production.

The paper further highlights the importance of distinguishing between fossil carbon and biogenic or renewable carbon sources. Fuels derived from renewable feedstocks, renewable electricity, atmospheric carbon capture and sustainable biomass pathways offer the greatest potential for achieving the IMO's long-term net-zero objectives. However, achieving these goals will require not only technological innovation but also robust regulatory frameworks, transparent carbon accounting methodologies and globally harmonised standards.

As the maritime sector moves toward the implementation of the IMO Net-Zero Framework and future greenhouse gas reduction measures, a comprehensive understanding of fuels and emissions will be crucial for shipowners, operators, policymakers, regulators and maritime professionals. The concepts presented in this paper provide the essential foundation upon which future discussions regarding alternative fuels, lifecycle emissions and sustainable maritime transportation can be built.

References

1) Authors: J.T Houghton, G.J Jenkins and J.J. Ephraums; First Published:1990; Title: Climate Change; Site: IPCC; URL: ipcc_far_wg_I_full_report.pdf
2) Authors: Greenpeace; Prepared by: Janos Maté (Greenpeace International) and David Kanter (Princeton University) Research by: Öko-Recherche GmbH in cooperation with HEAT GmbH (Germany); Downloaded from Google worldwide website on 15th April 2026; Title: The Benefits of Basing Policies on the 20 Year GWP of HFCs; Site URL: Microsoft Word - 2011 GP Report Benefits of 20GWP.doc
3) Authors: Kowtham Raj, NITI Aayog Pranav Lakhina, RMI Clay Stranger; First Published: June 2022; Title: Niti Aayog, Harnessing Green Hydrogen; Downloaded Google Worldwide Network on 16th April 2026; Site: Harnessing_Green_Hydrogen_V21_DIGITAL_29062022.pdf
4) Authors: British Geological Society; Title: The Carbon Story; Downloaded Google worldwide website on 22 April 2026; The carbon story - British Geological Survey
5) IMO Green Voyage; Presentations given to Indian delegates during online training session in 2021; however, can see GreenVoyage2050

About the Author

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

Email: vikrant.rai@gov.in

Regulatory Readiness for Ammonia as An Alternative Fuel to Decarbonise Shipping

Shantanu Paul

Ammonia, as a suitable low-carbon fuel, has gathered momentum in recent years for shipping decarbonisation despite its drawbacks. Newbuilding orders for ammonia-fuelled vessels have zoomed due to the anticipated economic benefits of the proposed NZF of IMO. Hence, regulatory readiness for ammonia as an alternative marine fuel has become a matter of great interest for the maritime industry. Thus, relevant codes were amended; guidelines and notices were issued by the IMO, Flag Administrations and Classification Societies. This article is a snapshot of recent developments on the regulatory front, including NZF, for ammonia to continue its suitability as an alternative marine fuel.

Introduction

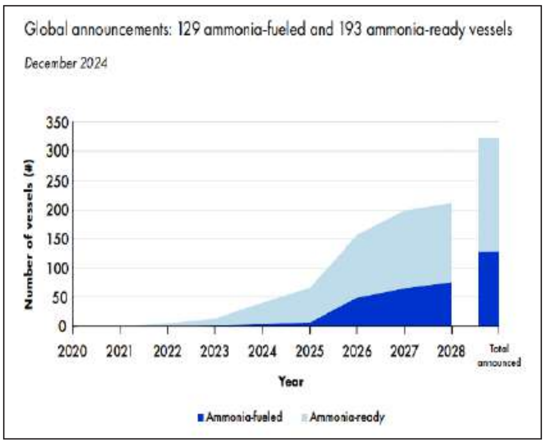
Ammonia as a fuel has emerged as a potential low-carbon option for shipping decarbonizsation, as it can achieve a lifecycle greenhouse gas (GHG) emission reduction of up to 90% based on its production method compared to fossil fuels, despite its drawbacks. Ammonia needs triple the volume of marine fuel oil for the same energy, reducing cargo space and the cost of ammonia-fuelled newbuilds is 15-20% more than conventional designs. The anticipated economic benefits overshadowed such drawbacks due to regulations for international shipping being developed at the IMO and current regulations in the EU (European Union) and EEA (European Economic Area). Ammonia being toxic, its safe and efficient utilisation as an alternative marine fuel requires specific attention. Hence, regulatory readiness became a priority for the IMO and the Flag Administrations, which revolve primarily between the IGC Code and the IGF Code. The application of these codes has often caused confusion and debate, now clarified under the **"one ship one code" policy of the IMO.**

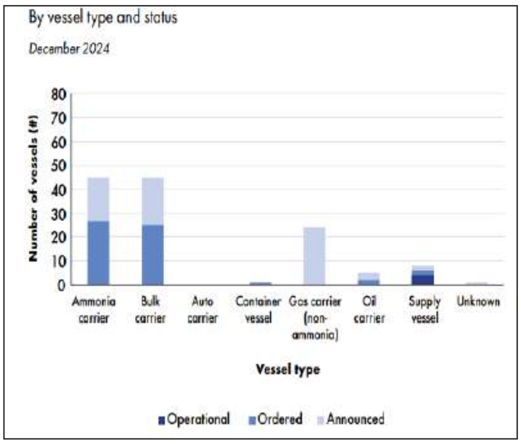
Technology readiness was also continuing at a high pace; large vessels with two-stroke ammonia-powered engines, such as ammonia carriers, as well as bulk carriers, were ordered and scheduled to join the global fleet from 2026

onward. However, recent happenings at the IMO towards adoption of the NZF (Net-Zero Framework) created great regulatory uncertainty, which is apparently affecting all investment scenarios for ammonia to be considered as a suitable low-carbon marine fuel option. The NZF is designed to incentivise shipping economically for the adoption of low-carbon fuels with the required GHG Fuel Intensity (GFI) to achieve the IMO's "Net-Zero" targets by 2050 and ammonia, especially green and blue ammonia, has become suitable to reap the economic benefits. Green ammonia is produced using renewable energy or electricity sources, and blue ammonia is produced from fossil sources with carbon capture and storage (CCS). However, brown ammonia is produced from fossil fuels without carbon emission reduction techniques, which results in higher life cycle emissions than the traditional marine fuels. Accordingly, in the last two years, newbuilding orders for ammonia-fuelled vessels were significant (Figures. 1&2), including in the Indian shipyard Swan Defence and Heavy Industries Limited, which has also secured an order for the construction of four 92,500 DWT dual-fuel ammonia bulk carriers with expected delivery from October 2029. Now, with great uncertainties in the international regulation of IMO and the limited impact of regional EU regulation, which can provide economic benefits, whether the momentum for ammonia-fuelled newbuilding will continue is yet to be seen. The following discussion highlights recent developments in the regulatory readiness for ammonia to continue its merits as a suitable alternative marine fuel.

Regulatory Readiness: IGC Code & IGF Code

IGC Code is the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk and IGF Code is the International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels, other than vessels covered by the IGC Code, operating with gas or low-flashpoint liquids as fuel. Historically, gas carrier regulations for the use of cargo as fuel and the IGC Code, mandatory under SOLAS since 1986, only permitted the burning of natural gas (LNG) as fuel under Chapter 16 (16.1). However, the adoption of the revised (2016) IGC Code by IMO Resolution MSC.370(93)(2) introduced the option to burn other non-toxic cargoes as fuel. This was done for LPG and ethane carriers to burn cargo in dual-fuel engines that operate on both LPG and ethane. While LNG is predominantly methane, LPG is primarily composed of propane and butane. In view of the launch of ammonia-fuelled vessels, MSC 109 in Dec-2024, adopted amendments to Par16.9.2 of the IGC Code to enable the use of ammonia as fuel on ammonia carriers, i.e. cargoes listed in Chapter 19 of the IGC Code can be used as fuel that includes Ammonia anhydrous (UN Number 1005), subject to the requirement of Chapter 16 (16.2), which states all safety features such as gas fuel lines should not pass through accommodation spaces, service spaces or control stations. The gas fuel line should be a double-wall piping system installed in a mechanically exhaust-ventilated pipe or duct, etc.





Source: Ammonia Energy Association, Figure 1 & Figure 2

SOLAS has historically prohibited the use of low-flashpoint fuel oils with a flashpoint below 60˚C, except for emergency generator use, where the limit is 43˚C. The adoption of the IGF Code introduced a framework and requirements under SOLAS for burning fuels with a flashpoint less than 60 Degree ˚C. The IGF Code, entered into force on January 1, 2017, includes detailed prescriptive requirements for natural gas under Part A-1. However, other low-flashpoint fuels, including ammonia, may also be used as marine fuels, provided they meet the intent of the goals and functional requirements of the IGF Code and provide an equivalent level of safety. In the longer term, it is expected that additional parts will be added to the IGF Code (i.e. Parts A-2, A-3, etc.) to cover other low flashpoint fuels as marine industry applications and experience grow. While the carriage of ammonia as cargo has been a common practice for many years, its chemical properties and characteristics, such as flammability, corrosivity and toxicity in particular, differ significantly from conventional fuels and require strict safeguards. Therefore, a common debate continued- which of the current regulations, the IGF or IGC Code, would be more suitable to be applied to "ships other than gas carriers using low-flashpoint fuels" and "gas carriers using low-flashpoint fuels."

Now, with the growing recognition of ammonia's potential as a marine fuel in support of decarbonisation goals, the IMO in February 2025 clarified the application of the IGF Code and amendments to SOLAS Chapter II-1 were approved at MSC 109 to ensure gaseous fuels, including ammonia, are explicitly covered. The IMO issued the Interim Guidelines for the Safety of Ships Using Ammonia as Fuel (MSC.1/Circ.1687). This guideline is for ammonia as fuel, either in its liquefied or gaseous state. This will certainly help designers with a regulatory framework to work with until binding Code amendments are in place. Indeed, the Interim Guidelines are closely aligned with the IGF Code. It is non-mandatory, covering ship design, equipment, operations, bunkering, toxicity, crew protection, etc. and Administrations/industry are to take into account and apply, as relevant, the applicable regulations of the IGF Code. However, divergent views on the application of the IGC Code and the IGF Code have often caused confusion and debate, which has now been clarified under the '**one ship one code' policy** of IMO. A ship subject to IGC Code should not additionally be subject to IGF Code, even when using low-flashpoint fuels that are not carried as cargo, such as a gas carrier using ammonia (a listed cargo under Chapter 19 of the IGC Code) as an alternate fuel. Also, the IGF Code should not apply to ships using gaseous or low-flashpoint fuels not listed in Chapter 19 of the IGC Code, which would be addressed by specific guidelines for such ships to be developed. Further, except for ships subject to the IGC Code burning cargo as fuel, the IGF Code applies to new ships and ship conversions, over 500GT using low-flashpoint fuels for which the building contract is on or after 1 Jan 2017 or keel laid on or after 1 July 2017 or delivery of which is on or after 1 January 2021.

Also, due to specific properties and toxic characteristics of ammonia, which is life-threatening if exposed to high concentrations, seafarers on board ships using ammonia fuel should complete training to attain the abilities that are appropriate to the capacity to be filled and responsibilities to be taken up. The master, officers, ratings and other personnel on ships using ammonia fuel should be trained and qualified in accordance with Section A-V/3 of the STCW Code, i.e. IGF Course (basic and advanced training course), taking into account the specific hazards of ammonia used as fuel. The application of the IGF Code for Indian flag vessels is mentioned in the MS Notice No. 06 of 2024 and for rules, i.e. MS (Use of Liquefied Gases as Fuel Appliances) Rules, 2026, is now under discussion.

Ammonia: Regulatory Advantage & Industry Interest

Due to high industry interest in ammonia-fuelled vessels, many classification societies have issued guidelines and granted Approval-in-Principle certificates for ammonia-fuelled ships developed by shipyards and engine manufacturers. In September 2025, the Indian classification society IRS (Indian Register of Shipping) also published guidelines on ammonia-fuelled vessels. Ammonia burns carbon neutrally, but produces NOx. However, the latest ammonia-fuelled large engines are compliant with IMO Tier II NOx emission limits without a DeNOx system and are compliant with IMO Tier III NOx emission limits with a DeNOx system. Ammonia is gaining traction as a marine fuel primarily due to its potential to reduce GHG emissions on a well-to-wake

basis and financial incentives associated with it, mainly the proposed NZF and newly introduced Fuel EU Maritime. Unlike existing IMO tools such as CII (Carbon Intensity Indicator) and EU rules, i.e. EU ETS (Emissions Trading System), which are tank-to-wake systems for carbon dioxide emissions, the NZF is a well-to-wake system for GHG emissions and is quite similar to the Fuel EU Maritime, but the NZF is less stringent in terms of GFI (gCO2eq/MJ) compliance; and non-compliance will attract some financial penalty for both. This is where the advantage lies with ammonia, green and blue, hence being considered a suitable candidate among other alternative fuel options for decarbonisation to achieve the Net Zero target.

Net-Zero Framework (NZF): Recent Developments & Industry Impacts

The NZF, which was provisionally agreed in April 2025, was due for adoption at IMO in October 2025, but failed due to strong opposition and threats from many oil-producing countries, mainly the USA, resulting in a one-year deferment. With the current world order and geopolitics, diplomacy and compromise through scientific, evidence-based decision-making have all been thrown out of the window. In March 2026, it was reported that a USA submission to the IMO had officially called for the total abandonment of the NZF. Hence, the USA-led objection to undermine the NZF in its current form is expected to be much higher at the upcoming IMO meetings. It is also reported that the USA demands that similar regional schemes, such as the EU emission rules, should be phased out. Under the circumstances, the prospect of ammonia continuing as a suitable marine fuel is extremely low, at least in the short-term. This regulatory uncertainty is causing some shipowners to revert to conventional engines rather than committing immediately to the more costly ammonia option. However, it is yet to be seen if the long-term shipping forecasts can hold the ammonia momentum, as IMO Member States are still committed to achieving net zero by or around 2050 as per MEPC 84.

Conclusion

The potential failure or significant delay in the relevant regulatory readiness, such as NZF, creates huge uncertainty for the adoption of ammonia as an alternative fuel. While ammonia remains a top candidate for decarbonising shipping, a weak or delayed regulatory framework leaves the near-term path for ammonia-fuelled vessels in limbo, even if other technical rules and developments progress. Ammonia became a choice as a suitable marine fuel due to the economic benefits derived under the relevant EU regulation and mainly the NZF of the IMO, which may become effective in the long run, may be in a different form, as MEPC 84 (27 April -1 May 2026) shows less hope for the proposed NZF. Hence, at this juncture, “wait and watch” may be a good strategy for new-building investments, as it is followed by some shipping companies, rather than opting for the conventional engine option!

Reference

1) *ABS advisory on gas and other low-flashpoint fuels of 2019*
2) *Class NK Technical Journal No 5 of 2022*
3) *IGC Code and IGF Code of IMO*
4) *MS Notice No. 06 of 2024 of DGS*
5) *MSC.1/Circ.1687, 26 Feb- 2025*
6) *News Brief: MSC 110 by ABS*
7) *News Brief: CCC 11 by ABS*
8) *IMO CCC 10: Interim Guidelines by DNV*
9) *Fuel for thought: Ammonia report by LR*
10) *IMO issues interim guidelines for the safety of ammonia-fuelled ships by BIMCO*
11) *Ammonia as a marine fuel: Prospects and challenges by DNV*
12) *Rules and Guidance for Ships Using Low-flashpoint Fuels by KR*
13) *Preliminary discussion report on the use of ammonia as fuel for ships by MTF*
14) *FAQs on the EU-ETS for shipping by Class NK*
15) *Guidelines on ammonia-fueled vessels, Revision 1, IRS, 2025*
16) *Jeffries (2025) IMO NZF delay- newbuildings will shift back to conventional engines*
17) *Wang, H, et al. (2025), Life cycle analysis of ammonia fuelled ship – case ship studies for marine vessels*
18) *Savvides, N. (2026), US hubris risks shipping's regulatory consensus and stability, Seatrade Maritime News, March 24, 2026.*
19) *Sagar Sandesh, US makes the case to torpedo 'flawed' Net-Zero Framework, March 20, 2026*
20) *MEPC 84 Summary Reports, May 2026 by Lloyd's Register*

Note: The opinion(s), view(s) and conclusion(s) expressed in this paper are purely the Author's personal

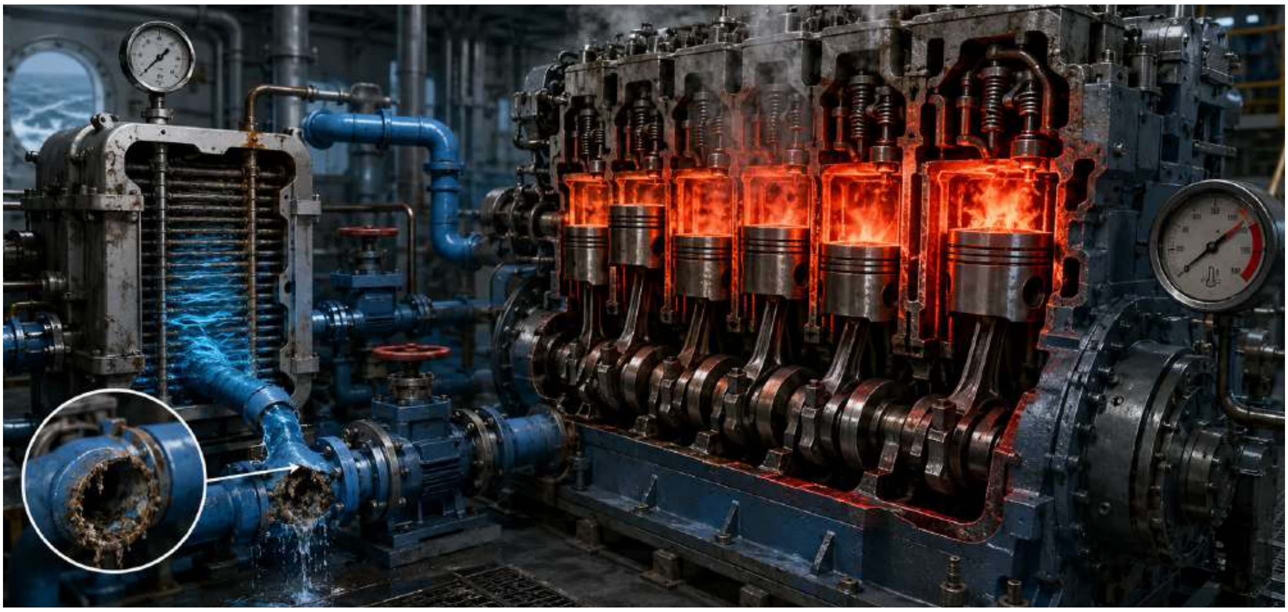
About the Author

Dr Shantanu Paul is a First-Class Marine Engineer, WMU (Shipping Management) and PhD (Management). He has worked for 25 years with The SCI Ltd, of which 10 years were at MTI Powai as faculty and Dean. He has published many articles in reputed national and international journals. Currently, he is associated with IMU Kolkata as a faculty and MEO Class-1 course coordinator.

Email: imuspkol@gmail.com

Cooling Water, Hot Trouble: Overheating and Thermal Distress of Marine Engines

Marine Engineering Accident Investigation Series – Marine Engineers' Review (MER)



Gajanan Karanjikar

Introduction

Marine propulsion engines operate within carefully controlled thermal limits, where effective cooling is essential for maintaining reliability, efficiency and structural integrity. While engine overheating is often perceived as an isolated machinery malfunction, accident investigations repeatedly demonstrate that it is usually the result of progressive deficiencies within the cooling system. Scaling, biofouling, reduced pump performance, uneven flow distribution and inadequate monitoring can gradually erode the thermal margins designed into marine machinery.

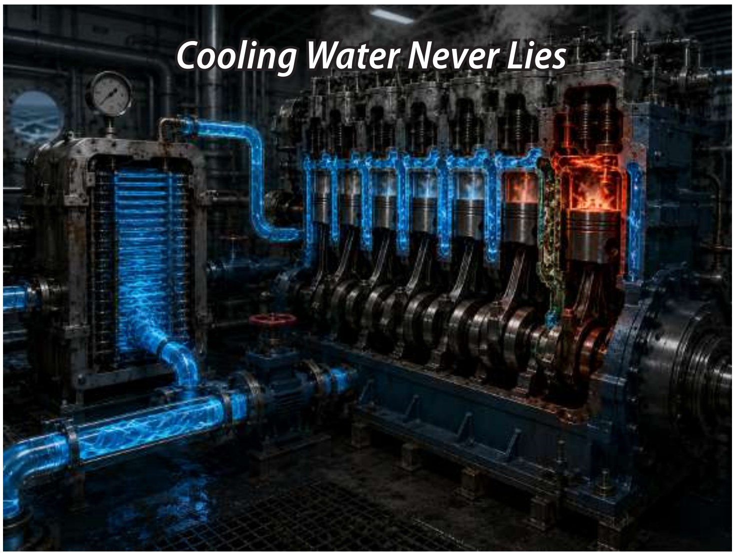
The consequences of cooling system failures extend far beyond elevated temperatures. Thermal distress can lead to piston scuffing, cylinder liner damage, exhaust valve failures, lubricating oil degradation, automatic engine slowdowns and complete loss of propulsion system. In congested waterways or environmentally sensitive regions, such failures may escalate into collisions, groundings, pollution incidents and substantial commercial losses.

This article examines the role of cooling water systems in marine engine casualty investigations, emphasising the importance of identifying root causes rather than focusing solely on the final machinery failure. Through the analysis of scaling, biofouling, hydraulic performance, temperature-profile reconstruction and maintenance practices, the article provides investigators, operators and marine engineers with a structured methodology for diagnosing overheating incidents. It also highlights the relevant regulatory framework under SOLAS, the ISM Code, classification society requirements and the legal implications arising from preventable cooling system deficiencies. By understanding the thermal history of machinery failures, stakeholders can move beyond symptom-based troubleshooting and adopt a more proactive approach to machinery reliability and safety.

In addition to the technical aspects, the paper addresses the legal and financial consequences that may arise when propulsion loss, engine damage, or navigational incidents are linked to inadequate cooling-system management. The findings demonstrate that effective cooling-water management is not merely a maintenance concern but a critical reliability barrier essential to vessel safety, operational continuity and regulatory compliance. A disciplined approach to monitoring, maintenance and investigation can significantly reduce the likelihood of thermal distress and prevent costly marine casualties.

Abstract

Engine overheating remains one of the most common precursors to serious marine machinery failures and propulsion losses. Although high-temperature alarms, piston seizures, liner scuffing and thermal cracking are often treated as the primary failures, accident investigations frequently reveal that the true causes originate within deteriorating cooling-water systems. This article explores the mechanisms through which scaling, biofouling, degraded pump performance, poor flow



distribution and ineffective temperature control contribute to progressive thermal distress in marine engines.

Keywords: Marine engine overheating; Cooling water systems; Thermal distress; Accident investigation; Scaling; Biofouling; Heat transfer; Pump performance; Flow distribution; Temperature-profile reconstruction; Propulsion failure; Jacket water systems; Machinery reliability; ISM Code; SOLAS compliance; Condition monitoring; Marine casualty investigation; Engine cooling efficiency; Root cause analysis; Predictive maintenance.

Marine engines seldom overheat without warning. Long before a piston starts scuffing, a cylinder liner begins to distort, or an exhaust valve suffers thermal distress, the cooling system has usually been offering clues: rising differentials, uneven temperatures, weak flow, unexplained fouling, or recurring alarms that were acknowledged but not deeply investigated. This article examines accident investigation techniques for marine engine overheating, with particular focus on scaling, biofouling, pump performance, flow distribution and temperature-profile reconstruction. It also outlines the regulatory framework under SOLAS, the ISM Code and class expectations and discusses the legal and financial exposure that owners may face when loss of propulsion, engine damage or navigational incidents can be traced to cooling system neglect or poor diagnosis. SOLAS Chapter II-1 addresses machinery and electrical installations as part of the ship's safety framework, while the ISM Code establishes the standard for safe management and operation of ships and pollution prevention.

1. The cooling system rarely lies

Among all shipboard systems, cooling water is one of the most deceptive. It appears humble, routine, almost secondary to the "real" work of combustion and propulsion. Yet cooling water determines whether metal remains within its designed thermal limits or crosses into distortion, loss of lubrication, cracking and seizure. In accident investigation, this is a crucial point: overheating is rarely a primary failure by itself. More often, it is the visible consequence of hidden deficiencies in heat transfer, circulation or temperature control.

When a main engine overheats, the immediate symptoms may include high jacket water temperature, exhaust temperature imbalance, reduced power, lubricating oil breakdown, piston seizure or even automatic slowdown and shutdown. But the investigator must resist the temptation to stop at the final symptom. The real question is not simply why the engine became hot, but why the cooling medium failed to remove heat where and when it should have done so.

2. How thermal distress begins

Marine engines rely on a balanced thermal regime. Jacket water, piston cooling oil or water, charge air cooling, lube oil cooling and in many cases central cooling systems all work together to control the heat generated by combustion. A disruption anywhere in this network can create local hot spots.

The earliest mechanisms are often ordinary and cumulative. **Scaling** narrows heat transfer passages and insulates surfaces from coolant. **Biofouling** in sea chests, coolers and piping reduces flow and undermines exchanger performance. **Weak pump performance** reduces circulation rates, particularly under manoeuvring or hot-weather conditions. **Poor flow distribution** inside cylinder jackets or through multi-pass coolers means some units receive less effective cooling than others. Over time, this produces uneven metal temperatures, thermal stress and differential expansion.

By the time the chief engineer sees a high-temperature alarm, the process may already be advanced. That is why accident investigation into overheating must be as much about thermal history as about the final breakdown.

3. Scaling: the slow thief of heat transfer

Scaling is one of the oldest marine engineering problems and still one of the most underestimated. Calcium salts, corrosion products, silicates and treatment residues build up on heat transfer surfaces and gradually reduce both flow area and thermal conductivity. The engine may continue to run, but the cooling system is quietly losing efficiency.

In post-incident investigation, scaling should not be treated as "poor housekeeping" alone. It may be central causation. Deposits inside cylinder liners, cylinder heads, charge air coolers and fresh water coolers create a thermal barrier. Metal temperatures rise locally, lubricating films weaken and components experience expansion beyond design assumptions. What finally emerges may be piston ring sticking, liner polishing followed by scuffing, cracked heads, or abnormal exhaust temperatures.

The investigation should therefore document not just the existence of scale, but its **extent, location and likely age**. Was scaling uniform, suggesting long-term neglect of water chemistry? Or was it concentrated in low-flow regions, indicating distribution defects? Samples should be analysed where practicable. The chemistry of the deposits may reveal whether the root issue was poor treatment control, use of unsuitable make-up water, or contamination from another system.

4. Biofouling: living growth, dead machinery

Sea-water cooled systems invite life. Marine growth, slime, shell fragments and biological films in sea chests, strainers, coolers and overboard lines can significantly reduce flow and exchanger performance. In warm waters, this process can accelerate dramatically.

Biofouling is especially dangerous because it often produces **intermittent performance loss**. The vessel may run satisfactorily in cool climates but struggle in tropical waters or at sustained high load. Engineers then respond tactically, opening bypasses, increasing pump use, throttling elsewhere, without appreciating that the system has already lost its original margin.

In a casualty investigation, biofouling must be treated as a dynamic operational hazard. The team should inspect sea chests, cooler tubes, sea strainers and branch lines and compare actual internal condition with planned maintenance records. If there were prior complaints of marginal cooling, repeated cleaning of strainers, or unexplained jacket-water trends, those become important evidence of foreseeability. Where the owner knew or ought to have known that cooling efficiency was deteriorating, the legal picture changes substantially.

5. Pump performance: flow lost in plain sight

A cooling system is only as good as its circulation. Pump wear, cavitation damage, loosened impellers, eroded wear rings, air ingress on suction, incorrect rotation after maintenance, or simply degraded pump curves can all reduce delivered flow.

Pump problems are particularly important in accident reconstruction because they can hide behind apparently normal pressure readings. A pump may show pressure yet deliver insufficient volume under real engine demand.

The investigator should therefore look beyond gauge indications and reconstruct **actual hydraulic performance**.

This may involve:

- Reviewing past suction and discharge pressure logs.
- Checking motor current and comparing with expected duty.

- Examining impeller condition, clearances and signs of cavitation.
- Assessing whether the system was operating near the limit of available NPSH.
- Determining whether standby pumps were available, operative and properly used.

Where two pumps operate in parallel or duty/standby mode, the failure history matters. A ship that repeatedly depended on one "good" pump while treating the other as unreliable was already signalling vulnerability. Under the ISM philosophy, repeated workaround operation is not benign; it is evidence that critical equipment management may have been inadequate. The ISM Code is intended to provide an international standard for safe management and operation of ships and for pollution prevention.

6. Flow distribution: when one cylinder runs hotter than the rest

One of the most revealing aspects of overheating investigations is temperature asymmetry. Engines rarely heat uniformly when cooling faults are involved. One bank, one liner, one cover, one cooler section, or one branch circuit may run significantly hotter.

That is why **temperature-profile reconstruction** is such a powerful tool. Instead of asking only whether the engine overheated, the investigator asks how heat was distributed across the machinery before failure. This can be reconstructed from alarm logs, engine monitoring trends, infrared images if available, manual watchkeeping records and physical evidence such as discoloration, varnish patterns, gasket distress and localised material degradation.

Flow distribution faults may arise from partially blocked branch passages, incorrect or stuck thermostatic valves, trapped air pockets, temporary maintenance errors, or design weaknesses that only become evident under certain loads. A cylinder that consistently ran hotter than its neighbours before the casualty may indicate long-standing local flow starvation rather than a sudden global problem. In legal disputes, such data can be highly significant because it tends to show that the failure was progressive and diagnosable, not truly sudden.

7. Temperature-profile reconstruction after the casualty

Post-accident reconstruction should combine documentary, digital and physical evidence. The best investigations proceed almost like medical diagnosis after fever and collapse.

First, gather all available **temperature history**: jacket-water inlet and outlet logs, individual cylinder exhaust temperatures, lube oil temperatures, cooler differential temperatures and alarm timestamps. Second, correlate these with operational context: manoeuvring, ambient sea-water temperature, fuel changeover, reduced engine speed, heavy weather or recent maintenance. Third, inspect the failed components for **thermal signatures**: blued metal, coked oil, seized rings, hardened seals, cracked paint, warped valve cages or differential expansion marks.

This reconstruction often reveals a thermal narrative. The engine may have been running acceptably at sea, then entering warmer waters with partially fouled coolers. One pump may have been underperforming. A thermostatic valve may have begun hunting. Flow to one section weakened. That cylinder's temperatures drifted higher over several voyages. Finally, under heavy manoeuvring, the margin vanished and the component failed.

Such reconstruction transforms "engine overheated and failed" into a defensible technical explanation.

Weak Flow, Strong Consequences

8. Codes, conventions and class expectations

Although no single convention is titled “cooling water management,” the applicable framework is clear. SOLAS Chapter II-1 covers machinery and electrical installations and is intended to ensure that essential services supporting ship safety are maintained. IMO describes the goal of machinery installations under the chapter as providing required functionality for safe navigation and safe carriage.

The ISM Code requires companies to establish safe management systems, including procedures for maintenance of ship and equipment, reporting non-conformities and corrective action. Where a ship experiences recurring cooling inefficiency, rising temperatures or repeated alarm events without proper root-cause analysis, the issue is no longer merely technical; it enters the realm of management system failure.

Classification societies also impose machinery survey and maintenance expectations and modern condition monitoring practice is increasingly guided by standards such as ISO 17359:2018, which gives general guidelines for setting up machine condition monitoring programmes. While not a statutory convention in itself, it is relevant where owners rely on trend monitoring and predictive maintenance to manage machinery risk.

9. Legal consequences and financial damage to the owner

Overheating casualties can become expensive very quickly. The direct costs are obvious: damaged pistons, liners, bearings, cylinder heads, coolers, pumps and associated labour. Dry-docking, spares logistics, class attendance and expert attendance add further expense. If the vessel loses propulsion in restricted waters, the cost escalates to tug assistance, towage, emergency repairs and schedule collapse.

But the larger exposure often lies beyond the engine room. If the vessel grounds, collides, blocks a channel or delays cargo due to propulsion loss traceable to preventable thermal distress, the owner may face off-hire claims, charterparty disputes, cargo claims and infrastructure claims. If environmental damage follows, the matter becomes even more serious. In court or arbitration, the decisive question is often whether the owner exercised **due diligence** to keep the vessel seaworthy and to maintain critical machinery properly.

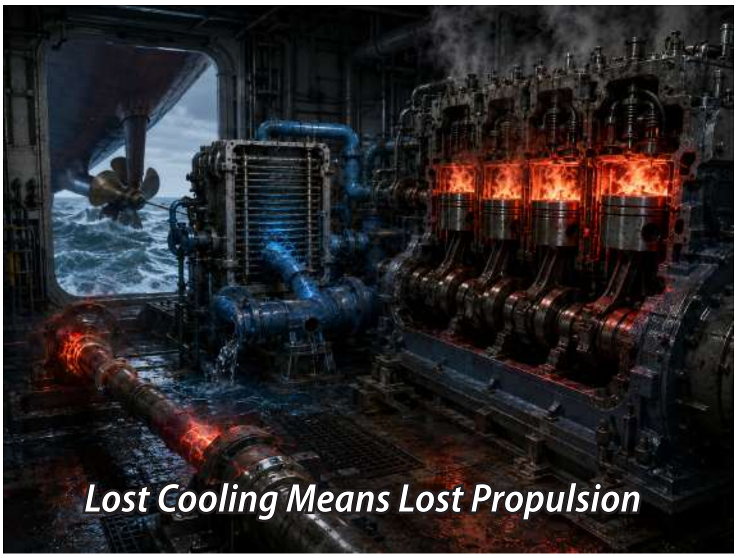
A cooling-water problem that had been “managed” through repeated temporary cleaning, manual valve adjustment or alarm acknowledgement can look deeply unattractive under legal scrutiny. The owner may argue that the failure was sudden. The claimant will argue that the warning signs were present for weeks or months. Temperature logs, maintenance records, chemical treatment records and crew reports become central evidence.

Insurers, too, will look closely at whether the machinery failure was fortuitous or the product of deferred maintenance and weak technical management. Thus, cooling water neglect can move from a technical nuisance to a major liability event.

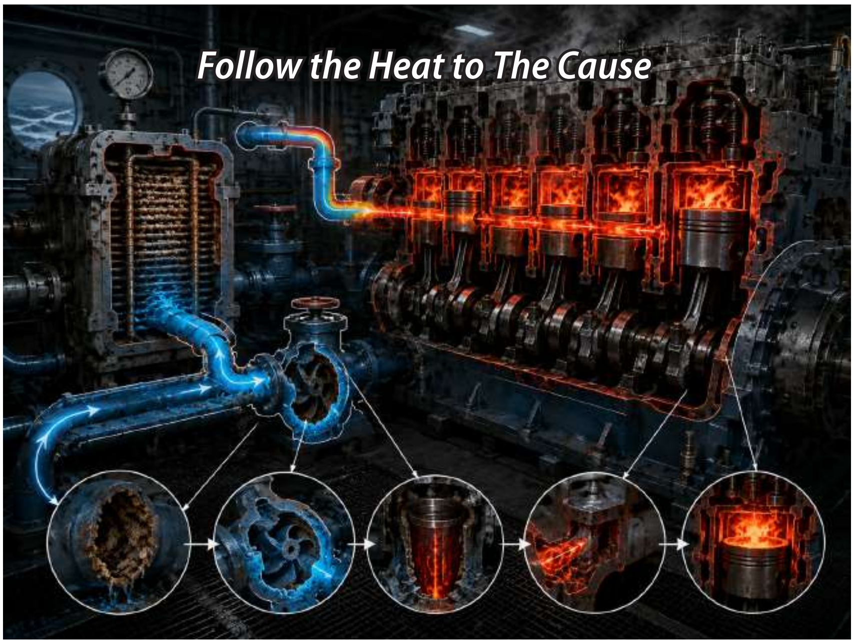
10. Lessons for accident investigators and operators

The central lesson is that overheating should never be investigated as a single-temperature problem. It is a **system problem** involving chemistry, biology, hydraulics, materials and control.

Investigators should therefore adopt a methodical structure:



Lost Cooling Means Lost Propulsion



Begin with the top event: overheating, thermal distress or propulsion loss. Trace backwards through temperature trends, flow performance, exchanger condition, pump capability, valve logic, water chemistry and maintenance history. Compare affected and unaffected cylinders or circuits. Reconstruct the thermal map. Ask not just what failed, but what margin was lost, when it was lost and whether the ship's systems and management should have detected it earlier.

Conclusion

Marine engine overheating is rarely a sudden or isolated event. In most cases, it represents the culmination of progressive deficiencies within the cooling system that have gradually reduced the machinery's ability to dissipate heat effectively. Scaling, biofouling, reduced pump efficiency, flow maldistribution and inadequate monitoring often develop over extended periods, providing numerous warning signs before thermal distress ultimately manifests as machinery damage or propulsion loss.

Effective accident investigation therefore requires a holistic approach that examines the complete thermal history of the machinery rather than focusing solely on the failed component. Temperature trends, hydraulic performance data, maintenance records, water-treatment practices and physical evidence must be integrated to reconstruct the sequence of events leading to the casualty. Such investigations frequently reveal that overheating incidents are both foreseeable and preventable when early indicators are properly recognized and addressed.

From an operational perspective, cooling-water systems should be regarded as critical safety and reliability barriers rather than auxiliary support services. Regular monitoring of temperature profiles, systematic performance testing of pumps and heat exchangers, disciplined water-treatment programs and prompt investigation of recurring alarms are essential elements of sound machinery management. These practices align with the expectations of SOLAS, the ISM Code and modern condition-monitoring philosophies.

Ultimately, the lessons from overheating casualties reinforce a fundamental engineering principle: machinery failures rarely occur without warning. Cooling systems communicate their deteriorating condition through changes in temperatures, pressures and flow characteristics long before catastrophic damage occurs. Organizations that listen to these signals, investigate them thoroughly and act proactively will significantly enhance vessel reliability, reduce operational risk and avoid the substantial legal, financial and safety consequences associated with thermal distress and propulsion failure.

For operators, the message is equally plain. A cooling system must be treated as a critical reliability barrier, not an auxiliary support service. Trending, water treatment discipline, periodic performance testing of pumps, cooler inspection and temperature-pattern analysis should all be part of serious machinery management.

Because when cooling water begins to fail, the engine almost always starts speaking first in degrees Celsius, long before it speaks in broken metal.

About the Author

Capt. Gajanan Karanjikar, Master Mariner and US-based casualty investigator, brings decades of sea and shore experience in vessel command, surveys and forensic investigations, advancing safety, seamanship and compliance globally.

Email: captgajanan@gmail.com

Reference list

1. International Maritime Organization (IMO) (1974, as amended) *International Convention for the Safety of Life at Sea (SOLAS).* London: IMO.
2. International Maritime Organization (IMO) *Ship Design and Stability / SOLAS Chapter II-1 overview*, including machinery and electrical installations. London: IMO.
3. International Maritime Organization (IMO) *The International Safety Management (ISM) Code.* London: IMO.
4. International Maritime Organization (IMO) (2017) *Revised guidelines on the implementation of the ISM Code by Administrations (Resolution A.1118(30)).* London: IMO.
5. International Organization for Standardization (ISO) (2018) *ISO 17359:2018 Condition monitoring and diagnostics of machines, General guidelines.* Geneva: ISO.
6. International Maritime Organization (IMO) (2008, as amended) *Code of the International Standards and Recommended Practices for a Safety Investigation into a Marine Casualty or Marine Incident (Casualty Investigation Code).* London: IMO.

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. Shashaank Gaur, Ms. Sukhjeet Kaur, Mr. Suresh Kumar

INMARCO 2026
STUDENTS' CORNER

27th to 29th October 2026 | Mumbai

The INMARCO (International Maritime Conference & Exhibition) is a quadrennial event hosted by the Mumbai Branch of Institute of Marine Engineers (India) since 1982.

THE CONFERENCE OFFERS

- Platform for students to network and connect with industry leaders.
- Opportunity for students to demonstrate their skills in activities specially curated for them.
- Forums for MTIs to showcase their capabilities.

ATTENTION STUDENTS

Inviting all students to Show Off their talents in INMARCO 2026

INSTRUCTIONS

Scan the QR code of the competition you want take part in.
Download / Read the guidelines and instructions carefully and follow as advised.

MODEL MAKING	POSTER / CARTOON MAKING	VIDEO MAKING
CUTOFF date for Concept Submission:	CUTOFF date for Submission:	CUTOFF date for Submission:
30 - June - 2026	**15 - July - 2026**	**15 - July - 2026**

Flaunt your SKILLS, not your Wealth

Be a Brand Ambassador of your Institute

This is a quick Access Flyer for Students.
Official e-mails have been sent to all MTIs by Students Committee of INMARCO 2026.

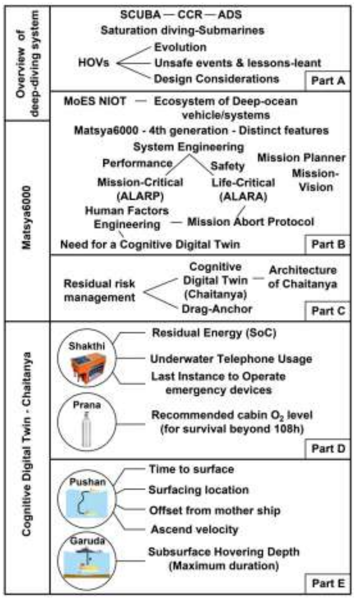
Cognitive Digital Twin "Chaitanya" for India's Deep-Ocean Human Submersible Matsya6000-Part D

N. Vedachalam, VBN Jyothi, J. Preetha Roselyn, G. Harikrishnan, Tamshuk Chowdhury, S Ramesh

Abstract

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

AI Predicts Emergencies Before Humans Can



Description of sub-modules of CDT Chaitanya

Emergency Power System of Matsya

Emergency Power System (EPS) of Matsya6000 is powered by two sets of 24V-2.5kWh lead-acid batteries located inside the human cabin (HC). Considering safety as the priority, matured lead-acid chemistry is used. Their capacity is sized to cater power/energy to the life-critical systems (LCS) during the emergency period of 96h. Based on the Emergency Operating Protocol (EOP), CO_2 scrubbers, Underwater Acoustic Telephone (UAT), shape-memory alloy (SMA) based actuators (of emergency drop weights, jettisoning and emergency rescue buoy) and HC lighting shall consume 62%, 8%, 6% and 4% of energy. About 20% of energy is for surface communication.

> *Chaitanya Thinks Ahead, Humans Stay Safe*

What are the hard-to-predict-scenarios/HTPS in the EPS?

HTPS-1

During the emergency period, when lead-acid batteries are discharging, predicting the real-time before which the emergency systems should be operated (so that they operate reliably above the device-specific voltage threshold) should be made known to the Matsya pilot in-advance, so that the availability of power/energy for operating the emergency systems is ensured till 96h. In addition to this, the real-time at which the battery's State of Charge (SoC) goes < 20% is to be informed to the pilot in-advance for advancing actions. **Figure.1** describes the voltage drop in a typical Pb-acid battery as a function of residual SoC & discharge current. These are the HTPS.

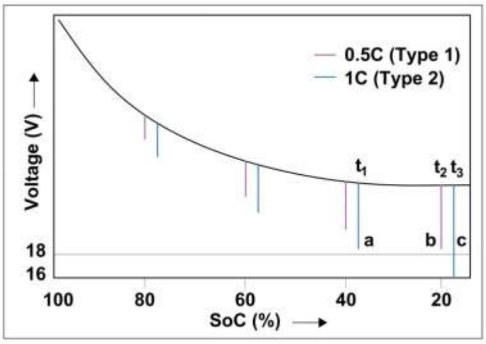


Figure.1. Discharge characteristics of lead-acid batteries at various SoC

The C-rating (during discharge) of a battery indicates its maximum safe discharge current, expressed as a multiple of its total capacity. For example, 1C rating on a 100Ah battery means it can be discharged at 100A for 1h, while 0.5C rating would allow a discharge of 50Afor 2h. The discharge performance of the battery under 0.5C load (Type-1) and 1C load (Type-2) is explained for understanding with reference to **Figure.1.** Assuming both types of loads require operating threshold voltage >18VDC, under the ongoing discharge pattern, it is required to understand the real-time up to which the battery could support their operations. With reference to **Figure.1,** by performing simulations ahead-of-time, it can be predicted that the battery could support Type-1 load only up to time t_2 (until SoC >40%), after which voltage falls below 18V. Likewise, the battery could support Type-2 load only until time t_1 (SoC >40%), after which voltage falls below 18V (refer t_3).

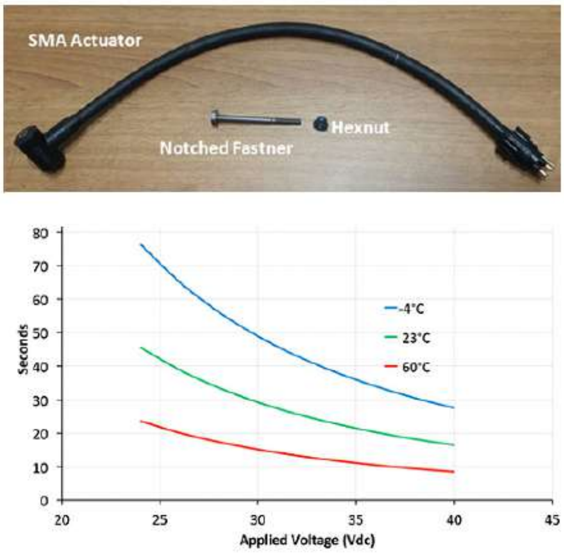


Figure.2. Frangibolt used in emergency device actuators

The shape-memory alloy (SMA) based actuators of LCS including emergency drop weights (EDW), emergency jettisoning systems (EJS) (including trim, manipulators and sampling tray) and the emergency rescue buoy/ERB) operated using multiple frangibolts (FB). Based on system weight, the number of FB used varies from 1 to 8. The basic principle of the FB relies on a pre-compressed SMA tube and a titanium bolt with a special notched section which is positioned through the cylinder and restrained at either end. When heated up to a temperature of ~ 90˚C, the SMA undergoes a phase change (from martensitic to austenite) returning to its original size thus developing enough tensile force to fracture the notched section of the FB. Redundant DC voltage powered heaters wrapped around the SMA generate heat for activation. The mechanism without any moving parts makes it reliable compared to other mechanisms. Since its invention in 1992 and its first application in spacecraft Clementine in 1994, the FB has attained unparalleled reliability.

The activation duration of the subsea FB depends on the applied voltage and ambient ocean water temperature **(Figure.2).** A DC-DC converter in the EPS provides constant voltage to the FB, until the battery voltage goes below 18V. As an example, during emergency, jettisoning of the trim system at 40% battery SoC results in a battery voltage drop from 23 to 20V, while at 20% SoC, the same operation results in voltage drop to <18V, which is insufficient to jettison. **Based on the ongoing current discharge profile, the real-time at which battery voltage drops below the thresholds of the LCS, that depends on the SoC and the current demand, are HTPS for the pilot/crew**.

HTPS-2

During the 12h mission, the Underwater Acoustic Telephone (UAT) shall be utilised every 30min to have voice communication between Matsya and the mother ship. Upon failure of voice communication, it is necessary that subsea mission has to be terminated and Matsya has to return to the sea surface. During the emergency period of 96h (energy-rationed scenario as per EOP), there are possibilities that the UAT is used more frequently (>2 times/h) by the crew to understand the status of recovery operations. Increased usage of UAT results in increased energy consumption from the batteries (than the allocated budget of 8%) which will affect the energy availability for other devices (such as scrubbers) to serve the remaining emergency period. Hence the utility of the UAT has to be restricted during the remaining emergency period. The question of "**If the UAT is restricted due to prior increased usage, then what is the allowable usage during the remaining emergency period**?" **is a HTPS for the crew**.

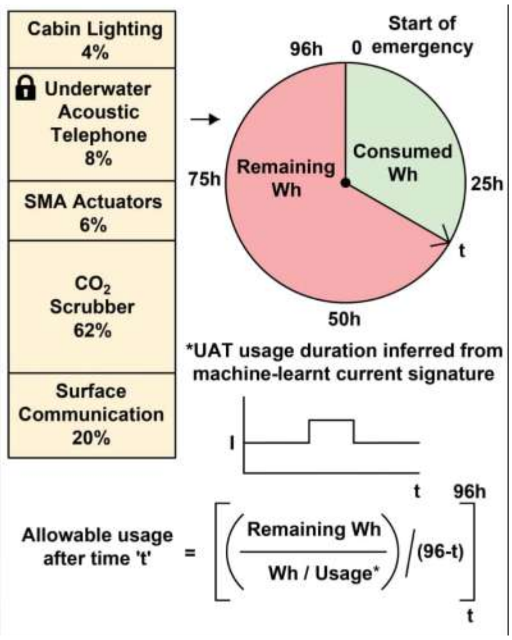


Figure.3. Energy rationing and restricting increased UAT usage

The methodology adopted for predicting the allowable futuristic usage, provided the UAT's energy utilisation is with its allocated budget is described in **Figure.3.** With the UAT usage energy inferred from the machine-learnt battery current signature, the cumulative energy consumed by UAT with time is computed, from which remaining UAT energy budget is calculated, based on which the allowable usage rate (usages/h) for the remaining period is determined, from any point of time.

Chaitanya- Shakthi

The architecture of Shakthi module developed to support the crew during the above HTPS is represented in **Figure.4.** At the core of Shakthi is the precise mathematical model of the lead-acid battery (third-order electrical equivalent circuit incorporating thermal effect, nominal and pulse discharge response). The pulse discharge represents the operation of the FB. It's priori inputs (A) include the ambient temperature (AT) profile inside the HC at various ocean depths, characteristics of the emergency devices and actuators and the mandatory reserve energy (B). With the load current input (C) in real-time from the emergency batteries as the **"only"** input, Shakthi takes into consideration the characteristics of the lead-acid battery chemistry, emergency devices and the dynamic ambient temperature conditions inside the HC (when Matsya is operating at different ocean depths), energy utilised, energy requirements for the remaining /extended mission period, surface communication and contingency energy as constraints, redefines the EOP(E) ensuring the power supply/energy availability during the entire period of emergency, thus ensuring human safety. Based on the input (D) and situation-awareness (current V and residual SoC), Shakthi issues the revised EOP (E) ensuring power/energy availability till the extended emergency period (T_F).

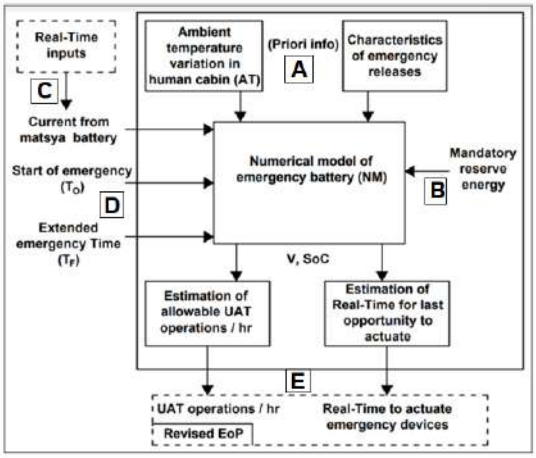


Figure.4. Architecture of Shakthi module

Human cabin ambient temperature (AT)

The performance of the emergency lead-acid batteries is influenced by the AT inside the HC. The AT profile inside the human cabin at various ocean depths is modeled and simulated using Siemens Magnet-Thermnet Finite Element Analysis (FEA) software. Simulation is done based on the environmental conditions (HC microclimate) during a practical 12h mission and emergency period of 96h. The properties of the Ti-alloy, 80mm thickness, internal heat loads and external sea water temperature prevailing at various depths are provided as inputs to the Magnet-Thermnet model. The details of the devices and their thermal behavior are not included in this article due to confidentiality reasons. The simulation results **(Figure.5)** show the AT inside the HC up to 8h (with 300W of human heat load and ~1000W of electronics) and during 8-108h (with 300W human heat load only, as systems shall be in

> *Survival Through Prediction, Not Reaction*

off condition per EOP). The identified AT serves as priori inputs to Shakthi.

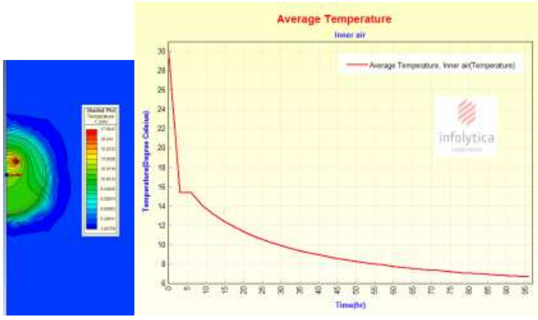


Figure.5. Ambient temperature variation inside the HC

Machine-learning of ocean water temperature profile

The ocean water current profile (Water depth Vs Temperature) in Central Indian Ocean basin where the water depth is 5500m is logged during a deep-ocean AUV OMe6000 scientific cruise undertaken in NIOT's Ocean Research Vessel Sagar Nidhi. The water current profile is machine-learnt using RNN-LSTM (identified by comparing with other techniques) and used as input to the AT-block **(Figure.4)** as priori input **(Figure.6).** The effectiveness of the various machine-learning (ML) processes is analysed using Mean Absolute Error and the results are summarised in **Table.1.** The closeness between the predicted and actual temperature is within 0.01ºC.

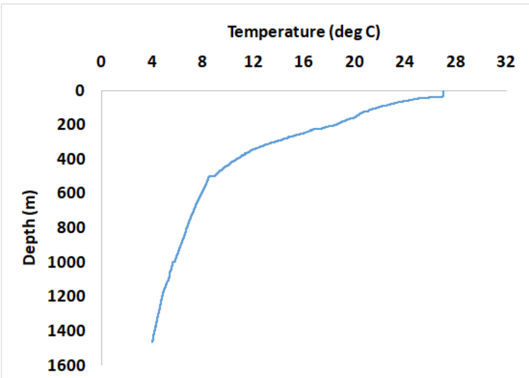


Figure.6. Machine-learnt Ocean temperature profile

Table.1. Machine-learning performance assessment

Method	MSE	RMSE	MAE
ARIMA	2.95	1.71	2.1
GRU	2.12	1.46	1.85
LSTM	1.86	1.36	0.96
RNN LSTM	1.05	1.024	0.65

Shakthi development and validation

Various stages involved in the development, tuning and validation of Shakthi is shown in **Figure.7.** Edge processor dSpace1104 is used for running the twin and LabView software is used as a visualisation platform. A programmable DC electronic load is to emulate the actual loading conditions. The digital twin of the battery is developed using numerically equivalent circuit and is adaptively tuned until the required prediction accuracy is obtained as that of the actual battery.

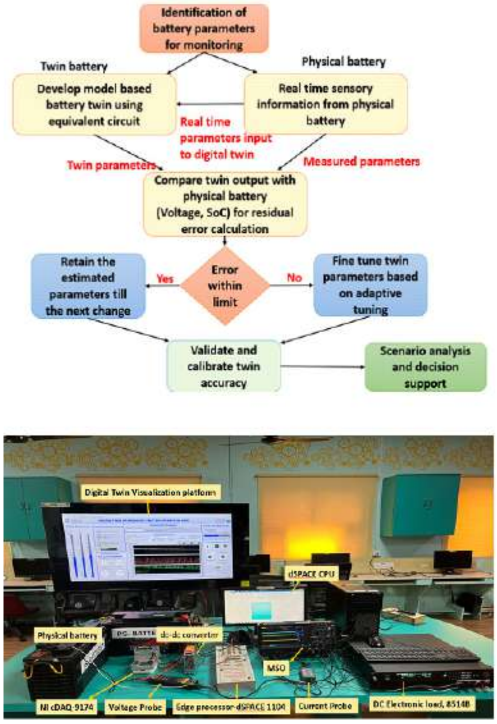


Figure.7. Stages of Shakthi module development

Identification of battery response various load patterns

A high-fidelity numerical model, used to digitally twin with the actual lead-acid battery is realised through an Electrical Equivalent Circuit Model (EECM) that emulates the battery behavior at different load conditions. All the parameters of the EECM are extracted from the nominal and pulse discharge test (PDT). The EECM comprises of two parts, including parasitic branch and main branch. The battery is characterised by a set of parameters that define the operational discharge properties. The resistances and capacitances of EECM are presumed as functions of the battery SoC and electrolyte temperature.

PDT refers to electrical discharge pulse pattern in battery involving short-duration high-current pulses. PDT is highly useful for estimating the battery parameters for model development and to understand the battery response during high discharge as well as dynamic loading conditions, as is the case of FB. The initial voltage drop due to the ohmic drop due to internal resistance and continues to drop due to internal resistance and electro-chemical polarisation. At the end of the current pulse, voltage instantly jumps up showing partial voltage recovery after the pulse. The voltage continues to relax as electrochemical system stabilises.

PDT was conducted on the actual fully-charged lead-acid battery to determine its dynamic response and voltage recovery behavior. Programmable DC load is used to create the short duration high current pulses, emulating the characteristics of the FB-based actuator. The response of the battery to the PDT to a current pulse (square waveform of amplitude 10 A) is shown in **Figure.8.** The results of PDT conducted on the battery are incorporated in the EECM.

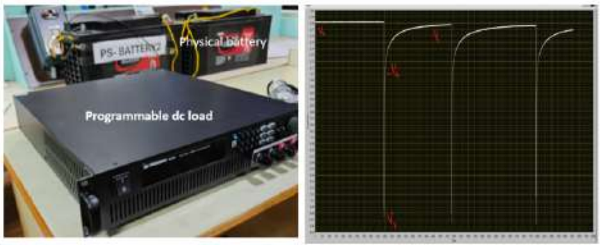


Figure.8. Pulse discharge test conducted on actual battery

Adaptive Parameter Tuning by Unsupervised Learning

The parameters of Shakthi are adaptively tuned (optimised) using unsupervised ML process. Optimisation is done using non-linear least-square optimisation method with trust region reflective (TRR) algorithm. The TRR algorithm is a numerical optimisation method used to solve bound-constrained non-linear minimisation problems. Subsequent to the adaptive tuning of Shakthi with the actual battery, its discharge performance under actual load conditions is validated in real-time with physical battery under different discharge conditions with varying loads, including actual pulsed patterns. The residual error between physical battery and digital twin is obtained as <0.3 V **(Figure.9 and Table.2),** which indicates the Shakthi has achieved a cognitive prediction accuracy of ~97%. The visualisation platform for the EPS, in real-time monitors the battery parameters, provides scenario analysis and physical parameter deviations for enable condition monitoring.

The validated Shakthi is used to predict the UAT usage during the emergency period based on the logic described in **Figure.3.** An off-normal UAT usage of 10 times/h during the 10-15h (of emergency period) results in allowable operations of every 43min, while at the end of the emergency period (70-75h) the emergency power system can support only 1 time every 240min (2h). The HMI periodically updates every 5min (update rate can be modified by the user) simulates the time-series SoC and voltage of the battery and predicts the real-time to reach 20% of SoC, real-time (last opportunity) before which the "voltage-sensitive" SMA-based emergency releases needs to be operated and the allowable operations for the UAT/h, enabling Matsya6000 crew to "foresee" scenarios and redefine the EOP.

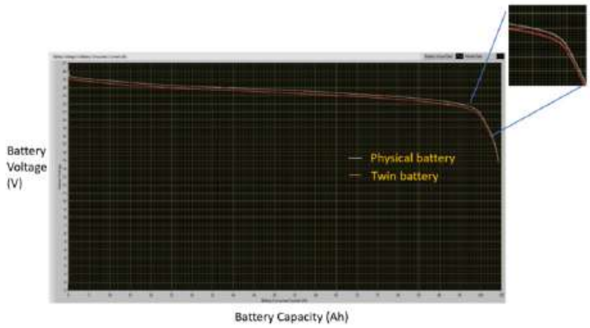


Figure.9. Battery voltage versus capacity (twin and actual)

Table.2. Performance of Shakthi during operation of emergency devices

Emergency FB-actuated device	Maximum threshold time to actuate		Critical voltage (V)	Accuracy %
	Shakthi	Actual battery		
EDW, ERB	95.2h	97.2h	20.77	97.3%
Manipulator, Sample Tray	90.4h	92.6h	21.65	97.6%
Trim	82.8 h	84.6h	22.29	97.9 %
Instance SoC falls below 20% (h)	107 h	98.6h	18	97.6%

> *Predict. Adapt. Survive*

Prana – O_2 supply system

The HC of Matsya is equipped with life-support systems including O_2 supply system (with 1045L of O_2 stored in 67 cylinders) for catering the requirements of 3 crew for 108h, two CO_2 removal scrubbers, four emergency breathers, smoke & fire detectors and environment monitoring sensors, alarms and data acquisition systems. Under nominal conditions, the O_2 concentration inside the human cabin shall be maintained at 21% by the crew by opening the O_2 cylinders one after other, as and when they are exhausted. The cylinders are equipped with needle valves so that the flow rate can be varied to maintain the desired O_2 concentration at the desired level. Based on OSHA standards, O_2 concentration inside the closed HC should be in the range 18.5-23%. Concentrations <18.5% is detrimental to the crew health and concentrations >23% creates an environment supporting combustion (possibility ignited by electrically-generated sparks) and creates O_2 toxic environment for the crew.

HTPS-3

During emergency scenarios, such as Matsya6000 stranded to the ocean floor, precise localisation shall be done using acoustic transponders and drag-anchor shall be used for rescue. The duration required for carry out the

Table.3. O_2 consumption during nominal and emergency period used for sizing the on-board O_2 storage

Phase	Duration	O_2 consumption (litres)		
		Pilot	Co-pilot	Obser-ver
Nominal operations (12h mission)				
On ship deck	30min	20	13	8
Surface floating	30min	10	9	5
Descent	180min	77	77	45
Survey at altitude	120min	79	52	30
Near ocean-floor survey	90min	59	39	39
Intervention /Sampling	60min	40	40	26
Ascent	180min	72	72	45
Retrieval till disembark	30min	20	13	8
Up to 12h	**12h**	**377**	**314**	**205**
Emergency period				
12-20h	**8h**	**316**	**316**	**316**
Up to 96h	**76h**	**1961**	**1961**	**1961**
Crew-wise consumption	**108h**	**2654**	**2591**	**2482**
Total consumption for 108h		***7727 Litres***		

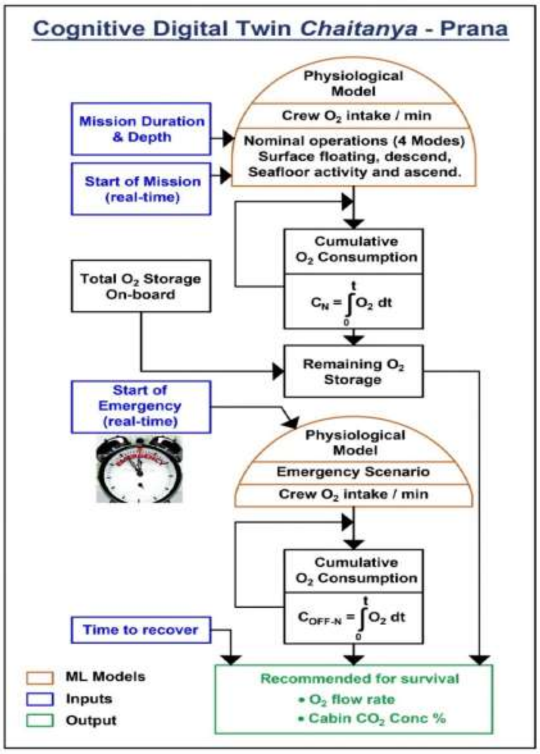


Figure.10. Architecture of Prana module

operations forms the basis of definition of the emergency period (96h). However, in case of delays beyond 96h, optimised consumption of O_2 shall help in surviving beyond 96h, before they are rescued. However, **predicting O_2 flow rate required to sustain for the additional period (beyond 96h) in-advance, is a HTPS for the crew, when physical and physiological stresses dominate**.

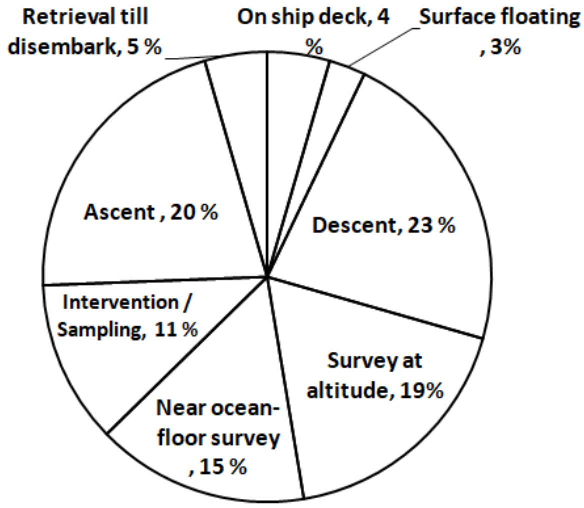
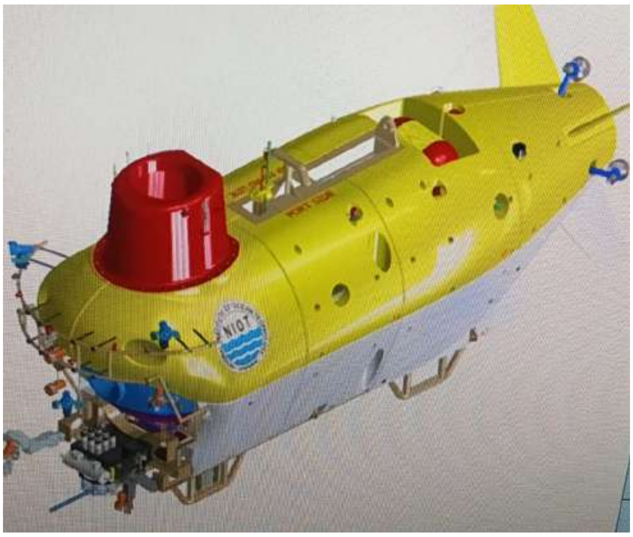


Figure.11. O_2 consumption by the crew during 12h mission

The O_2 consumption pattern by Matsya6000 crew during various phases of 5500m depth-rated scientific mission forms the basis of Prana module. Based on the physiological models and the metabolic activity, O_2 consumption rate during the nominal and emergency operational phases of Matsya are incorporated in the models. Based on the actual physical and cognitive work load of the crew during piloting phases, O_2 consumption of the pilot, co-pilot and observer is computed as 660 ml/min, 430 ml/min and 250 ml/min, respectively. During the seafloor observations, all three consume 430m/min. During the initial emergency period (8h) all three consume 660m/min and 250m/min during the rest of the emergency period, till recovery. Taking into consideration maintenance requirements, residual O_2 requirements in the cylinders and the plumbing lines, total O_2 required onboard is ~9kL **(Table.3).** However, to comply with DNV regulations 10450L of O_2 stored in 67 cylinders is used for the mission.

Figure.12. Crew in Matsya HC in surface floating condition



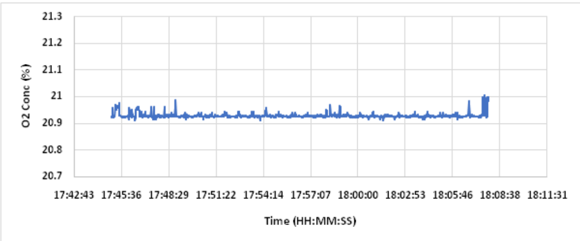


Figure.13. O_2 concentration inside HC during surface floating

The O_2 consumption for three crew was monitored during the Matsya qualification tests conducted in L&T ship-building port in **Chennai (Figure.12).** The cabin O_2 concentration log on-board Matsya is shown in **Figure.13.** During the stabilised period (15.40hrs -16:04hrs), the O_2 concentration was constant (21%) for a fixed O_2 flow rate of 1.5LPM. The measured O_2 consumption was closely matching (with an accuracy of 3%) with the OSHA model. The obtained consumption pattern was used as an input for the Prana module.

Based on the architecture of Prana described in **Figure.10,** Prana shall be started once the crew embarks the human cabin and the entry hatch is shut and thereafter the computation of the cumulative O_2 consumption is done based on the mission plan with pre-defined O_2 consumption pattern. During an emergency scenario, the start of the emergency (real-time) shall be provided as an input and thereafter Prana switches to emergency mode of operation. Once it enters into the emergency mode, the remaining O_2 onboard serves as an input to Prana. During the emergency, at any instant, Prana accepts the "time-to-retrieve" as input and recommends cabin O_2 concentration and flow rate that has to be maintained to survive for the specific additional duration. The output of the CDT Prana for a query raised after 20^{th} hr of emergency is shown in **Figure.14.** It can be seen that, for an emergency period that started at 20^{th} hr, with a flow rate of 1.3LPM, the crew survival can be extended up to 114h, while with 1.14LPM, the crew can survive up to 127h.

Virtual Intelligence, Real-World Safety

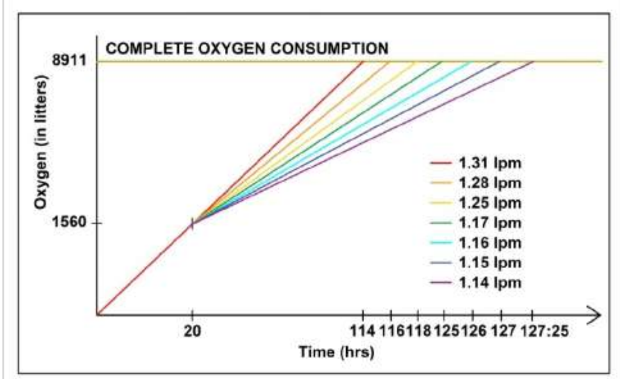


Figure.14. Prana decision support for survial beyond 96h

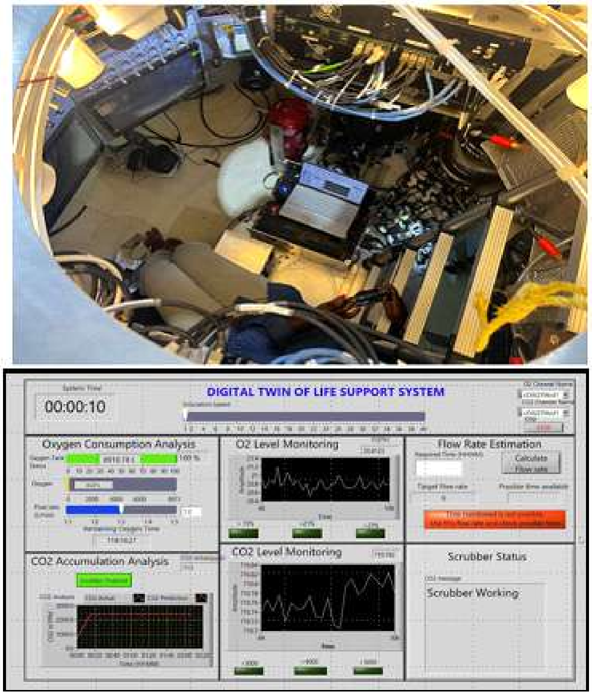


Figure.15. CDT-Chaitanya-Prana deployed in HC and the HMI

In the next issue

The development and validation of Pushar and Garuda modules of CDC Chaitanya shall be presented.

Abbreviations

AI	Artificial Intelligence
AH	Ampere-hour
AT	Ambient Temperature
ALARA	As Low As Reasonably Achievable
APoS	Acoustic Positioning Systems
ARIMA	Autoregressive integrated moving average

AUV	Autonomous Underwater Vehicle
CDC	Cognitive Digital Copilot
CDT	Cognitive Digital Twin
CO_2	Carbon Dioxide
DC	Direct Current
DNV	Det Norske Veritas
EDW	Emergency Drop Weight
EECM	Electrical Equivalent Circuit Model
EJS	Emergency Jettisoning System
EOP	Emergency Operating Procedures
EPS	Emergency Power System
ERB	Emergency Rescue Buoy
FB	Frangibolt
FEA	Finite Element Analysis
GRU	Gated Recurrent Unit
HC	Human Cabin
HMI	Human-Machine Interface
HTPS	Hard-To-Predict-Scenarios
LCS	Life critical systems
LPM	Liters per Minute
LSTM	Long Short-Term Memory
MAE	Mean Absolute Error
ML	Machine Learning
NIOT	National Institute of Ocean Technology
O_2	Oxygen
OSHA	Occupational Safety & Health Administration
PDT	Pulse Discharge Test
RNN	Recurrent Neural Networks
SoC	State of Charge
SMA	Shape Memory Alloy
TRR	Trust Region Reflective
UAT	Underwater Acoustic Telephone

Acknowledgement

The authors acknowledge the support extended by their colleagues in the Deep-Sea Technologies Division of NIOT and SRM University and the encouragement given by Ministry of Earth Sciences, Government of India for this development.

References

1. P. Moorhouse, 2015, A modern history of the manned submersible,MTS Journal.
2. M. Ravichandran, 2025, India's deep ocean mission, Current Science Journal.
3. N. Vedachalam et al, https://sea-technology.com/matsya6000-digital-twin-co-pilot-for-emergency-rescue
4. N. Vedachalam et al, 2014, **Review** of technological advancements and HSE-based safety model for deep-water human occupied vehicles, MTS Journal.
5. C. Folleau, & N. Vedachalam, 2022, Methodologies for reliability and functional safety assessment of offshore systems, MTS Journal.
6. M.Palaniappan et al, 2025, Development of cognitive digital twin-aided emergency response and rescue systems for Matsya6000, Current science.
7. M.Palaniappan et al, 2024, A method for evaluating safety reliability of descend/ascend drop-weight system and mission abort decision for deep-ocean scientific human submersibles. Nature Scientific reports.
8. India tests first crewed deep-sea submersible, 2025, Nature India.
9. N. Vedachalam, 2025, Cognitive digital twins in Strategic Anti-submarine warfare- A scoping review, ORF special report number 268.

About the Authors

Dr. N. Vedachalam Scientist-G and Director, Deep Sea Technologies Group, NIOT, brings 30 years across industrial power, offshore, subsea, robotics and ocean technologies. He has 100+ publications, patents and expertise in subsea power, underwater vehicles, renewable energy, reliability and systems.

Email: veda1973@gmail.com

Dr. V. Bala Naga Jyothi, Scientist-E at NIOT, is a lead electronics engineer for navigation, positioning and communication systems in Matsya6000 and ROVs. Formerly with ISRO, she specialised in control systems, autonomous guidance, digital twins, with 40+ publications and professional memberships.

Dr. J. Preetha Roselyn is a Professor in the Department of Electrical and Electronics Engineering in SRM Institute of Science and Technology, having established the Centre for Intelligent Marine and Energy Systems (CIMES). She specialises in model-based development, digital twinning, grid integration of renewables and microgrids, with 75+ publications and four international awards.

Mr. G Hari Krishnan., Scientist -F NIOT is the lead Electrical and Electronics Engineer for the Power distribution system of manned and unmanned submersibles including Matsya6000, ROSUB6000, PROVe500 and Autonomous Coring Systems. He has more than 25 years of R&D and Industrial experience and his expertise spans power system design, protection & switchgear, solid-state drives, battery systems, high voltage-high frequency systems and special purpose electric machines. He has 2 National awards, 15+ publications and 4 Patents to his credit.

Dr. Tamshuk Chowdhury is Scientist –F at NIOT, has 19 years of experience & expertise in Underwater Systems & Vehicle Design, Materials Modeling & Development, Solid & Fracture Mechanics, Quality Control & Quality Assurance and Corrosion. He has 25+ publications and member of Intra-Institutional Committees & International Technical Societies

Dr. S. Ramesh is Scientist-G and Deputy Director, NIOT, is a marine geologist with 32+years in deep-sea mineral exploration. His work spans gas hydrates, nodules, paleo-climate studies, polar expeditions and he represents India at the International Seabed Authority (LTC)


Achieve lifelong financial independence with LIC s Govt Guaranteed lifelong Of Pension income plans
bas LIC ka protection
LIC 2026 Pension plans
Guaranteed LIC plans
Good News LIC pension & Life plans Cheaper!!!
With geopolitical Risks of War and Trump Tarriffs and bullying, Balance your Equity Risks with LIC Guaranteed Pension plans
LIC PENSIONS FOR MARINERS
GIRISH BHATIA-LIC-9820048188 Call/ wapp
Girish Bhatia
27 Jul ·

"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