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Editorial

"The future always comes too fast and in the wrong order." — Alvin Toffler

Engineering Safe Pathways Amidst Decarbonization Uncertainty

The global maritime industry stands at a critical technical crossroads. While MEPC 84 advanced negotiations on the proposed IMO Net-Zero Framework, its adoption faces political uncertainty. Yet shipboard realities cannot wait: CII requirements continue to tighten, demanding an 11% cumulative reduction in operational carbon intensity by year-end.

Geopolitical instability compounds the challenge. Attacks in the Black Sea, Strait of Hormuz, Red Sea and Bab el-Mandeb are disrupting trade, increasing war-risk exposure and threatening seafarers. The *Tihamah* attack off Yemen claimed four crew lives, while piracy and armed robbery remain persistent threats, with ICC-IMB recording 38 incidents and 67 crew members taken hostage during the first half of 2026. Overall, **piracy and security threats appear to be intensifying in and around the Bab el-Mandeb, making seafaring increasingly challenging and less attractive amid growing geopolitical and security risks**

Technology is advancing simultaneously. IMO's MASS Code provides a global framework for autonomous ships, while the IAEA's ATLAS initiative is exploring nuclear propulsion and small modular reactors. But technology must remain anchored in human competence.

Decarbonisation demands practical engineering. LNG requires methane-slip mitigation; methanol requires specialised fuel-supply arrangements; ammonia demands stringent safeguards against toxicity. These technologies require appropriate training, competence and emergency preparedness.

For India, this turbulence presents opportunity. Expanding shipbuilding, ship repair and maritime-industrial capability can strengthen resilience while accelerating technological development.

The future will not be defined by one fuel, route or technology. It will depend on **engineering excellence, digital intelligence, safety, skilled people, resilience and strategic foresight**.

Our task is clear: translate complex technologies into safe, reliable shipboard realities. **Tomorrow's ships must be greener and smarter—but above all, safer for the people who operate them**

This first article by Winson reveals how AI can read, reason, recommend and act while keeping engineers in control. Artificial Intelligence is moving ship management beyond dashboards and data overload. Discover how intelligent assistants can reclaim attention for decisions that truly matter onboard. A must read article for all engineers written from Superintendents perspective

Prakash Narayanan explores using the 90:10 principle - how design maturity, specifications, contracts and early decisions determine lifecycle performance, reliability and cost. This is the first article in six-part series. Great ships are engineered long before steel is cut. A compelling case for India to build smarter, not simply bigger, shipbuilding capability.

The third article by Kaushik Seal and Dr Saptarshi examines alternative marine fuels are not simply replacements for diesel, but as fuel that can transform combustion itself. They examine how methanol, ammonia, hydrogen, LNG, LPG and biofuels alter ignition, flame behaviour, emissions and engine requirements, revealing why successful maritime decarbonisation begins with combustion science today.

When a shipboard generator fails, theory must become action. In this practical guide J Majumdar demystifies brushless alternators, excitation systems, rotating diodes, AVRs and common defects, providing engineers with systematic troubleshooting and rectification approaches to restore electrical power safely and confidently at sea.

This accident-investigation article by Capt. Gajanan reconstructs the chain from oil leakage and ignition to escalation, human response and firefighting. An engine-room fire rarely begins with the visible flame! He details how thermal evidence, timelines and management failures can reveal why fires become casualties.

This article from the NIOT team examines - Can tropical cyclones leave a carbon footprint in the ocean? Using deep-ocean observations from the Bay of Bengal, this study explores cyclone-driven air-sea CO_2 exchange, ocean acidification and climate interactions, revealing a connection between extreme weather, oceans and India's future.

Happy reading!

Mani Ganapathi Ramachandran
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The Digital Transformation of Ship Management: The Role of Artificial Intelligence

B. A. Winson

Abstract / Summary

Ship management has digitalised steadily for three decades, yet a superintendent's week is still dominated by searching, reading, re-entering and cross-checking information scattered across systems that do not talk to each other. This article, based on the experience of building SIYA, Synergy Marine Group's Artificial Intelligence initiative that today supports more than 630 vessels, argues that the industry's real constraint is not a shortage of data but a shortage of attention. It explains what Artificial Intelligence genuinely offers ship management once the buzzwords are set aside: systems that read, understand, reason, recommend and act, with a human approving every step that matters. Working examples are drawn from across the fleet, from scavenge-space image analysis to vessel inspection reports that draft themselves, together with the time savings measured in service. The challenges are discussed candidly, hallucination, data quality, cyber security and governance among them, along with a practical way for any ship-management company to begin.

Keywords: AI Agents; Decision Support; Superintendent Workload; Fleet Operations; Human-in-the-Loop

Introduction / Background

Marine engineers are trained by the situation itself. At sea, when machinery fails at two in the morning, there is no expert waiting on a telephone line; there is the engineer, perhaps one senior to consult and one junior to think aloud with. That is the whole support system. At sea, we are our own best help: tuned to think through a problem, find the best solution with whatever is available and implement it ourselves. That habit of self-reliant judgement is the profession's defining asset.

Most of us come ashore expecting the work to remain similar in character: technical decisions, taken on our best judgement. The reality of shore-based ship management is different. The technical work becomes one slice of a role that now spans administration, logistics, owner relationships, procurement, agents, third-party inspectors, surveys and certification. The job, as defined, has quietly grown beyond what one person can hold at consistent quality.

The industry's toolkit has evolved in parallel. Paper records gave way to spreadsheets; spreadsheets to ERP and planned maintenance systems; those to integrated platforms with dashboards and real-time reporting. Each generation changed how information is stored and

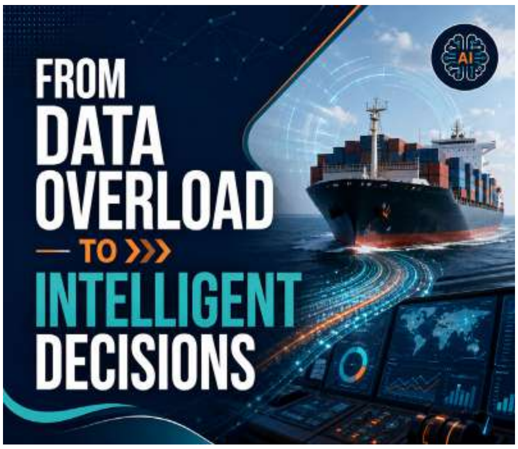

Figure 1 The superintendent as the manual integration layer between disconnected systems

displayed. None of them changed who does the thinking. Artificial Intelligence is simply the next tool in that same line, with one decisive difference: for the first time, the tool assists with the thinking itself. This article sets out, from implementation experience rather than theory, where AI genuinely helps ship management, how it is being applied across a large fleet today and how it should be adopted responsibly.

The Real Bottleneck: Attention, Not Data

Ship management expects its superintendents to be, in effect, superhuman: to remember everything, to miss no communication and to know each vessel in their portfolio technically, operationally and logistically. What the superintendent is actually given is data scattered across many systems, occasionally duplicated between systems that disagree with each other and a working day that has not grown to match.

Figure.1. shows the honest picture. The planned maintenance system, ERP, budget tools, certificate trackers, crew systems, purchase portals, inspection databases and email all feed into one person. Each system solves its own problem well; none of them talk to each other. The superintendent therefore becomes the integration layer, manually connecting dots that software should connect. This is not a shortage of data. It is a shortage of attention with which to process that data.

Most shore-based readers will recognise the working day this produces. It begins with an inbox holding a couple of hundred overnight emails from across the fleet. Defects reported from three vessels compete for priority. A stack of purchase requisitions waits to be checked against budget lines. A status report for management is assembled largely by copy-and-paste from systems that already hold the data and the afternoon disappears into certificate follow-ups and charterer or class queries answered from four separate systems. Three questions make the point quickly: how many emails arrive in a single day? How many systems must be opened to complete one task? And how many reports simply restate data somebody else has already entered?

The consequence is measurable. An internal review of how a typical superintendent's week is spent, summarised in **Figure.2,** found roughly a quarter of the week

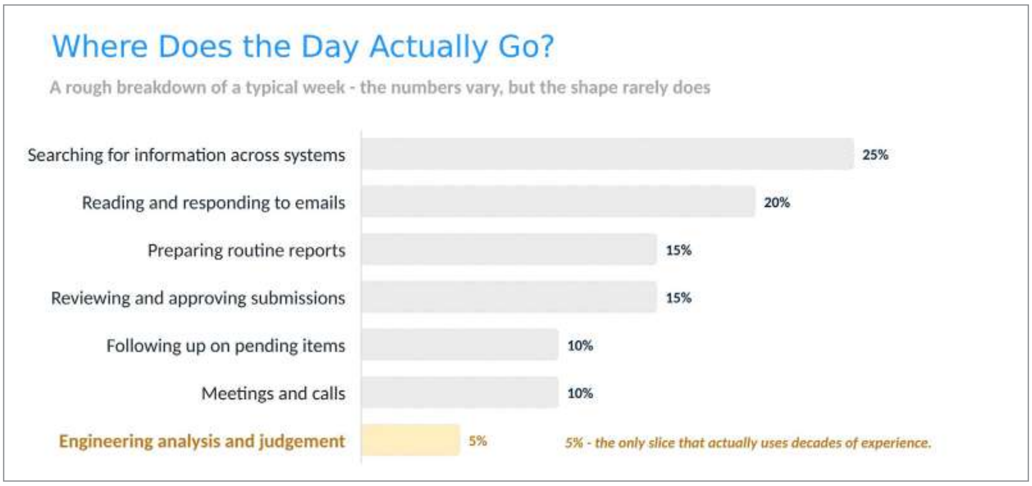

Figure 2 Distribution of a typical superintendent's working week

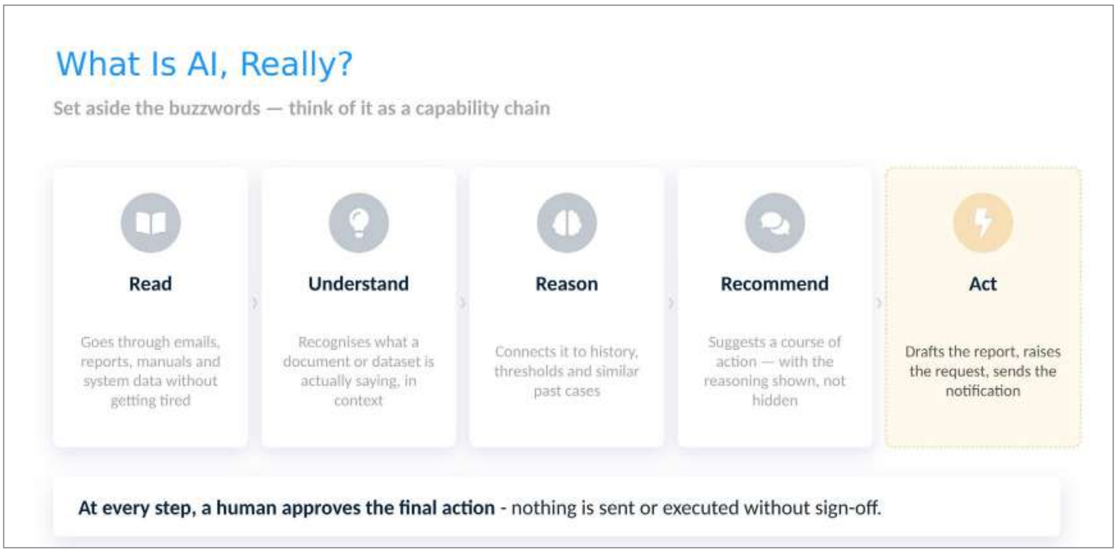

Figure 3 The AI capability chain, with a human approving every final action

consumed by searching for information across systems, a fifth by reading and responding to email and substantial further shares by routine report preparation, approvals and follow-up. Engineering analysis and judgement, the only activity that genuinely requires decades of hard-won experience, accounted for approximately five per cent. The percentages vary from person to person; the shape rarely does.

It is also worth being precise about why raw data does not become action by itself. A number in a system, say a main-engine cylinder oil consumption of 250 liters per day, must first become information (20 per cent above the three-month average), then knowledge (the same pattern preceded liner wear on a sister vessel), then a decision (inspect the liners at the next port and alert the engine maker) and finally a documented action taken before the window closes. Today every one of those steps runs manually, in the superintendent's head, under time pressure. Those four gaps between data and action are exactly where attention is spent and exactly where intelligent assistance can be applied.

What AI Really Is: A Capability Chain

Set aside the buzzwords and AI as applied to ship management is best understood as a chain of five capabilities, illustrated in **Figure.3.** It can read: go through emails, reports, manuals and system data without fatigue. It can understand: recognise what a document or dataset is actually saying, in context. It can reason: connect the content to history, thresholds and similar past cases. It can recommend: suggest a course of action with the reasoning shown, never hidden. And it can act: draft the report, raise the request, send the notification. One rule governs the entire chain: a human approves the final action. Nothing is sent or executed without sign-off.

Placed in a familiar lineage, each generation of decision support removed one layer of manual work: search engines found where information might be, ERP stored it reliably, dashboards made patterns visible, predictive analytics flagged what was likely, generative AI now summarises and drafts in plain language and AI agents carry out multi-step tasks end to end with a human checkpoint. Each generation is additive: agents sit on top of the systems a company already runs, rather than replacing them.

In daily use, this assistance takes two distinct forms. The first is work on demand: ask and the AI delivers, searching across all enterprise systems in minutes and returning evidence-based answers with source references attached. The second is autonomous operation: the AI monitors emails and systems continuously, identifies and tracks issues, builds and maintains case files and prepares reports and documentation for human review. It is the practical equivalent of a diligent junior colleague who works around the clock and shows the provenance of every figure.

The SIYA Experience: Building From the Inside

SIYA, Synergy Marine Group's AI initiative, did not begin with Artificial Intelligence and did not begin as a product. It began when a group of like-minded technical superintendents and marine engineers came together around a simple question: could a superintendent's daily

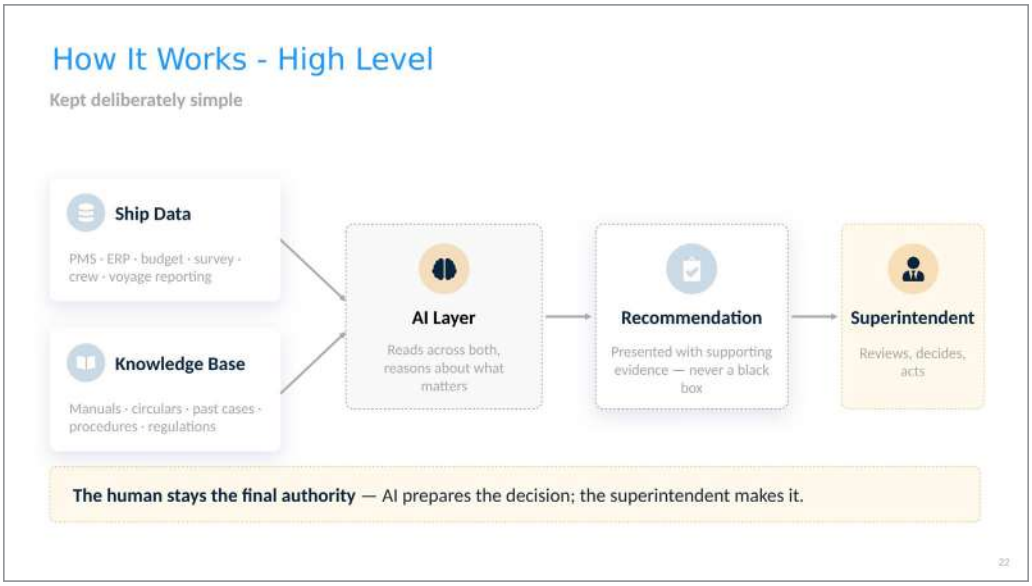

Figure 4 High-level architecture: AI prepares the decision; the superintendent makes it

work be made lighter without replacing their judgement? The first steps were deliberately small: automating repeated tasks and building dashboards that pulled data out of siloed, fragmented software so that the things a superintendent was expected to have at his fingertips genuinely were. Those early efforts succeeded and credit is due to the organisation for placing faith in a group of marine engineers experimenting with software and giving them room to continue.

The arrival of large language models prompted a more ambitious question: why look at dashboards at all? On board, a puzzled engineer does not open a dashboard; he asks a colleague. Ashore, colleagues are equally busy with their own vessels and do not hold each other's data. The goal therefore became a virtual colleague: an assistant one can simply talk to, which already holds the required data from all systems, curated in advance, almost anticipating the question. Early general-purpose models lacked maritime context entirely and that gap had to be closed the hard way, in parallel with the rapid maturing of the underlying technology.

One lesson from this journey deserves emphasis because it applies to every company considering adoption: data has been and remains, a problem in every shipping company. Data is the foundation; any AI, however capable, is only as good as the data beneath it. Experience shared with peer organisations, including some of the industry's largest, confirms that the logos change but the data problem does not. A fair first question to any AI vendor is therefore not about the model, but about what has been done with the data underneath.

Where the work stands today: several months of development conducted side by side with technical and marine superintendents; more than fifty existing shore and vessel systems integrated as a connective layer rather than a replacement; and support for operations across more than 630 vessels. The architecture, shown in **Figure.4,** is kept deliberately simple. Ship data (PMS, ERP, budget, survey, crew and voyage reporting) and the knowledge base (manuals, circulars, past cases, procedures and regulations) are read together by the AI layer, which reasons about what matters and presents a recommendation with its supporting evidence, never as a black box. The superintendent reviews, decides and acts. The human remains the final authority throughout.

It is the author's firm view, from having lived both sides, that this class of system is best built by marine engineers working with software specialists, not by either group alone. Domain expertise identifies which pain is worth solving and what a good answer looks like; software expertise makes the solution robust and scalable. Without the domain half, the pain point cannot even be seen clearly. Marine engineers are not spectators in this industry's AI transition; in the parts that matter most, they are leading it.

Use Cases Across Ship-Management Functions

The following applications are in daily use across the fleet. A single shape repeats through all of them: AI performs the reading, sorting and cross-checking; a person makes the call.

Scavenge space inspection, by image analysis. Each month a vessel submits its scavenge inspection report with photographs of every unit. Reviewing hundreds of near-identical images is monotonous and monotony is precisely where a tired eye misses the one abnormal photograph. The AI analyses every image, grades each unit for carbon deposits, ring condition and breakage, liner lacquering and scuffing and correlates the findings with performance data and that unit's previous inspections, producing trends rather than snapshots. The superintendent reviews a flagged summary; attention goes only to the units that need it. Pattern recognition does not get tired.

Machinery condition, computed rather than compiled. Answering the simple question of how the main engine is performing today once meant manually assembling noon reports, performance logs, PMS counters, inspection findings, shop and sea trial baselines and maker limit curves. That picture now arrives assembled: deviation from baseline computed, sources correlated and cited, workings shown. The engineer judges what the condition means, starting from an answer rather than a pile of raw data.

Troubleshooting and the fleet's memory. When machinery misbehaves, the answer usually exists already, in two places: the maker's documentation and past correspondence. Every manual, drawing and circular is now searchable in plain language, returning troubleshooting steps in seconds with page references cited. More valuable still, years of troubleshooting emails have been mined into a fleet knowledge bank recording what was tried, what worked and what the maker finally advised; sister-vessel history surfaces automatically when a similar defect appears. The fleet has usually seen the problem before. Now it remembers and is available both to ship crew and shore staff.

Vessel inspection reports drafted from photographs. A vessel visit ends with hundreds of photographs and, traditionally, evenings of sorting, typing and formatting. The AI groups images by compartment and system, flags visible issues such as corrosion, leaks, housekeeping and missing signage and assembles a draft report with each photograph placed against its finding. The superintendent's eye found the issues on board; the AI does the paperwork and the report is issued the same day.

QHSE campaign tracking. A fleet campaign to thirty vessels once meant weeks of inbox archaeology. An agent now logs each vessel's emailed response as it arrives, checks it against the campaign requirements, writes back to the vessel for missing evidence and presents QHSE with a completion board and final summaries instead of three hundred emails. The follow-up runs itself; people review the findings.

PMS building and EMS data validation. Constructing a vessel-specific planned maintenance system requires reading maker manuals page by page, exactly the work that historically got done generically and in a hurry. The AI reads those thousands of pages without fatigue, builds component trees and job plans from the actual manual rather than a sister-ship template and populates spares against every component, with humans verifying rather than transcribing. Separately, daily consumption logs are validated every day and discrepancies chased with the vessel automatically, so that CII and EU MRV filings rest on data that has been clean all year rather than cleaned in a year-end panic.

Beyond the technical department, procurement runs a buying agent from requisition to purchase order, crewing uses AI for sourcing and relief planning, accounts for invoice processing and training for preparing material from manuals. Every department, it turns out, has its own version of the same three words: search, read, draft. **Figure.5** summarises measured turnaround improvements on four representative tasks.

The Road Ahead

It helps to place the present moment on a short timeline. Around 2024, enterprise AI meant a chat assistant: it answered questions and drafted text while a person did the actual work. In 2026, AI agents execute multi-step tasks inside company systems while a person reviews and the agent delivers. The next step, already visible, is agent teams: agents coordinating with one another across functions, with people setting goals and handling exceptions. AI has stopped being something one asks and is becoming something that does the work.

Will AI replace superintendents? No and the actual division of labour is instructive. What moves to AI is

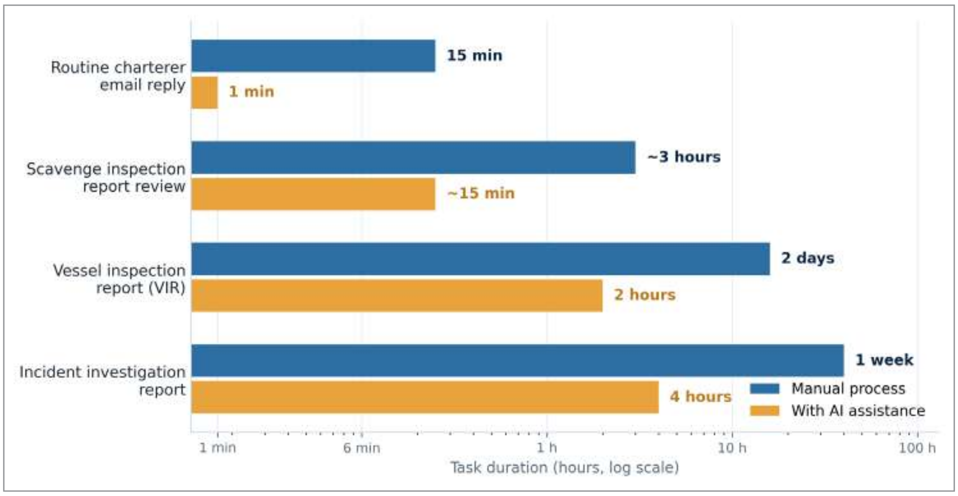

Figure 5 Measured turnaround times before and after AI assistance (log scale)

searching across systems, reading long threads and documents, drafting routine reports and cross-checking data for mismatches. What stays with the human is engineering judgement on unusual cases, experience-based risk assessment, negotiation with owners, class and vendors and leadership, accountability and final decisions. The tedious moves to the machine; the judgement stays with the engineer. Rather than shrinking, the role concentrates: the same expertise applied where it is actually needed.

No technology deserves an unqualified sales pitch and eight challenges demand active management:

1. Hallucination (confidently wrong is still wrong, so every output must be verifiable against its sources);
2. Data quality (recommendations are only as good as the data feeding them);
3. Cyber security (deeper integration widens the attack surface);
4. Change management (crews and shore staff need training and time to trust new workflows);
5. Trust (recommendations must show their reasoning);
6. Integration (connecting fifty-plus legacy systems is real engineering, not a checkbox);
7. sustained cost;
8. Governance (clear rules on what AI may decide versus what requires sign-off).

For companies beginning this journey, the guidance from experience is consistent. Start small, with one painful, well-defined workflow rather than everything at once. Choose high value: tasks that consume disproportionate time relative to their complexity. Make it measurable, tracking time saved and error rates before and after, not anecdotes. Augment rather than replace, designing every workflow so that a human reviews before anything is sent or actioned. And iterate with the users, because the people using the tool daily find the real gaps faster than any planning session. In short, adopt AI with the same engineering discipline applied to every other system on board: sea trials before service.

Conclusion

The maritime industry's real challenge is attention, not a lack of data. AI's value lies in the unglamorous middle steps between a number in a system and an action on board: reading, cross-referencing, drafting and chasing, performed tirelessly and always subject to human sign-off. The experience of building and deploying such systems across a large fleet shows that the superintendent's role does not shrink; it concentrates on the decisions that genuinely require a human. The judgement stays ours; the engineering stays ours. Everything else is overhead and for the first time in our careers the overhead has somewhere else to go. Marine engineers, who have spent their working lives being their own best help, are well placed not merely to adopt these tools but to lead their creation: let us do only the work we ideally should be doing and leave the rest to AI.

Acknowledgements

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B. A. Winson is Senior General Manager – Maritime AI and Head of SIYA at Synergy Maritime, an AI-powered platform transforming ship management through intelligent decision support and agentic automation. A Marine Engineer with over two decades of experience, he has served as Chief Engineer, Class Surveyor, Technical Superintendent/Manager, managing LPG/LNG fleets. He holds a B.E. in Mechanical Engineering, M.S. in Shipping & Port Management and is a Member of the Institute of Chartered Shipbrokers (UK) and Institute of Marine Engineers (India).

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The 90:10 Principle: Why Great Ships Are Engineered Before They Are Built

Narayana Prakash

Abstract

Shipbuilding is commonly judged by visible achievements—steel cutting, block erection, launching, sea trials and delivery. Yet many of the factors that ultimately determine a vessel's performance, reliability, maintainability, lifecycle cost and commercial value are established long before the first steel plate is cut.

The **90:10 Principle of Shipbuilding Success** proposes that approximately 90% of these outcomes are effectively determined during design, technical specification development and contract negotiation, while the remaining 10% depends upon disciplined execution during construction, commissioning and delivery. The ratio is conceptual rather than mathematical. Its purpose is to highlight a fundamental shipbuilding reality: **the greatest opportunity to improve a shipbuilding project exists before construction begins**.

For India, where renewed attention is being given to shipbuilding and ship repair, this principle has particular relevance. Building larger docks and increasing fabrication capacity are important, but engineering maturity, specification quality, contract clarity, constructability and early multidisciplinary decision-making may ultimately determine whether Indian shipyards can deliver predictable, high-value vessels competitively.

Keywords: Shipbuilding; Indian Shipbuilding Industry; 90:10 Principle; Pre-Contract Engineering; Ship Design; Technical Specifications; Engineering Maturity; Shipbuilding Contracts; Lifecycle Cost; Maintainability; Reliability; Shipyard Competitiveness; Digital Engineering; Multidisciplinary Design Review; Shipbuilding Project Management; Maritime Engineering; Shipbuilding Quality; Lifecycle Value; Engineering Before Steel Cutting.

1. Introduction: The Ship Begins Before the Shipyard

When people think about shipbuilding, they usually picture a shipyard. They see massive dry docks, enormous gantry cranes, steel plates being cut, blocks being assembled, engines being lowered into machinery spaces and the gradual transformation of thousands of tonnes of steel into a vessel. Finally comes the launching ceremony, harbour acceptance testing, sea trials and delivery to the owner. These are highly visible stages of shipbuilding. They are also the stages in which enormous amounts of labour, material and capital are committed.

Where does the ship really begin?

The answer is not necessarily the fabrication shop. A ship begins in the owner's operational requirement, the designer's engineering office, the technical specification and, ultimately, the shipbuilding contract. Long before steel cutting, decisions have already been made concerning the vessel's intended service, cargo, machinery, electrical systems, equipment, environmental performance, maintainability, testing requirements, documentation and quality expectations.

The shipyard eventually converts those decisions into physical reality. This distinction is central to the **90:10 Principle of Shipbuilding Success**. The principle emerges from practical experience across newbuilding

projects involving bulk carriers, tankers, floating docks and specialised vessels. A recurring observation is that many problems encountered during construction are not actually created in the fabrication shop. Their origins can often be traced to decisions—or failures to make decisions—months or even years before steel cutting.

This does not diminish the importance of shipyard execution. Quite the opposite. Excellent production planning, workmanship, quality control, commissioning and sea trials remain indispensable.

The argument is that **excellent execution cannot completely compensate for poor engineering foundations**.

2. The 90:10 Principle

Approximately 90% of a vessel's long-term performance, maintainability, reliability, operational efficiency, quality, contractual certainty, lifecycle cost and commercial value is determined during the design, specification and contract negotiation stages.

The remaining 10% depends upon disciplined execution during production planning, steel fabrication, block assembly, machinery installation, commissioning, testing, sea trials, documentation and delivery. The numbers **90 and 10 should not be interpreted as a statistically validated mathematical relationship**.

They are deliberately conceptual. Their purpose is to shift the industry's attention towards the point in the project lifecycle where decisions can be made most effectively and economically.

Consider two situations.

1. An inadequate maintenance access arrangement is identified during the design review. The designer changes the arrangement. A drawing is revised. Perhaps a few engineering hours are consumed.
2. The same problem is discovered after machinery has been installed and surrounding structures, piping, cables and insulation are complete.

Now the solution may require dismantling, additional steelwork, piping modifications, revised drawings, additional labour, delay to commissioning and perhaps contractual discussions. The technical problem is the same. The **cost of discovering it is completely different**. This is the fundamental logic behind the 90:10 principle.

3. A Ship Is Built Twice

One of the most powerful ways of understanding the principle is to recognise that **every ship is effectively built twice**.

The first ship exists in the form of engineering information. It includes:

- Owner's requirements;
- Technical specifications;
- Contract clauses;
- General arrangement;
- Machinery selection;
- Electrical philosophy;
- Structural calculations;
- Production drawings; and
- Equipment interfaces.

Only when this engineering model has reached sufficient maturity does the physical ship begin to emerge through fabrication and construction. The first ship is therefore an **information ship**.

The second ship is the physical vessel. The quality of the second ship is heavily influenced by the quality of the first. If the engineering model contains ambiguity, contradictions, omissions or unrealistic expectations, those deficiencies do not disappear when construction starts. They are transferred into steel, machinery, piping, electrical systems and production processes.

This leads to a practical management principle: **Do not use the production stage to solve problems that should have been solved during engineering.** Production should primarily be the controlled execution of a mature engineering definition. That does not mean construction will never generate changes. Shipbuilding is too complex for that. It means that **avoidable changes should be driven out before production**.

4. Engineering Decisions Have a 25–30 Year Consequence

A common mistake is to view engineering decisions only in terms of construction. In reality, many engineering decisions remain with the vessel for decades. Consider something as apparently simple as selecting a ballast pump. The selection affects much more than pump procurement.

It influences:

- Energy consumption;
- Electrical load calculations;
- Piping arrangements;
- Machinery-room layout;
- Maintenance accessibility;
- Spare-parts inventory;
- Commissioning procedures;
- Crew training; and
- Lifecycle operating cost.

Multiply this decision by the thousands of components installed on a modern vessel. The cumulative effect becomes enormous. The ship's future operating profile is therefore embedded within countless engineering decisions made before construction. A vessel may remain in service for 25–30 years. During that period, the owner will pay for fuel, maintenance, spare parts, repairs, crew time, downtime and regulatory compliance.

Consequently, the economic question should not be: **"What is the cheapest equipment we can install?"**

It should be: **"What engineering solution provides the best value over the vessel's operational life?"**

This is the beginning of lifecycle thinking.

5. The Cost of Change Curve

One of the strongest arguments for pre-contract engineering is the changing cost of modification as a project progresses. During concept design, a modification may require only a few hours of engineering effort.

- During detailed engineering, the same change can affect several disciplines.
- During procurement, it may require cancellation or modification of purchase orders.
- During production, it may require dismantling completed work.
- During commissioning, testing may have to be repeated.
- After delivery, the same modification could require operational downtime, dry-docking, class approval and substantial expenditure.

Simple economic principle: The earlier a problem is identified, the cheaper it is to solve. The implication for shipbuilding management is significant. A project manager should not measure the productivity of the pre-contract engineering team merely by the number of drawings produced. The team should also be evaluated on its ability to **identify and eliminate future problems before they become physical problems**. In that sense, engineering hours spent before steel cutting are not overhead. They are **risk-reduction investment**.

6. Technical Specifications: The Engineering DNA of the Vessel

The technical specification is often treated as an attachment to the shipbuilding contract. This is a BIG mistake. The specification is effectively the **engineering DNA of the vessel**. It establishes equipment quality, performance requirements, inspection requirements, testing philosophy, commissioning procedures, documentation, training, warranty obligations and lifecycle maintainability. **A weak specification creates room for interpretation.** One party may interpret "high-quality equipment" differently from another.

One party may understand "adequate access" as sufficient; another may expect complete maintenance clearance. One may interpret "equivalent equipment" as any product meeting basic performance requirements, while another may expect equivalent reliability, lifecycle support and spare-parts availability.

These differences often remain invisible until construction begins. Then they become technical queries, commercial negotiations, variation orders or disputes.

A strong specification converts expectations into measurable requirements.

It answers:

- What is required?
- What performance must be achieved?
- How will performance be demonstrated?
- Who is responsible?
- What documentation is required?
- How will the equipment be maintained?

The better these questions are answered before contract signing, the lower the uncertainty during construction.

7. Shipbuilding Contracts Are Also Engineering Documents

Shipbuilding contracts are naturally viewed as legal and commercial documents.

However, they are also **engineering documents**.

- A contract clause concerning owner's supply affects procurement.
- A clause concerning builder's supply affects responsibility.
- A variation clause affects design control.
- Acceptance-testing requirements affect commissioning.
- Guarantee clauses affect performance verification.
- Interface responsibilities affect engineering coordination.
- Commissioning responsibilities determine who must provide resources and technical attendance.

The source document therefore argues that contractual provisions must be considered as part of the engineering framework rather than being developed independently of it.

This has an important implication for shipbuilding organisations.

- Contract departments,
- Engineering departments,
- Procurement teams,
- Production teams and
- Owner representatives

All these teams should not operate as isolated silos during contract development. A technical issue that appears minor to the commercial team may create a major engineering consequence. Similarly, an engineering decision may have a substantial contractual implication.

The contract should therefore be engineered as carefully as the vessel. A balanced contract provides clarity regarding responsibilities and encourages collaboration rather than creating uncertainty that later turns into claims.

8. Why Production Excellence Alone Is Not Enough

Modern shipyards can possess impressive production capabilities.

They may have:

- advanced CNC cutting;
- Automated welding;
- Large dry docks;
- Heavy-lift cranes;
- Sophisticated planning software;
- Modular construction;
- Highly trained production teams.

Yet production capability alone does not guarantee project success. Imagine a vessel where the machinery arrangement was developed without adequate maintenance-access review. The shipyard may fabricate every component perfectly. The welding may be excellent. The dimensional accuracy may be outstanding.

The coating may be flawless. But if a critical pump cannot be removed without dismantling adjacent equipment, the vessel still has a lifecycle problem. Similarly, a technically perfect installation of equipment that was poorly specified may result in:

- Excessive energy consumption;
- Difficult maintenance;
- Inadequate spare-parts support;

- Poor crew ergonomics;
- Unexpected operating costs.

The shipyard has executed the engineering correctly. The engineering itself was inadequate. This distinction is crucial. **Construction quality and engineering quality are different dimensions of shipbuilding performance.** India's competitiveness therefore requires attention to both.

9. What Leading Shipbuilding Nations Teach Us

The source identifies an important characteristic of leading shipbuilding nations: competitiveness is associated not merely with production capacity but with **engineering maturity**.

Successful shipbuilding organisations commonly employ:

- standard vessel platforms;
- mature technical specifications;
- repeat production;
- integrated engineering systems;
- disciplined project scheduling; and
- continuous improvement.

This provides an important lesson for India. There is often a temptation to measure shipbuilding competitiveness through **physical infrastructure—dock size, crane capacity, fabrication area** or **annual steel-processing capability**. These are important metrics. But a globally competitive shipbuilding ecosystem also requires an **engineering knowledge infrastructure**. That includes:

- Standard specifications;
- Design libraries;
- Approved equipment databases;
- Standard contract clauses;
- Lessons-learned repositories;
- Digital engineering platforms;
- Experienced review teams;
- Disciplined configuration management.

A shipyard that repeatedly starts engineering from zero for every project may spend more time and incur greater risk than one that has mature platforms and standards. Standardisation is therefore not the enemy of innovation. It can be the foundation upon which innovation becomes faster and safer.

10. Implications for Indian Shipbuilding

India possesses significant maritime advantages. The country has a long coastline, a large maritime workforce, established engineering capabilities and increasing policy support for maritime development. The source places these advantages in the broader context of initiatives such as **Maritime India Vision 2030** and **Maritime Amrit Kaal Vision 2047**. The opportunity now is to convert these advantages into sustained shipbuilding competitiveness. Infrastructure expansion is necessary. But infrastructure must be accompanied by engineering maturity.

Several areas deserve particular attention.

10.1 Nationally Standardised Technical Specifications

India could develop mature baseline specifications for commonly built vessel categories. These could subsequently be customised for individual owners and projects. Such an approach could reduce repetitive engineering effort and shorten negotiation periods.

10.2 Multidisciplinary Pre-Contract Reviews

Owners, designers, shipyards, production engineers, operators, classification societies and equipment specialists should participate before contract finalisation. The objective should be to identify technical, commercial and operational problems while changes are still inexpensive.

10.3 Greater Owner Involvement

Operational personnel possess knowledge that is sometimes absent from design offices. Masters, Chief Engineers and experienced superintendents understand the practical consequences of maintenance access, equipment reliability, crew workload and system usability. Their involvement before contract signing can improve the quality of the engineering definition.

10.4 Digital Engineering

Digital engineering provides an opportunity to identify clashes, interface problems and design inconsistencies before construction. The objective is not simply to produce attractive 3D models. The objective is to use digital engineering as a **decision-making platform**.

10.5 Integrated Plan Approval

Plan approval should be integrated with engineering development rather than treated as a completely separate regulatory step. Early coordination among owners, shipyards, designers, classification societies and suppliers can reduce late modifications.

10.6 Schedule Engineering

Schedules should be based on engineering maturity rather than optimism.

A production schedule that assumes engineering will somehow catch-up during construction is inherently fragile.

10.7 Lessons Learned

Every delivered vessel should become a source of engineering knowledge for the next vessel.

Lessons should come from:

- Construction;
- Commissioning;
- Sea trials;
- Warranty claims;
- Maintenance;
- Operational experience; and
- Owner feedback.

Without a formal mechanism for capturing these lessons, the industry repeatedly pays to learn the same lessons.

11. A New Performance Metric: Engineering Readiness

The traditional shipbuilding milestone structure often emphasises steel cutting, keel laying, launching and delivery. These remain important. However, India could benefit from introducing another concept: **Engineering Readiness Before Steel Cutting**. Before production begins, management should ask: **Is the vessel sufficiently engineered to justify steel cutting?**

A meaningful readiness review could examine:

1. Are operational requirements frozen?
2. Is the technical specification sufficiently mature?
3. Are major equipment selections confirmed?
4. Are critical interfaces resolved?
5. Are required drawings sufficiently advanced?
6. Are long-lead equipment decisions complete?
7. Are class and owner approval processes adequately progressing?
8. Are construction and commissioning requirements understood?
9. Are quality requirements defined?
10. Are major risks identified and assigned?

The objective is not to demand that every detail be complete before steel cutting. That would be unrealistic. The objective is to ensure that **production is not being used to discover fundamental engineering requirements**.

12. The Role of the Owner

The 90:10 principle also places a significant responsibility on shipowners.

Owners sometimes expect shipyards to interpret broad operational expectations and convert them into detailed engineering solutions. That approach can produce ambiguity. The owner must first define what the vessel is expected to accomplish.

Questions should include:

- What trades will the ship perform?
- What cargoes will it carry?
- What ports will it visit?
- What operating conditions are expected?
- What level of reliability is required?
- What maintenance philosophy will be followed?

- What crew competencies are expected?
- What future regulatory changes should be anticipated?
- What lifecycle cost is acceptable?

Once these requirements are defined, they can be converted into measurable technical requirements.

This is where the owner transitions from being merely a purchaser of a ship to becoming an **active participant in engineering the ship**.

13. The Role of the Shipyard

The principle should not be interpreted as shifting responsibility away from shipyards.

The shipyard remains responsible for disciplined execution.

Once engineering decisions have been properly established, the shipyard must convert them into a physical vessel through:

- Production planning;
- Fabrication;
- Block assembly;
- Equipment installation;
- Testing;
- Commissioning;
- Sea trials;
- Documentation; and
- Delivery.

The source explicitly recognises this execution phase as the remaining component of the 90:10 framework.

The strongest shipbuilding model is therefore not **engineering versus production**.

It is: **Engineering Excellence + Production Excellence.** The first defines what should be built. The second ensures that it is built correctly.

14. A Practical Model for Indian Shipyards

The 90:10 principle can be converted into a practical management philosophy:

Step 1 — Define the mission

Understand what operational problem the vessel must solve.

↓

Step 2 — Convert mission into requirements

Develop measurable operational and technical requirements.

↓

Step 3 — Develop the engineering baseline

Prepare the technical specification, design philosophy and equipment standards.

↓

Step 4 — Test the engineering

Conduct multidisciplinary reviews involving owners, designers, production teams, operators, class and suppliers.

↓

Step 5 — Test the commercial framework

Ensure responsibilities, interfaces, guarantees, variations and acceptance criteria are clearly allocated.

↓

Step 6 — Test constructability

Ask whether the vessel can actually be built efficiently using the proposed design.

↓

Step 7 — Test lifecycle value

Evaluate maintenance, energy consumption, reliability, spares, training and future modifications.

↓

Step 8 — Establish engineering readiness

Only then proceed confidently towards production.

This sequence shifts the shipbuilding mindset from **"Start Building and Solve problems as they appear"** to **"solve problems before building begins."**

15. Beyond the 90:10 Ratio

The greatest value of the 90:10 principle is not the number 90. It is the question that the number forces us to ask. **How much effort are we investing before steel cutting?** If an organisation spends enormous resources correcting problems during construction, commissioning and operation, it should examine whether more effort should have been invested earlier. The ratio is therefore a management philosophy.

It encourages:

- Early decision-making;
- Engineering discipline;
- Multidisciplinary collaboration;
- Specification maturity;
- Lifecycle thinking;
- Contract clarity;
- Digital engineering;
- Risk reduction; and
- Continuous learning.

It also changes the definition of productivity. Productivity is not simply how quickly steel is fabricated. It is also how effectively uncertainty is removed before fabrication begins.

16. From Building More Ships to Building Better Ships

India's aspiration to become a stronger global shipbuilding nation will require more than increasing physical capacity. The country needs to build an ecosystem in which **engineering knowledge is treated as strategic infrastructure**.

This means developing national approaches to:

- Technical specification standardisation;
- Pre-contract engineering;
- Engineering reviews;
- Digital design;
- Plan approval;
- Project scheduling;
- Quality planning;
- Contract development; and
- Lessons-learned management.

The source proposes several such directions, including a National Shipbuilding Standardisation Committee, model technical specifications, standard contract clauses, a **National Maritime Lessons Learned Database, digital engineering** and **digital-twin technologies, standardised inspection** and t**esting, national training programmes** and closer **collaboration among shipyards, owners, designers, classification societies, universities** and **equipment manufacturers**. These initiatives can collectively strengthen the engineering foundation upon which Indian shipbuilding is built.

17. Conclusion: Excellence Begins Before Steel Cutting

Modern shipbuilding is becoming increasingly complex. Alternative fuels, environmental regulations, digitalisation, automation, cybersecurity, advanced machinery and sustainability requirements are adding new layers of engineering complexity. Yet one principle remains unchanged:

A successful ship is rarely the product of construction excellence alone - It is the result of sound engineering, comprehensive specifications, balanced contracts, realistic planning and disciplined execution. The 90:10 Principle is therefore best understood not as a mathematical formula but as a challenge to conventional shipbuilding thinking. The principle says that the most valuable opportunity to improve a vessel exists before the physical vessel exists. A ship is first created through requirements, specifications, designs, calculations, contracts and engineering decisions. It is then reproduced in steel. If the first ship is well engineered, the second has a strong foundation. If the first ship contains ambiguity, contradictions or omissions, the second ship will inevitably inherit them.

For India, this has profound implications - As the country seeks to strengthen its position in global shipbuilding and ship repair, investment in docks, cranes, fabrication technology and production capacity must be accompanied by equal attention to **pre-contract engineering excellence**.

The strategic question should therefore not simply be: **How many ships can India build?**

It should be: **How predictably, efficiently and economically can India engineer and build the right ships?**

The answer begins before the first steel plate is cut. The future competitiveness of Indian shipbuilding will depend on whether the industry is prepared to invest as much intellectual effort in engineering the vessel before construction as it invests physical effort in constructing it afterwards.

If that balance is achieved, India will not merely build more ships. It will build **better ships, with greater lifecycle value, fewer disputes, fewer avoidable changes and greater confidence among international owners**. That is the essence of the 90:10 Principle. **Great ships are engineered before they are built.**

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Combustion Fundamentals and Fuel Chemistry for Marine Alternative Fuels

Kaushik K. Seal, Saptarshi Basu

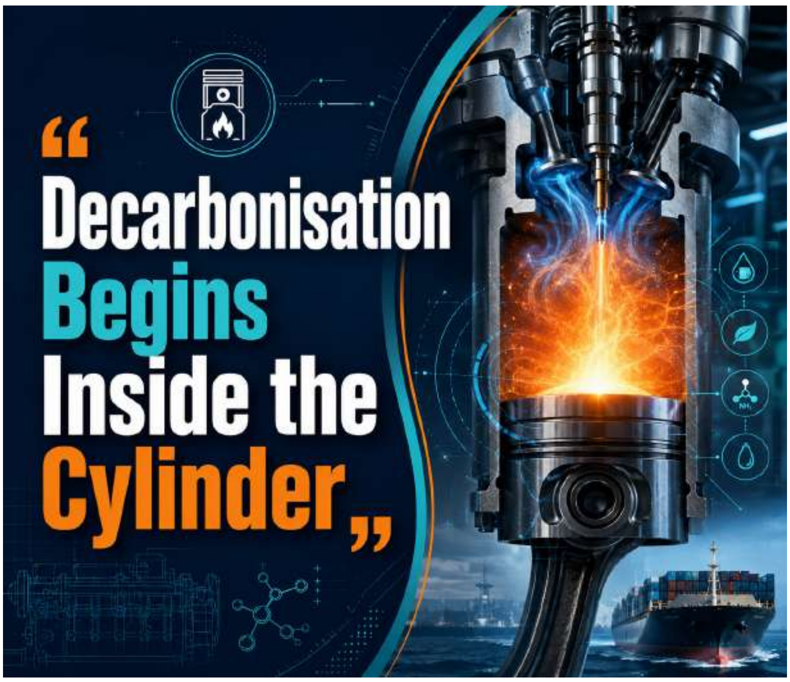
Abstract

Marine propulsion systems have historically relied on compression-ignition diesel engines optimised for fossil fuels with high energy density and predictable ignition behaviour. The International Maritime Organization's revised 2023 greenhouse gas reduction strategy mandates net-zero CO_2-equivalent emissions by 2050, with interim reduction targets of approximately 40 percent by 2030 and 70–80 percent by 2040. These regulatory drivers necessitate the rapid adoption of low- and zero-carbon marine fuels.

However, alternative fuels such as methanol, ammonia, LNG, LPG, hydrogen and biofuels exhibit combustion characteristics fundamentally different from conventional hydrocarbons. Differences in ignition delay, flame speed, heat-release behaviour, emissions formation and thermal stability require systematic modifications to engine design, control systems and operational practices. This paper presents a structured analysis of combustion fundamentals and fuel chemistry for emerging alternative marine fuels, integrating experimental research with practical large-bore marine engine considerations. The analysis demonstrates that safe, efficient and compliant decarbonisation depends not solely on fuel selection but on coordinated adaptation of combustion systems, injection strategies, air management and after-treatment technologies.

1. Introduction

Marine propulsion has relied on residual and distillate petroleum fuels for over a century due to their favourable ignition quality, high volumetric energy density and well-established handling practices. Compression-ignition



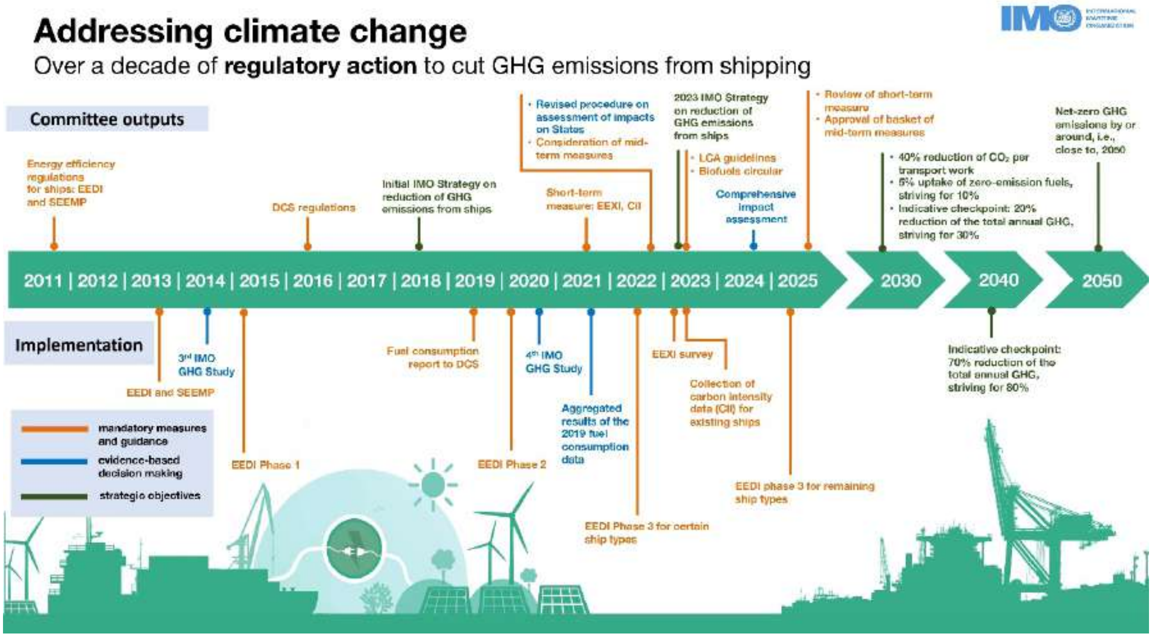


Figure 1: Drivers for Alternative Marine Fuel Adoption

diesel engines evolved around these fuels, achieving high reliability and thermal efficiency. The current regulatory environment, driven by the IMO GHG Strategy, regional emissions trading schemes and fuel carbon-intensity regulations, has disrupted this historical equilibrium.

Alternative marine fuels are increasingly required to meet future emissions targets. These fuels differ fundamentally from diesel in chemical composition, physical properties and combustion behaviour. Unlike conventional hydrocarbons, many alternative fuels possess low cetane numbers, high auto-ignition temperatures, or atypical flame propagation characteristics. As a result, marine decarbonisation has become a combustion-science challenge rather than a simple fuel-substitution exercise.

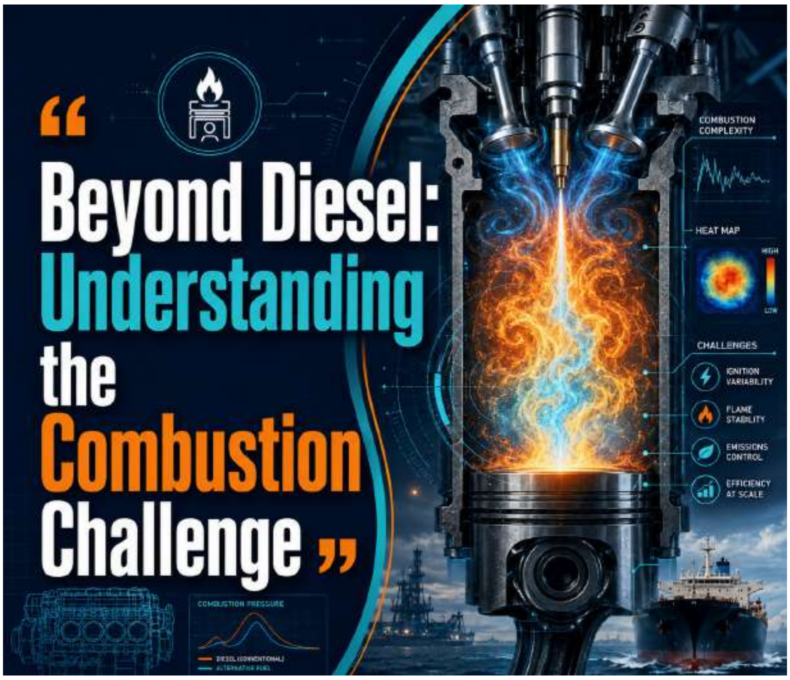
2. Scope and Methodology

This paper synthesises combustion research, spray-atomisation studies, engine-manufacturer data and classification-society guidance related to alternative marine fuels. The analysis focuses on compression-ignition engines, examining how fuel chemistry and physical properties influence ignition delay, flame development, heat-release rate and emissions formation. Findings are interpreted in the context of large-bore two-stroke and four-stroke marine engines operating under IMO Tier III and future GHG constraints.

3. Combustion Fundamentals of Marine Fuels

3.1 Fuel Molecular Structure and Reactivity

Fuel molecular structure governs ignition quality, flame speed and pollutant formation. Conventional marine fuels consist of long-chain hydrocarbons with moderate to high cetane numbers, enabling reliable auto-ignition. Methanol is a simple oxygenated alcohol with very low cetane number, resulting in poor compression-ignition capability but inherently clean combustion. Ammonia contains no carbon and therefore produces no CO_2 during combustion, yet its slow chemical kinetics and narrow flammability range severely constrain stable ignition. Hydrogen exhibits extremely high reactivity and flame speed, creating challenges in ignition control. LNG and LPG consist of shorter hydrocarbon chains that reduce soot formation but resist auto-ignition due to high octane



characteristics. Biofuels resemble diesel most closely, though oxygenated variants alter combustion chemistry and emissions behaviour.

3.2 Ignition Delay Characteristics

Ignition delay is a critical determinant of combustion stability and pressure-rise rate. Diesel fuel exhibits short ignition delay due to high cetane number. Methanol shows prolonged ignition delay and typically requires pilot fuel or assisted ignition. Ammonia displays the longest ignition delay among candidate fuels and cannot sustain stable combustion without pilot fuel, increased compression, or hydrogen blending. Hydrogen ignites readily but is prone to pre-ignition and knock. LNG and LPG require pilot ignition and careful air–fuel ratio control. Biofuels generally exhibit ignition behaviour close to diesel, with modest variations depending on composition.

3.3 Spray Atomisation and Mixture Formation

Fuel atomisation strongly influences mixture quality and combustion completeness. Diesel produces heterogeneous sprays with relatively large droplets, contributing to soot formation. Methanol's low viscosity promotes fine atomisation and rapid evaporation, though charge cooling can delay ignition. Ammonia injection presents challenges due to storage conditions and narrow flammability limits, requiring specialised injector design. LNG and LPG rely on gaseous mixing rather than liquid spray behaviour. These differences underscore the need for fuel-specific injection-system design.

3.4 Flame Development and Heat-Release Behaviour

Heat-release characteristics vary significantly among fuels. Methanol generally produces a longer, smoother heat-release profile than diesel, reducing peak pressure-rise rates. Ammonia combustion is characterised by slow flame propagation and extended combustion duration, often continuing into the expansion stroke. Hydrogen burns extremely rapidly, increasing peak pressures and combustion noise. LNG and LPG exhibit moderated flame temperatures and reduced soot but can suffer from unburned fuel slip. Biofuels typically follow diesel-like heat-release patterns with improved soot oxidation.

4. Pollutant Formation Mechanisms

Pollutant formation depends on flame temperature, oxygen availability and fuel chemistry. Thermal NOx formation increases with peak flame temperature

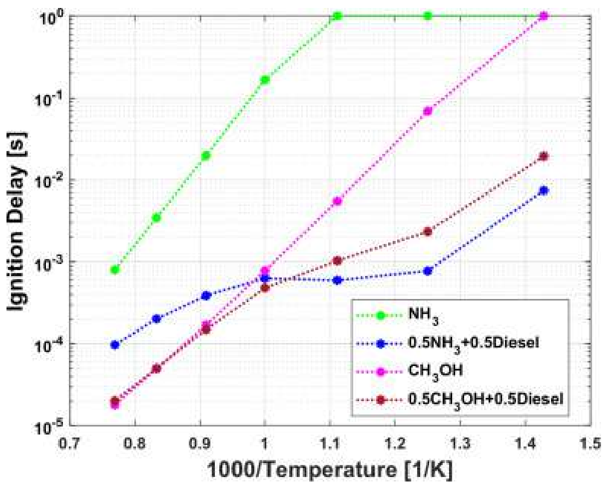
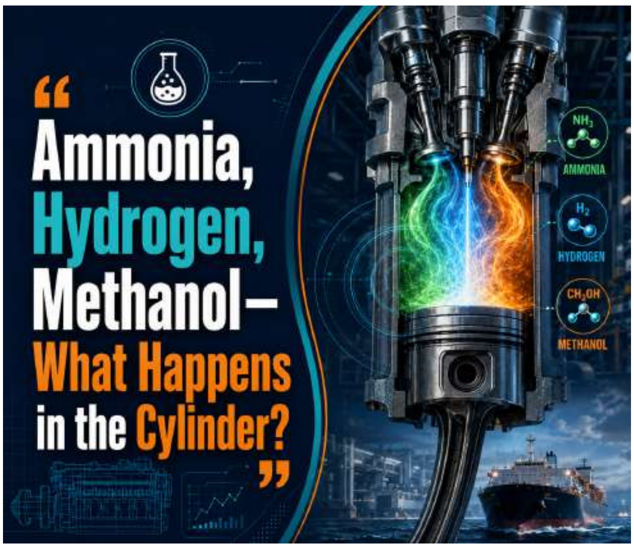
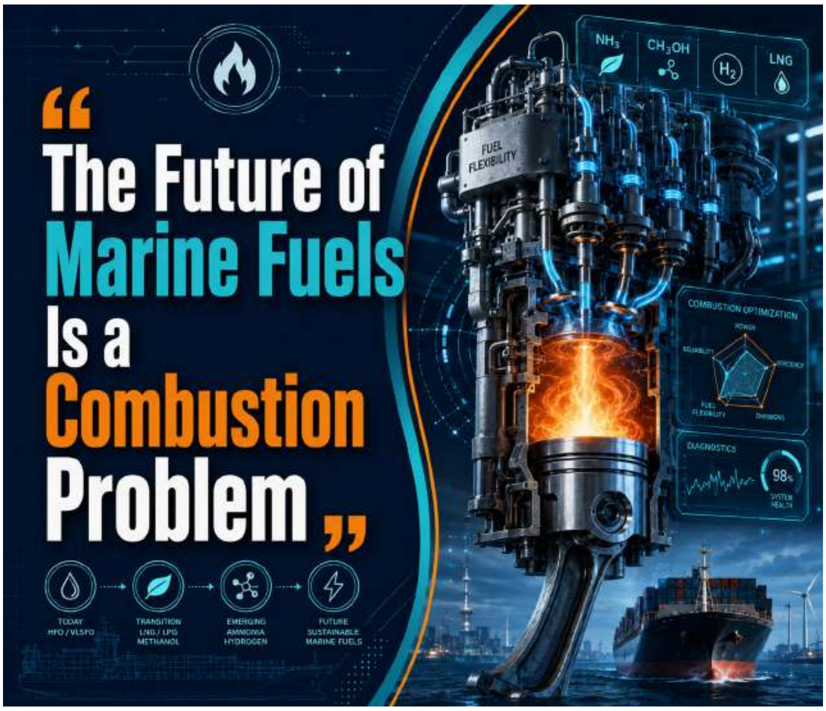


Figure 2: Comparative Ignition Delay Behaviour of Marine Fuels





and residence time. Ammonia introduces fuel-bound nitrogen, which can form NOx and nitrous oxide, a potent greenhouse gas. Soot formation correlates with carbon-chain complexity and locally rich zones, explaining the low particulate emissions of methanol, hydrogen, ammonia and gaseous fuels. Methane slip from LNG engines presents a significant life-cycle climate challenge. CO_2 emissions scale directly with fuel carbon content, highlighting the potential advantages of zero-carbon fuels.

5. Fuel-Specific Combustion Challenges

Methanol offers clean combustion with minimal soot but suffers from poor auto-ignition. Ammonia provides zero-carbon combustion yet requires extensive combustion enhancement and advanced after-treatment to control NOx and ammonia slip. Hydrogen delivers high efficiency but presents severe ignition control and safety challenges. LNG and LPG reduce particulate and sulphur emissions but rely on pilot ignition and methane-slip mitigation. Biofuels offer near drop-in compatibility but require attention to material compatibility, fuel stability and cold-flow properties.

6. Discussion

The comparative analysis demonstrates that conventional diesel engines owe their success to favourable ignition quality and predictable combustion. Alternative fuels disrupt this balance by altering ignition delay, flame speed and emissions pathways. Effective adoption requires integrated engine redesign, including injection strategies, combustion-chamber optimisation, air-management systems and after-treatment technologies. Without this integrated approach, emissions benefits may not materialise and operational risks may increase.

7. Conclusion

Marine decarbonisation is fundamentally a combustion challenge. Alternative fuels cannot be implemented successfully without understanding how their chemical and physical properties influence ignition, flame development, heat release and pollutant formation. Engine performance, safety and regulatory compliance depend on coordinated adaptations across fuel systems, combustion hardware, control strategies and emissions after-treatment. A combustion-science-based framework is therefore essential for guiding future marine engine development, retrofit strategies and multi-fuel propulsion pathways.

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Understanding Shipboard Brushless Alternators and Practical Defect Rectification

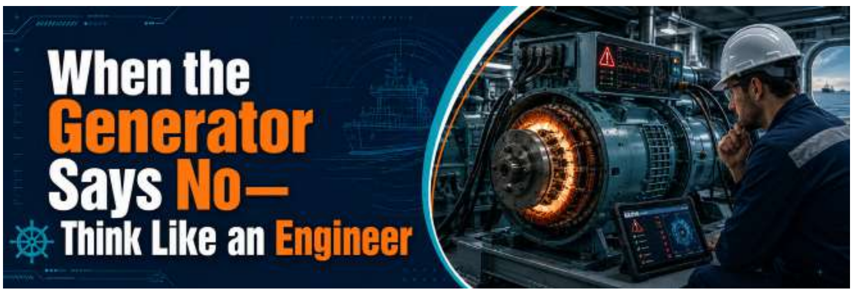
Jagabandhu Majumder

Abstract

This article presents an in-depth, practical guide to the construction, operating principles, static excitation arrangements, common faults and step-by-step troubleshooting procedures for shipboard brushless alternators. It is written for industry professionals who may be required to diagnose and rectify alternator defects aboard ship, often without an ETO present. The document preserves the original figures and includes placeholders for photographic and schematic material. It adds expanded troubleshooting flows, test methods, maintenance practices, safety precautions and recommended repairs to enable confident, safe restoration of generator service at sea or in port.

Introduction

The alternator is the prime onboard electrical power source for a vessel and is central to the safe operation of propulsion auxiliaries, navigation systems, communications and hotel services. Brushless alternators are the preferred machine on many ships because they eliminate slip-ring brushes and commutator wear, thereby lowering maintenance requirements and improving operational reliability.



However, the excitation and rectification subsystems of brushless machines remain common failure points. Without prompt and correct diagnosis, faults in the exciter, rotating rectifier (diode plate), varistor, AVR, or associated wiring can lead to loss of output, erratic voltage regulation, overheating, or complete generator failure, creating hazardous situations at sea.

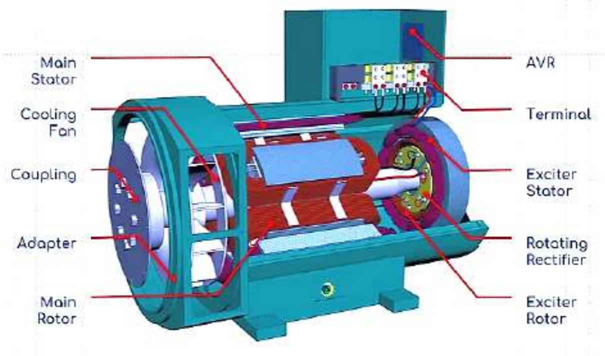
This article provides a systematic approach to understanding these machines, the static excitation systems commonly fitted on ships and the practical steps required to rectify defects. It integrates theory with practical test procedures, describes inspection and measurement techniques and suggests appropriate corrective actions consistent with safety and maker guidance.

Construction and Key Parts of a Brushless Alternator

A brushless alternator is effectively two electrical machines mounted coaxially on the same shaft: an exciter and a main alternator.

Each component plays a specific role in producing regulated three-phase output:

- **Exciter:** The exciter may be configured as a rotating field with a stationary armature or the reverse depending on the design. The exciter generates an alternating voltage that is subsequently rectified by the rotating rectifier assembly.
- **Rotating rectifier assembly (diode plate):** This assembly contains the diodes (and sometimes thyristors) that convert the exciter AC into DC. The DC feeds the main field winding (rotor) and thereby establishes the magnetic flux required for the main alternator output.
- **Main rotor (field winding):** Receives DC excitation via the rectifier assembly. Its magnetic flux, combined with rotor speed, determines the induced emf in the stator.
- **Main stator:** The stationary three-phase winding that generates the usable AC output to the ship's switchboard.
- **Automatic Voltage Regulator (AVR) and static excitation circuitry:** Measures generator output and controls the firing or bypassing of rectifiers/thyristors to regulate field current and maintain terminal voltage within specified limits.
- **Protective components:** Varistors, blocking diodes, current transformers (CTs), potential transformers (PTs), reactors and capacitors are often included to manage surge protection, sensing and transient response.



Operating Principle and Voltage Control

The fundamental operating principle follows Faraday's law: the induced emf E in the stator is proportional to the magnetic flux Φ and the rotational speed N ($E \propto \Phi \cdot N$). With the prime mover maintaining a relatively constant rotational speed during generation, the terminal voltage is controlled by adjusting the rotor flux (Φ), achieved by varying the DC current in the main field winding.

In brushless systems, the rotating exciter and diode plate provide DC to the main rotor without the need for external brushes. The AVR regulates the excitation by sensing terminal voltage (and sometimes frequency) and controlling the excitation unit to maintain voltage under load changes. Static excitation systems use a combination of sensing transformers, compound transformers, reactors, capacitors and thyristor bypasses or controlled rectifiers to achieve fast and stable voltage regulation.

Static Excitation System — Components and Functions The static excitation arrangement commonly encountered on ships features a compound transformer with PT and CT primary windings, an exciter, rotating rectifiers, AVR electronics and thyristor bypass/SCR devices. The compound transformer vectorially adds PT and CT inputs on its secondary and contributes to control signals that help correct excitation during load transients.

Key elements and roles:

- **Compound transformer (PT and CT primaries)**: Produces a composite secondary voltage that represents combined voltage and current feedback for improved regulation.
- **Reactor coils (L1–L3) and capacitors (C1–C3)**: Create inductive effects and resonance conditions that assist voltage build-up at no load and shape the dynamic response during load changes (impedance matching).
- **Rotating diodes (rotary rectifier)**: Convert exciter AC to DC for the main rotor; diodes must be sound and thermally secure to provide consistent excitation.

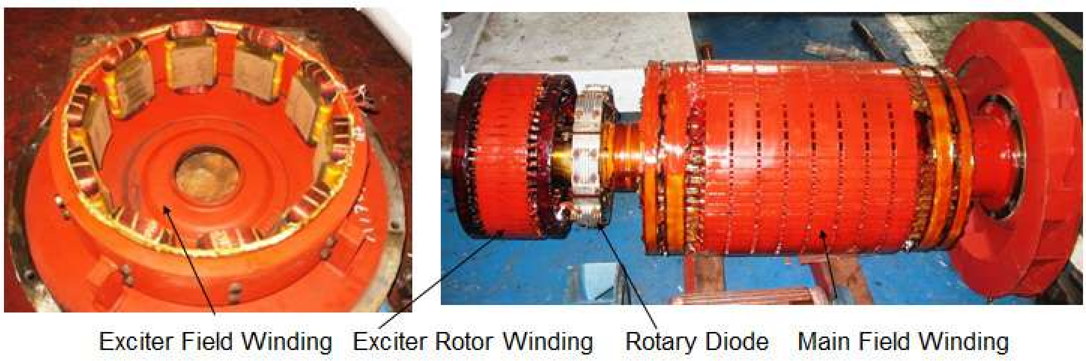


Figure 1. Parts of Brushless Alternator

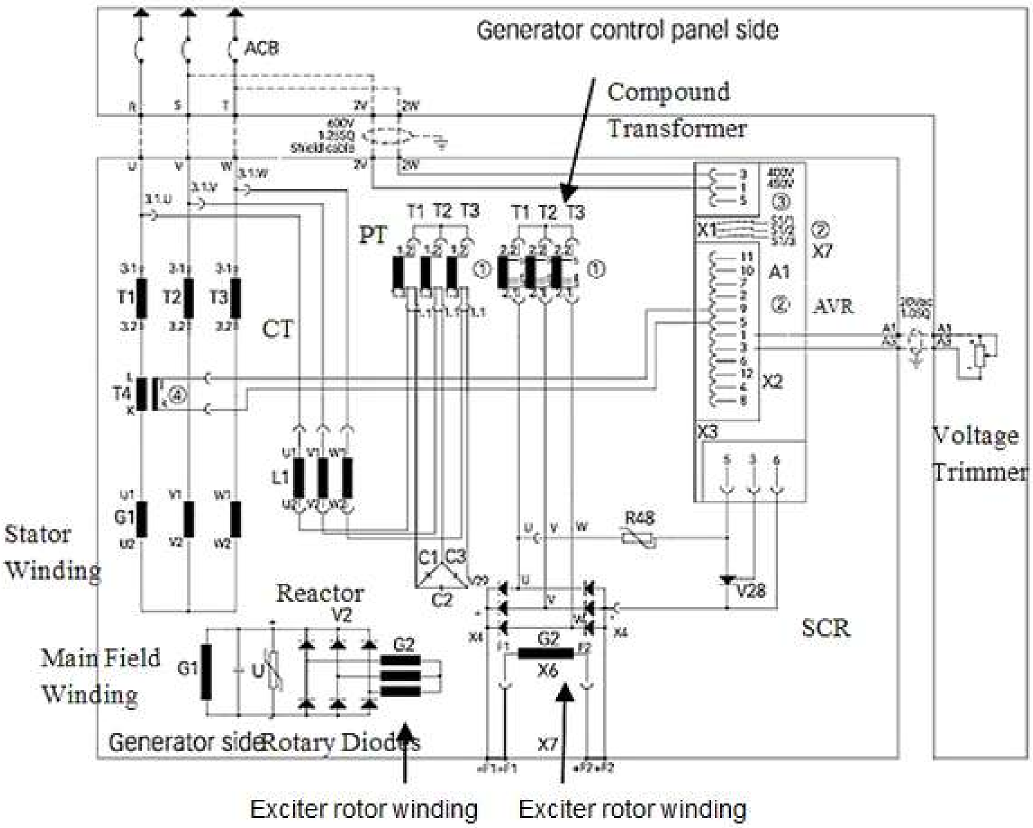


Figure 2. Circuit diagram of Brushless Alternator

- **SCR V28 and thyristor bypass**: Controlled by the AVR gating signal to bypass variable excitation, enabling fine voltage control and rapid correction of deviations.
- **Varistor (MOV)**: Protects diodes and rotor windings from voltage surges; a failed varistor that short-circuits the excitation supply will prevent the main rotor from energising.

Residual Magnetism and Voltage Build-Up Residual magnetism in the rotor and iron core is essential for the initial generation of induced voltage when the alternator shaft is first driven. This small remnant flux produces the initial excitation for the exciter, which, after rectification, supplies field current to the main rotor and causes voltage to build up. Extended periods of generator inactivity or demagnetising events (high-temperature exposure, mechanical impact, or prolonged over-excitation) can remove residual magnetism and prevent voltage build-up on start. Field flashing (controlled application of DC) is used to restore residual flux when required.

Common Faults:

Symptoms, Causes and Detailed Rectification Procedures

The following faults are the most prevalent issues in brushless ship alternators. For each, this section provides likely causes, diagnostic tests and step-by-step corrective actions.

Fault 1 — Generator output is 0 V Likely causes:

- Loss of residual magnetism.
- Open circuit in the rotor main field winding.
- Shorted varistor or other protective device shunting excitation.
- Total failure of exciter or diode plate; disconnected or open wiring.

Diagnostic and rectification flow:

1. **Safety and isolation:** Place the generator in maintenance mode, isolate from the switchboard, tagout and ensure the prime mover cannot start accidentally.
2. **Confirm zero output:** Measure line-to-line and line-to-neutral voltages at terminals and the AVR sensing points.

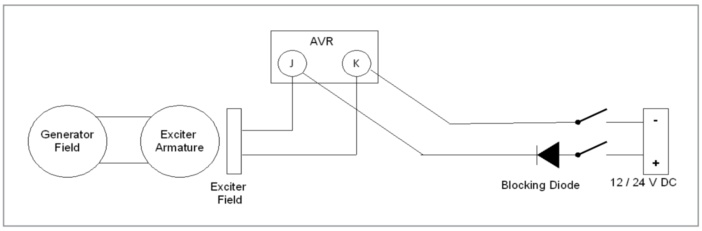


Figure 3. Rotary Diodes and Break in Main Field Winding

3. **Check for absence of residual magnetism:**

- If the generator has been idle for long periods, attempt a controlled field flash following OEM guidance.
- Use a current-limited DC source and observe correct polarity when applying across the diode plate or dedicated flashing terminals for only a few seconds.
- Immediately remove supply and attempt to turn the generator; observe whether voltage begins to build.
- Field flashing must be performed by a qualified person with awareness of potential damage to diodes and varistors if applied incorrectly.

4. Inspect rotor continuity and diode plate:

- Visually inspect the diode plate. Look for browning, cracks, or signs of overheating.
- Disconnect the diode plate wiring and measure resistance across rotor field terminals (between + and – of the diode plate) with an appropriate instrument. A very high or open reading indicates an open rotor field requiring rewind or repair.
- Perform an insulation resistance test (megger) between rotor winding and shaft/earth. Low insulation indicates degraded winding insulation or shorting that must be addressed.

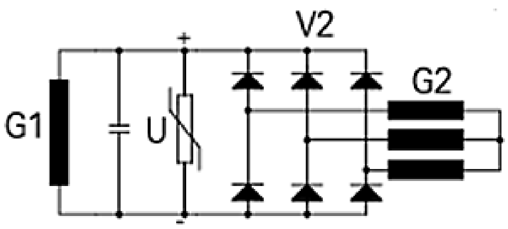


Figure 4. Checking for rotor continuity

5. Test varistor and protective components:

- A shorted MOV will clamp the excitation supply and prevent field buildup. If removable, measure resistance; replace any MOV showing short or degraded characteristics.
- Check blocking diodes and low-voltage DC supplies to the AVR (12/24 V circuits) for continuity and correct operation.

Corrective actions:

- If residual magnetism was the only issue and field flashing restored voltage, monitor for stable output and record the event.
- If rotor winding open: arrange for rotor removal and rewinding or replacement of the field winding; this is a workshop-level repair requiring specialised equipment.
- If diode plate faults are identified: replace the rotating rectifier assembly, ensure correct installation torque and perform dynamic balancing if required by the maker.

- Replace shorted varistors and verify the integrity of surge arresting components.

Fault 2 — Alternator output low (approx. 50 V) Possible causes:

- Broken connection or partial open-circuit in the exciter field winding or its wiring.
- Partial failure or leakage in rotating rectifier diodes reducing DC output.
- AVR misadjustment (trimmer) or defective sensing circuit.

Testing and rectification:

1. Inspect and tighten all exciter field connections, terminations and bonding points.
2. With the prime mover turning and generator isolated, measure DC excitation voltage at the rotor via the diode plate. Compare against expected values from the OEM manual.
3. Test diodes individually (after safe isolation) using a diode tester or multimeter in diode mode; detect leakage or partial shorting.
4. Check AVR input signals: PT/CT wiring, voltage sensing leads and compound transformer outputs. Incorrect vectorial addition or faulty CT/PT primaries will mislead AVR and reduce excitation drive.
5. Corrective actions include repairing broken connections, replacing faulty diodes, correcting PT/CT wiring and recalibrating or replacing the AVR.

Fault 3 — Voltage drops as load increases (voltage collapse under load)

Probable causes:

- One or more rotating diodes open-circuit, limiting excitation under load.
- AVR or thyristor misfiring, reducing field current when load increases.
- Current-limited excitation transformer or insufficient excitation due to resistor/reactor failure.

Diagnostic steps:

1. Observe DC excitation current while increasing load in a controlled manner; a decreasing excitation current under load strongly indicates rectifier or AVR/SCR issues.
2. Test rotating rectifier diodes and static rectifiers under load conditions where practical, or remove and bench-test if necessary.
3. Inspect AVR gate signals and SCR V28 firing under varying loads using an oscilloscope to detect missed pulses or inconsistent gating.
4. Replace any open diodes and repair gating circuits or SCR devices; recalibrate AVR to respond correctly to load transients.

Fault 4 — Output low around 100 V (partially reduced excitation)

Causes and remedies:

- Multiple diodes open or degraded, reducing DC field supply.
- Defective SCR V28 (if present) or bypass thyristor not functioning.
- Replace defective rectifier diodes and/or SCR devices, verify thermal management of the rectifier assembly and ensure proper mechanical fit and insulation.

Fault 5 — Output high or low but adjustable only with voltage trimmer (AVR suspected)

Symptoms and action:

- If generator voltage can be slightly adjusted by the trimming pot but regulation remains poor, the AVR electronics may be failing or its sensing circuit compromised.
- Use diagnostic procedures in the AVR manual to inject reference signals, monitor gate pulse amplitude and timing and verify internal component health.
- Replace the AVR if it cannot maintain regulation within specified tolerances or if repairs are not feasible at sea.

Practical Test Equipment and Measurement Techniques

Proficient diagnosis requires an appropriate suite of tools:

- Digital multimeter (true RMS) for AC and DC voltage and basic diode tests.
- Insulation resistance tester (megger) for rotor winding to ground tests and stator insulation checks.
- Clamp-on DC ammeter (or Hall-effect clamp) to measure excitation currents where accessible.

- Oscilloscope or portable scope to observe AVR gate pulses, SCR firing and waveform distortions.
- Diode tester or dedicated rectifier test jig for bench testing of rotating diodes removed from the assembly.
- Current-limited DC source or battery with suitable limiting resistor for controlled field flashing (strictly following OEM guidance).

Maintenance Best Practices and Preventative Measures

- Operate generators under periodic load to maintain residual magnetism and exercise excitation components; prolonged idling increases risk of lost residual flux.
- Keep records of AVR trim positions, excitation currents, diode plate temperatures and historical repair actions to support trend analysis and predictive maintenance.
- Inspect rotating rectifier assemblies and varistors during scheduled maintenance for discoloration, cracked insulating supports, loose fasteners, or thermal damage.
- Replace varistors after major surge events as a preventive measure if their health is uncertain.
- Keep wiring diagrams for the generator control panel accessible and ensure terminals are labelled correctly to expedite troubleshooting.

Safety and Workshop Considerations

- Always follow lockout/tagout and safety procedures before performing any tests or opening generator housings. Electrical tests on rotating assemblies must be performed with the generator isolated and the prime mover secured.
- Field flashing can damage diodes or varistors and should be performed only with the correct current-limited supply and by personnel trained in the procedure.
- Rotor removal, rotating rectifier replacement and rotor rewinding are major operations that typically require specialised lifting, balancing and testing equipment. When in doubt, coordinate with the manufacturer or an experienced electrical workshop.

Troubleshooting Flow Summary (step-by-step)

1. Verify and isolate: Confirm symptoms and isolate generator from distribution.
2. Check residual magnetism: Attempt controlled field flashing if necessary.

3. Measure DC excitation: Verify rectifier output and rotor field voltage.
4. Inspect diode plate/varistor: Visually and electrically test rotating rectifier assembly.
5. Test AVR and sensing: Check PT/CT wiring and AVR gate signals during a controlled run.
6. Replace defective components: Diodes, varistors, SCRs, or AVR modules as indicated.
7. Reassemble and restart: Test without load, then gradually introduce load while monitoring voltage and excitation stability.
8. Record findings and corrective actions for future reference.

Conclusion

This article synthesises the fundamental construction, operating principles and static excitation architecture of shipboard brushless alternators and has translated common failure modes into a practical, stepwise diagnostic and rectification framework for maritime engineering practitioners. Emphasis on the roles of residual magnetism, the rotating rectifier assembly, varistor protection and the AVR/thyristor control loop highlights that the majority of operational outages are attributable to excitation-path defects that are detectable through systematic measurement, visual inspection and controlled intervention (field flashing, diode testing, insulation measurement).

The practical troubleshooting sequences and test methods presented herein are intended to reduce at-sea downtime by enabling accurate fault isolation—distinguishing between reversible field-loss conditions and workshop-level mechanical or winding defects that necessitate rotor removal or rectifier replacement. Preventive measures (periodic loaded operation, routine inspection of diode plates and MOVs, record-keeping of AVR settings and excitation currents) are shown to materially lower failure incidence and simplify corrective actions.

From a safety and asset-management perspective, adherence to lockout/tagout procedures, OEM-specific field-flashing protocols and prescribed workshop practices for rotor repairs remain indispensable. Finally, integrating the diagnostic workflow with trend recording and supplier-assisted overhaul strategies will improve reliability and lifecycle outcomes and should be considered standard practice for shipboard electrical plant management.

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Manufacturer-Specific References

For any actual shipboard troubleshooting or repair, the following vessel-specific documents should additionally be consulted:

1. Alternator manufacturer's *Installation, Operation and Maintenance Manual (IOM)* for the specific generator model installed onboard.
2. Alternator manufacturer's *Excitation System and Rotating Rectifier Circuit Diagram*.
3. AVR manufacturer's *AVR Commissioning, Adjustment and Fault-Finding Manual*.
4. Vessel's *Main Generator and Main Switchboard Electrical Schematic Diagrams*.
5. Vessel's *Planned Maintenance System (PMS) — Main and Emergency Generator Maintenance Procedures*.
6. Vessel's *Generator Protection, Synchronising and Load-Sharing System Manuals*.
7. Classification society-approved *Generator Protection and Electrical Distribution Drawings* applicable to the vessel.

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Fire in the Machinery Spaces: Engineering Reconstruction of Engine-Room Fire Scenarios

(Marine Engineering Accident Investigation Series)

Gajanan Karanjikar

Abstract

Machinery-space fires remain among the most serious casualties encountered on board ships because machinery spaces contain multiple sources of fuel, heat, electrical energy, lubricants and combustible materials within a confined environment. A seemingly minor oil leak can rapidly develop into a major fire when combustible oil comes into contact with an inadequately protected hot surface or electrical source.

For an effective accident investigation, an engine-room fire should not be treated simply as a fire event. It should be reconstructed as a sequence involving fuel release, ignition, fire development, fire detection, crew response, fuel and ventilation isolation, fixed firefighting-system operation and eventual containment. The location showing the greatest fire damage is not necessarily the point of origin.

This article presents an engineering approach to reconstructing machinery-space fire scenarios. It examines ignition-source identification, oil-leak management, fire-load assessment, fixed firefighting-system performance, thermal damage mapping, event reconstruction, human factors and the contribution of shipboard management systems. The article also considers the relevance of SOLAS Chapter II-2, the Fire Safety Systems (FSS) Code, the ISM Code and the IMO Casualty Investigation Code.

The objective is to move accident investigation beyond identifying the immediate cause and towards understanding the complete chain of technical, operational and organisational failures that allowed the fire to occur and develop.

Keywords: Machinery-space fire, engine-room fire, accident investigation, hot surfaces, oil leakage, fire load, CO_2 system, fire detection, SOLAS Chapter II-2, FSS Code, ISM Code, thermal damage mapping, human factors.

1. Introduction

Engine-room fires remain among the most feared casualties at sea. Unlike many other shipboard emergencies, a machinery-space fire can escalate rapidly because the engine room contains virtually all the ingredients required for sustained combustion: fuel oil, lubricating oil, hydraulic oil, electrical energy, hot surfaces, rotating machinery, insulation, plastics, paints and other combustible materials.

The confined geometry of the machinery space can further accelerate fire development. Once ignition occurs, flames and hot gases can spread vertically and horizontally through the machinery space, while ventilation systems may provide a continuous supply of oxygen. At the same time, fuel pumps, pressurised oil systems and hydraulic systems can continue feeding the fire unless they are rapidly isolated.

SOLAS Chapter II-2 establishes a comprehensive philosophy of fire prevention, detection, containment and extinction. Its fundamental approach is particularly relevant to accident investigation: ignition should first

be prevented; a fire should then be detected rapidly; its spread should be controlled; boundaries should contain it; and the fire should ultimately be extinguished effectively.

This philosophy also provides a useful framework for reconstructing an accident. An investigator should therefore avoid treating an engine-room fire as a single event. The fire seen by the crew is the final visible manifestation of a chain of events that may have started hours, days or even months earlier.

The central question is therefore not simply: **"How did the fire start?"**

It should be: **"What sequence of technical, operational and organisational conditions allowed a combustible release to become an uncontrolled machinery-space fire?"**

2. Understanding the Point of Origin

One of the first and most important questions in an engine-room fire investigation is:

What burned first?

This apparently simple question is surprisingly difficult to answer. By the time a machinery-space fire has been extinguished, the original scene may have been substantially altered. Firefighting water can redistribute soot and residues. Fire hoses may disturb equipment. Cable insulation may have been consumed. Lagging may have fallen away. Ventilation conditions may have changed dramatically during the event. Secondary combustibles can also produce extensive damage well away from the original ignition point. Consequently, the area showing the greatest damage is not necessarily the seat of the fire.

A sound investigation must distinguish between:

- the **primary ignition location**;
- subsequent flame spread;
- heat-radiation damage;
- secondary combustible involvement;
- smoke and hot-gas movement; and
- damage caused during firefighting and boundary cooling.

This approach is consistent with the principles of systematic casualty investigation, where evidence must be collected and evaluated to identify not only immediate causes but also underlying contributing factors.

2.1 Reconstruction rather than observation

The investigator should therefore reconstruct the fire backwards.

A useful conceptual sequence is:

Combustible release → ignition source → initial flame → fire growth → secondary involvement → detection → crew response → isolation → fixed-system activation → containment/extinction

Each stage must be supported by physical evidence, records or credible witness testimony.

3. The Classic Machinery-Space Fire Triangle

From an engineering perspective, many machinery-space fires can be explained through the interaction of three fundamental elements:

1. **A combustible material or fuel release**
2. **An ignition source**
3. **Failure of separation between the two**

A common initiating mechanism is oil escaping from a pressurised fuel-oil, lubricating-oil or hydraulic-oil system and impinging on an inadequately protected hot surface.

IMO guidance specifically addressing prevention of fires in engine rooms and cargo pump rooms identifies high-temperature surfaces above approximately **220°C**, together with oil leakage, surface protection and spray shielding, as important risk factors.

This makes the investigation of the oil-release pathway particularly important.

It is not sufficient to state: "Oil was present in the bilge."

Nor is it sufficient to state: "The exhaust system was hot."

The critical engineering questions are:

- Where did the oil originate?
- Was it under pressure?
- What component failed?
- What was the direction of the spray?
- Was the oil atomised?

- What surface did it contact?
- What was the temperature of that surface?
- Was the surface adequately insulated?
- Was spray shielding fitted?
- Had the shielding deteriorated?
- Was oil-soaked insulation present?

The difference between these questions can mean the difference between identifying a genuine causal mechanism and merely describing the post-fire condition.

4. Tracing the Ignition Source

Ignition-source tracing is therefore one of the most important phases of the investigation.

The investigator should establish the earliest credible contact between the combustible material and the heat or spark source.

4.1 Pipe and fitting failures

Particular attention should be given to:

- fractured pipes;
- failed fittings;
- loosened compression unions;
- damaged hose assemblies;
- failed hose reinforcement;
- vibration marks;
- leakage around pumps and filters;
- fuel-return manifolds;
- drains and valves; and
- temporary repairs.

The direction of oil spray can sometimes be reconstructed from the distribution of deposits and damage.

4.2 Hot-surface ignition

Where a hot surface is suspected, the investigator must determine more than whether the surface was hot.

Three questions are essential:

1. Was the surface hot enough?
2. Was it exposed sufficiently?
3. Was the released combustible material able to reach it?

An exhaust manifold, turbocharger component, boiler surface or other machinery component may have operated at a temperature capable of ignition. However, the presence of a hot component alone does not prove that it initiated the fire.

4.3 Electrical ignition

Electrical equipment presents a different investigative problem. Arc beads, localised melting, damaged terminals and signs of overheating may be present after almost any major machinery-space fire. Therefore, investigators must establish whether electrical arcing **initiated** the fire or whether the electrical equipment was **damaged by an already established fire**. This distinction is fundamental.

5. Oil Management: The Fire Often Begins Before the Flame

A significant number of engine-room fires can be regarded initially as **oil-management failures** rather than fire events.

Small and chronic leaks may become normalised during routine operation. Leakage from purifier lines, fuel pumps, filters, drains, return manifolds and quick-closing arrangements may be tolerated because the machinery continues to operate. Such conditions are dangerous because they progressively establish the fuel pathway required for a fire.

Typical warning conditions include:

- oil-soaked insulation;
- missing or damaged spray shields;
- overflowing drip trays;
- accumulated oil residues;
- leaking fittings;
- temporary hose repairs;
- degraded pipe supports;
- poor housekeeping; and
- persistent minor leakage.

These should not be treated merely as cosmetic defects. SOLAS Chapter II-2 addresses arrangements associated with oil fuel, lubricating oil and other flammable oils in machinery spaces, while the ISM Code establishes requirements for safe ship management, equipment maintenance and operational procedures.

5.1 The significance of temporary repairs

Temporary repairs deserve particular attention during an investigation. A temporary hose, clamp, seal or bypass arrangement may have been installed as an immediate operational measure but subsequently remained in service for an extended period.

The investigator should therefore ask:

- When was the temporary repair installed?
- Why was it installed?
- Was a permanent repair planned?
- Was the defect entered in the maintenance system?
- Was the risk formally assessed?
- Were repeated leak reports recorded?
- Did previous inspections identify the same condition?

The answers can reveal whether the fire resulted from an isolated component failure or from a deeper maintenance-management weakness.

6. Fire-Load Assessment

Once the ignition mechanism has been identified, the next step is to understand the **fire load**. Fire-load assessment is not merely a design calculation. It is highly relevant to post-casualty investigation.

The investigator should establish:

- The quantity of combustible material available;
- The rate at which fuel could be released;
- Whether the release was continuous or intermittent;
- Whether the fuel was under pressure;
- The presence of secondary combustibles;
- The availability of oxygen;
- The effect of ventilation; and
- The ability of the fixed firefighting system to control the resulting fire.

Secondary combustibles may include:

- Cable insulation;
- Lagging;
- Paint systems;
- Plastics;
- Cleaning materials;
- Oil residues;
- Rags; and
- Stored items.

A small leak that rapidly loses pressure may produce a short-duration fire. A pressurised oil spray that continues to be supplied can produce an entirely different fire scenario.

Similarly, an oil fire beneath cable trays can introduce substantial secondary fire load and smoke production.

Therefore, the investigator must determine whether the actual fire exceeded the assumptions under which the fixed firefighting system was designed and approved.

7. Fixed Firefighting Systems: Did the System Fail?

One of the most misunderstood questions following an engine-room fire is:

"Why did the fixed firefighting system fail?"

The answer cannot be determined simply by observing that a fire continued after the system was activated.

SOLAS Chapter II-2 requires appropriate fixed fire-extinguishing arrangements for relevant machinery spaces, while the FSS Code establishes the performance framework for fixed systems such as CO_2 and equivalent arrangements. Approved equivalent gas or water-mist systems may also be used where the required level of protection is demonstrated.

The investigation should therefore examine the entire suppression sequence.

7.1 Was the system ready?

The investigator should verify:

- Cylinder condition;
- Pressure and maintenance records;
- Release mechanism;
- Control-system condition;
- Alarms;
- Distribution piping;
- Nozzles;
- Remote controls;
- Inspection records; and
- Previous defects.

7.2 Was ventilation stopped?

If ventilation remains open, oxygen can continue to feed the fire and hot gases can continue to move through the space.

7.3 Was fuel isolated?

If quick-closing valves and remote fuel shut-offs are not operated, the fire may continue receiving fresh fuel.

7.4 Was the space properly secured?

The effectiveness of a fixed gas system depends on appropriate compartment isolation. Open doors, dampers, ventilation paths or boundary defects may reduce effectiveness.

7.5 Was the system released in time?

Delay is critical. A fire that could initially have been controlled may develop into a much larger event if the crew spends excessive time attempting local firefighting before deciding to evacuate and release the fixed system. Thus, a fixed firefighting system that appears to have "failed" may actually have been defeated by the **sequence of emergency response**.

8. Thermal Damage Mapping

A particularly valuable technique in post-fire investigation is **thermal damage mapping**.

This involves systematically recording the effects of heat throughout the machinery space.

Relevant evidence may include:

- Paint blistering;
- Aluminium deformation;
- Cable-tray collapse;
- Soot gradients;
- Cable-insulation failure;
- Warped deck plates;
- Melted polymers;
- Oxidised steel;
- Damaged lagging; and
- Directional flame-impingement patterns.

The purpose is not merely to create a photographic record. The objective is to reconstruct the spatial development of the fire.

By comparing hotter and cooler regions, investigators can identify:

- Likely areas of origin;
- Flame-travel paths;
- Smoke movement;
- Shielding effects;
- Areas of secondary fire involvement; and
- Areas subjected primarily to radiant heat.

Thermal mapping can also be used to test witness statements. A witness may report that the fire started near one item of machinery, while the physical damage pattern may indicate that the highest early thermal intensity occurred elsewhere. Physical evidence should therefore be treated as an essential partner to eyewitness testimony.

9. Reconstructing the Fire Minute by Minute

A strong investigation should develop a **minute-by-minute casualty timeline**.

Potential sources of information include:

- Fire detection records;
- Engine-room logs;
- Bridge logs;
- Alarm history;
- Vdr data, where available;
- Emergency-generator start records;
- Ventilation shutdown records;
- Remote-shutdown actions;
- Fixed firefighting-system activation records; and
- Crew testimony.

Such a timeline can expose important gaps between detection and response.

For example: **Fire detected → alarm acknowledged → crew investigates → fire confirmed → personnel evacuate → ventilation stopped → fuel isolated → fixed system released**

The time between each event may have had a decisive influence on fire development. The investigation should therefore identify not only **what action was taken**, but also **when it was taken**.

10. Human Factors and Decision-Making Under Pressure

Machinery-space fire investigations should not become exercises in blaming the crew. Human factors are an essential component of the engineering reconstruction. Crew members may hesitate before releasing a fixed gas system because doing so is operationally and commercially significant. They may believe that the fire can still be controlled locally. They may fear machinery damage, or they may be uncertain whether every person has escaped from the machinery space. These decisions are made under intense pressure, often in smoke, heat, noise and reduced visibility. Consequently, investigators should examine the system within which the crew was operating.

Questions should include:

- Were emergency controls intuitive?
- Were remote stops clearly marked?
- Were quick-closing valves readily accessible?
- Were fixed-system release procedures understood?
- Were drills realistic?
- Did the crew practise under blackout or reduced-visibility conditions?
- Had nuisance alarms become common?
- Were previous oil leaks treated as routine?
- Was the machinery space excessively cluttered?
- Could personnel safely reach critical controls?

These questions recognise that human behaviour is influenced by the design of equipment, procedures, training and organisational culture.

11. The Role of the ISM Code

The ISM Code becomes particularly important when the investigation moves beyond the immediate technical cause. Suppose a fuel-oil pipe failed and sprayed oil onto an exhaust surface. The immediate cause may be described as: **"Failure of fuel-oil pipe resulting in oil spray onto a hot surface."** But this does not explain the entire casualty.

A deeper investigation should ask:

- Was the pipe previously reported as defective?
- Was vibration known in that area?
- Were pipe supports adequate?
- Was the maintenance interval appropriate?
- Had previous leaks occurred?
- Was the hot surface adequately protected?
- Were spray shields fitted?
- Had insulation become oil-soaked?
- Did inspection procedures identify the condition?
- Were corrective actions closed effectively?

The ISM Code is intended to address safe ship management, maintenance, emergency preparedness and corrective action. Therefore, these organisational issues are not peripheral to an engine-room fire; they can form part of its causal chain.

12. Regulatory Framework

The principal regulatory instruments provide a coherent framework for analysing machinery-space fires.

SOLAS Chapter II-2

SOLAS Chapter II-2 addresses:

- Fire prevention;
- Fire detection;
- Fire containment;
- Structural protection;
- Means of escape; and
- Fire extinction.

Fire Safety Systems (FSS) Code

The FSS Code establishes performance requirements for fire detection and fixed firefighting arrangements, including systems protecting machinery spaces.

ISM Code

The ISM Code addresses the management system behind safe operation, including:

- Maintenance;
- Emergency preparedness;

- Procedures;
- Drills;
- Corrective action; and
- Safety management.

Casualty Investigation Code

The IMO Casualty Investigation Code provides the framework for systematic investigation of marine casualties and incidents.

Together, these instruments provide a benchmark against which shipboard practice, equipment condition, management systems and emergency response can be evaluated.

13. Legal and Financial Consequences

The consequences of a machinery-space fire can extend far beyond the damaged equipment.

Direct losses may include:

- Main and auxiliary machinery damage;
- Switchboard replacement;
- Cable renewal;
- Steel renewal;
- Insulation replacement;
- Specialist cleaning;
- Class attendance;
- Repairs and dry-docking.

If the fire results in blackout or loss of propulsion, the casualty can develop into a much larger maritime accident involving:

- Grounding;
- Collision;
- Berth damage;
- Salvage;
- Loss of cargo operations; or
- Pollution.

There may also be:

- Charter-party consequences;
- Off-hire;
- Cargo delay claims;
- Contamination claims;
- Voyage abandonment;
- Personal injury claims; and
- Fatality-related liabilities.

The investigation may also examine whether the vessel was seaworthy and whether the owner exercised due diligence in maintenance, leak prevention, hot-surface protection and emergency preparedness.

The significance of the maintenance record is therefore considerable.

14. From Immediate Cause to Root Cause

The greatest investigative error is to treat a machinery-space fire as an unfortunate and isolated event.

In many cases, the energy pathway was established well before flames became visible.

A typical causal chain can be represented as:

Equipment deterioration

↓

Oil leakage

↓

Loss of containment

↓

Oil accumulation or spray

↓

Inadequate hot-surface/electrical separation

↓

Ignition

↓

Fire development

↓

Delayed detection or response

↓

Continued fuel/oxygen supply

↓

Escalation beyond local control

↓

Activation of fixed firefighting system

↓

Fire containment or major machinery-space damage

This chain illustrates why accident investigation must look beyond the component that physically failed.

15. Engineering Lessons for Prevention

The investigation of machinery-space fires should ultimately produce practical preventive actions.

15.1 Control the fuel pathway: Regular inspection should focus on pressurised oil systems, fuel pumps, filters, manifolds, flexible hoses, drains and connections.

15.2 Protect hot surfaces: High-temperature surfaces should remain properly insulated and protected against oil spray.

15.3 Eliminate oil-soaked insulation: Oil-soaked lagging should never be regarded as a minor housekeeping issue.

15.4 Treat repeated leaks as safety signals: Recurring minor leakage should trigger investigation rather than repeated cleaning.

15.5 Maintain fire boundaries: Doors, dampers, ventilation arrangements and other boundary controls must remain capable of rapid isolation.

15.6 Verify fixed-system readiness: The firefighting system should be maintained as a complete operational system rather than simply as a collection of cylinders, pipes and controls.

15.7 Improve emergency drills: Fire drills should test actual decision-making, including:

Detection → alarm → confirmation → evacuation → fuel isolation → ventilation shutdown → boundary control → fixed-system release.

15.8 Learn from near misses: Repeated oil mist, leakage, abnormal temperature or nuisance alarms should be treated as precursors rather than isolated technical annoyances.

16. A Practical Accident-Investigation Framework

For Chief Engineers, marine surveyors, investigators, technical superintendents and safety managers, a machinery-space fire investigation can be structured around six principal question which will help prevent investigators from stopping at the first apparent failure:

Investigation Stage	Key Question
1. Origin	Where did the fire actually start?
2. Fuel	What combustible material fed the fire?
3. Ignition	What provided sufficient energy for ignition?
4. Escalation	Why did the fire grow beyond initial control?
5. Response	Were detection, isolation and firefighting actions timely and effective?
6. Management	What technical, procedural or organisational conditions allowed the casualty to occur?

17. Conclusion

A machinery-space fire should never be regarded simply as an unexpected outbreak of flames. In most serious cases, the conditions necessary for the fire existed before the fire itself became visible.

Oil escaped containment. A hot or electrically active surface was inadequately separated from the combustible material. Combustible inventory accumulated. Warning signs may have been tolerated. Maintenance or inspection weaknesses may have remained unresolved. Emergency response may then have been delayed or compromised.

The role of the accident investigator is to reconstruct this chain with sufficient technical precision to determine not merely **what failed**, but **why the system permitted the failure to become a casualty**.

Ignition-source tracing, fire-load assessment, thermal damage mapping, fixed-system performance analysis, timeline reconstruction and human-factors assessment provide powerful tools for achieving this objective.

The ultimate value of an investigation is therefore not the production of a casualty report alone. Its real value lies in converting the lessons of one ship's fire into engineering, maintenance, operational and management improvements across the fleet.

A well-conducted investigation should ensure that the next machinery-space fire is either prevented altogether or detected and controlled before it becomes a major casualty.

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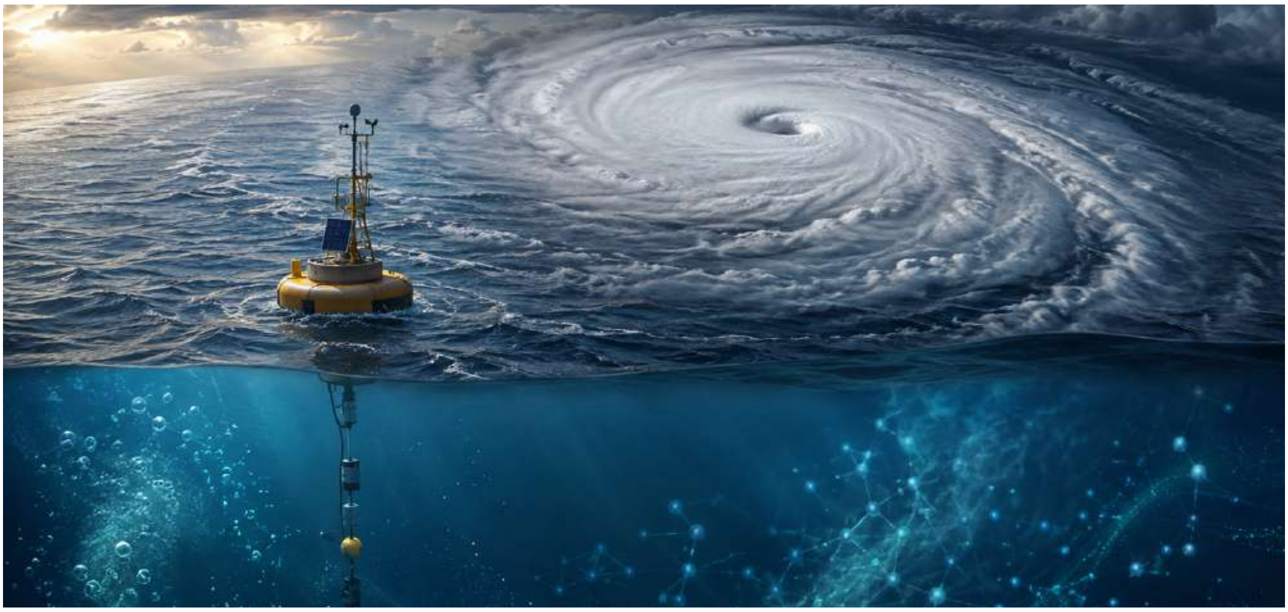
Carbon dioxide Footprint of Bay of Bengal Cyclones-Evidences from Deep-Ocean Moored Observatory



N. Vedachalam, R. Balaji, B. Kesavakumar, S. Praveen Kumar, K. Jossia Joseph

Abstract

Historically, tropical cyclones (TC) contributed 9-23% of ocean CO_2 outgassing (efflux) across major basins. With the continued ocean-warming and widening upper-ocean temperature gradients, during TC, major ocean basins are expected to shift into net CO_2 sinks by 2025, accelerating ocean acidification. Basins in the North-West Pacific and the Northern Indian Ocean, specifically Bay of Bengal (BoB), feature heavy riverine fresh water stratification that frequently turns localised TC into net sinks, rather than sources. The rapid CO_2 efflux due to violent winds during TC passage, post-storm surface cooling (cold wakes) and phytoplankton blooms that absorb CO_2 is a complex location-and season-specific process, that needs detailed analysis based on in-situ measurements made during and post-TC passage. The April-May season in the BoB is a pre-monsoon transition period characterised by extreme ocean-heating and atmospheric moisture, leading to TC. We analysed ocean-atmosphere CO_2 exchange (OACE) of TC Marutha that formed during pure pre-monsoon transition and TC Mora that formed during the exact onset of the south-west monsoon, based on the data obtained from the BoB Ocean Acidification (BOBOA) moored observatory. Since the deployment of BOBOA mooring, Marutha and Mora were the only two back-to-back TCs that transited closer to the mooring (<100km), compared to other TCs. Based on NSF-OOI approach and a novel alternate pH change NIOT approach, we identified that the annual CO_2 footprint of BoB cyclones is ~10.4Million Tons (MT) and ~10MT during rest-of-the-year. The estimated annual CO_2 influx in the BoB is 8% of India's present annual CO_2 emissions or 0.6% of global emissions. For improving scientific investigations, we recommend increasing the spatial density of offshore moored platforms, OACE measurements based on pH changes in mixed layer region and development of reliable, precise and cost-effective subsea pH sensors.

Ocean generates 50% of the oxygen we need, absorbs 30% of all carbon dioxide (CO_2) emissions and captures 90% of the heat excess heat generated by these emissions. While the atmospheric CO_2 concentration has reached a record average of 423 ppm in 2025 and the global ocean

surface pH has dropped by 0.1, analysing the Ocean Carbon Cycle (OCC) is essential to understand the effect of such changes in planet life and ecology and enact timely environmental policies. The OCC is determined by a series of complex interactions involving the ocean-atmosphere CO_2 exchange (OACE), inorganic carbon chemistry, ocean general circulation and marine biological processes. High latitude oceans act as a major sink absorbing CO_2 from the atmosphere (influx), while equatorial oceans act as a major source releasing CO_2 into the atmosphere (efflux). As atmospheric CO_2 increases, its interaction with the surface ocean

changes the chemistry of the water (forming carbonic acid and its dissociation products) resulting in ocean acidification.

Long-term observations of the global atmospheric CO_2 concentration (since 1958) are enabled by Mauna Loa atmospheric baseline observatory in Hawaii (keeling curve, that plots the ongoing accumulation of CO_2 in our atmosphere); and the Bermuda Atlantic Time-Series Study (BATS) and the Hawaii Ocean Time Series (HOTS) monitors oceanographic physical, chemical and biological, climate-driven changes, including OCC and acidification, since 1988.

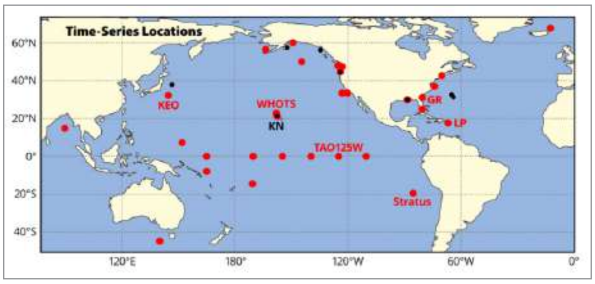


Figure.1. Location of $MAPCO_2$ moored observatories

For spatio-temporal CO_2 observations, over the past two decades, significant progress is in-place through satellite observations, ship-of-opportunity, moored observatories (mainly $MAPCO_2$ systems), gliders, profiling floats and unmanned surface vehicles. The US National Oceanic and Atmosphere Administration-Pacific Marine Environmental Laboratory (NOAA-PMEL) maintains a global ocean carbon observation network to measure OACE, OCC and ocean acidification time-series through Moored Autonomous pCO_2 ($MAPCO_2$) moorings **(Figure.1).** The Surface Ocean CO_2 Atlas (SOCAT) database hitherto aggregated ~4.1 million observations from multiple observational platforms since 1957.

Figure.2. RAMA-BoBOA buoy deployed from NIOT Sagar Nidhi vessel in 2013

The BoB, significantly influenced by massive river discharge, monsoons and biological activity, is as a complex and heterogenous system, resulting in a seasonal carbon source and sink to the atmosphere. More specifically, the northern BoB receives massive organic discharge driven by the Ganges-Brahmaputra-Meghna (GBM) river system, that contributes to high concentrations of dissolved organic carbon (DOC). The enormous warm riverine discharge creates a freshwater lens that limits vertical mixing, but traps terrestrially-derived organic matter near the ocean surface.

Quantifying the OACE during normal and TC is important for understanding BoB role in atmospheric CO_2 budgets (in-turn climate foot-print) and ocean acidification. Presently, one buoy in the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) network moored in 2700m water depth in the central Bay of Bengal (BoB) location 90°E-15°N (popularly known as BoBOA/BoB Ocean Acidification Mooring) is equipped with $MAPCO_2$ systems. This BOBOA is deployed in 2013 by PMEL, in collaboration with Ministry of Earth Sciences-National Institute of Ocean Technology (MoES-NIOT) using Ocean Research Vessel Sagar Nidhi **(Figure.2).**

The OACE is a physio-chemical process, primarily controlled by the difference in CO2 concentrations across the ocean-atmosphere boundary and the exchange coefficient. The difference is primarily driven by the effect of wind speed, temperature on CO2 gas solubility, differential CO2 partial pressure and ocean circulation patterns. Whenever the partial pressure of CO2 in the atmosphere is higher than in the ocean, the CO2 will

diffuse into that water, until the partial pressures across the air-water interface are equilibrated. During TC, cooling of surface waters decreases the ocean partial pressure of CO2 (pCO2), thereby favouring an increase in ocean CO2 influx. The direction of the CO2 flux in response to a TC depends on the local imbalance in pCO2 between the surface ocean waters and the atmosphere (Figure.3).

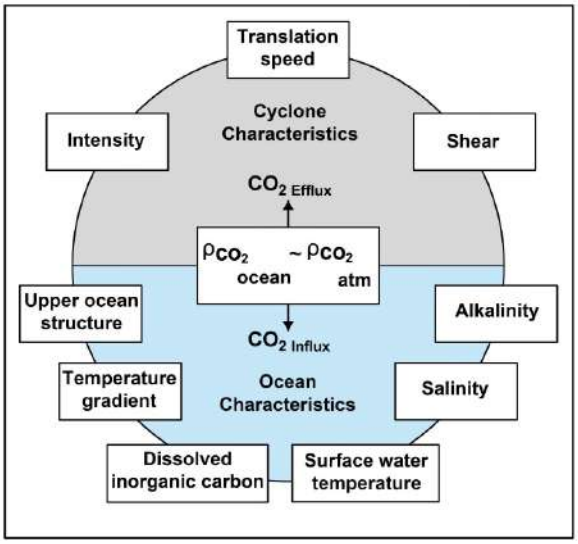


Figure.3. Factors determining OACE

Thus, the effect of the TC on the CO2 fluxes is region-specific, determined by the upper-ocean structure, pre-existing temperature gradient, dissolved inorganic carbon, alkalinity, salinity, cyclone intensity, translation speed and cyclone's ability to induce vertical mixing. The reported region-specific OACE flux (as carbon source and sink) are presently numerically estimated and wide-ranging values (**Table.1)** indicates the complex and heterogenous nature of the BoB system, which is due to the influence in the upper-ocean structure by high river discharges and resulting mixed layer depth (MLD) (Figure.4).

Table.1. OACE in different locations of BoB (mmol/m²/day)

BoB location	OACE (Mag & direction)
Northern	-1.1 to 0.4
Southern	0.1 to 1.3
South-east	-0.3 to 0.7
Negative indicates Influx & Positive indicate Efflux	

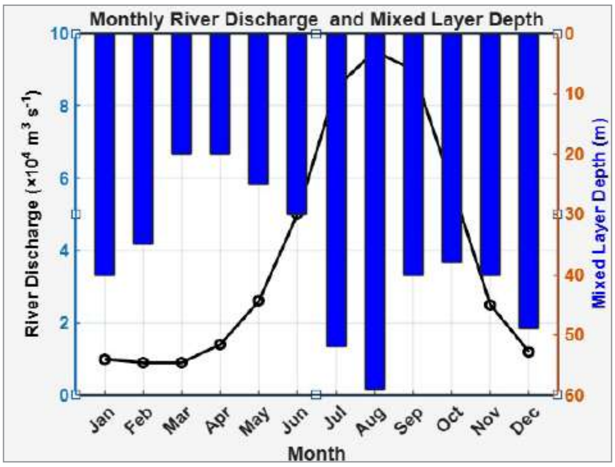


Figure.4. River discharge in northern BoB and MLD

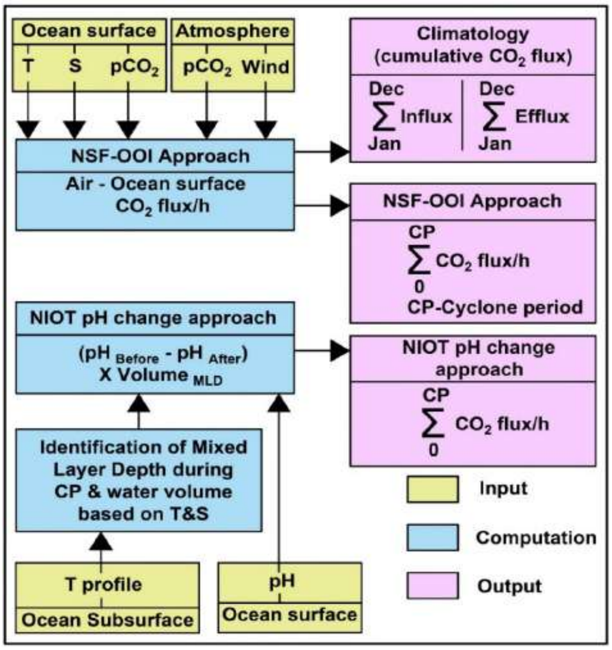


Figure.5. Approaches for computing the OACE (NIOT's pH-change approach is first-of-its kind alternate)

Since the deployment of the BoBOA mooring, two tropical cyclones, Maarutha and Mora consecutively transited closely to the mooring (<100km) during the April-May period. These two months represent the primary spring transition period in the BoB, bridging the dry north-east winter winds and the wet south-west summer monsoon. This window brings intense heat, atmospheric instability and a high likelihood of severe TC before the onset of the monsoon.

We analysed the OACE in the central BoB (15N/90E) during the period using the in-situ atmospheric and oceanographic measurements obtained from the BoBOA based on US National Science Foundation-Ocean Observations Initiative (NSF-OOI) approach and first-of-its-kind novel NIOT-pH change approach **(Figure.5)** and the results were comparable with mean difference of ±13%. The NSF-OOI approach is based on OACE computed from measurements of pCO_2 in air and in ocean water surface and bulk metrology. The state-of-the art LICOR non-dispersive, infrared CO_2 analyser used for in-situ gas analyses is designed to operate for ~1 year at sea with an accuracy of better than 2 µatm. In the NIOT-pH change approach, the change in pH in the ocean water inside the MLD is used to compute the OACE influx/efflux. In simple terms, NSF-OOI and NIOT-pH approaches, are based on cause and effect, respectively.

The MLD is determined by identifying the depth where temperature, salinity and density, remains invariant. It is practically defined as the depth where temperature drops by 0.2ºC from surface temperature. The MLD identified for a range of wind speeds (during TC Maarutha) using subsurface temperature log is depicted in **Figure.5.** The MLD pertaining to wind speeds of 5, 7, 12 & 15 m/s are 11, 13, 14 and 21m, respectively (denoted as A, B, C & D) **(Figure.6).** High winds create intense turbulence & mechanical mixing that forces surface water downward.

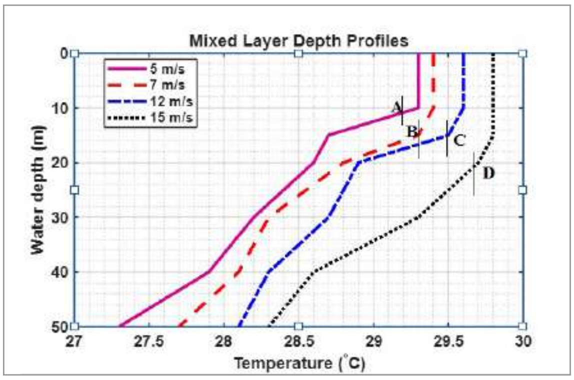


Figure.6. MLD during TC passage, based on T-0.2°C gradient

The OACE observed from NSF-OOI and NIOT pH-change approach during the period Apr-May 2017, including the passage of Maarutha and Mora cyclones are shown in **Figure.7.** It is observed that, during Maarutha and Mora Cyclones, the CO_2 footprint is -85 mmol-C m^2/day (influx) and +324 mmol-C m^2/day (efflux). The reversing trend in the flux is seen during intermittent spring transition period.

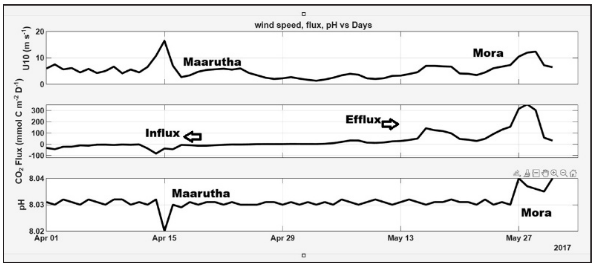


Figure.7. OACE during Apr-May 2017

From the OACE climatology during Apr-May **(Figure.7),** it is observed that during April, there is an influx of CO_2 and in May it is efflux. The direction of OACE reversal observed during early-May and back in October is a result of the reversal of pCO_2 difference between the ocean surface water and atmosphere. The reversal reported to be triggered by biological processes (driven by nutrient deposits by increasing river influx) in which organisms rapidly consume dissolved inorganic carbon (DIC) for photosynthesis (biological removal of carbon exceeds the buildup caused by warming temperatures), as well as, the reversal of East India Coastal Current (ECC) that transports highly saline, carbon-rich waters northward. The OACE climatology in the central BoB during the 2017 **(Figure.8)** shows an annual influx is -6.8 moles/m^2/yr and efflux is 5.8 moles/m^2/yr, while the net flux is -1 mole/m^2/yr (influx).

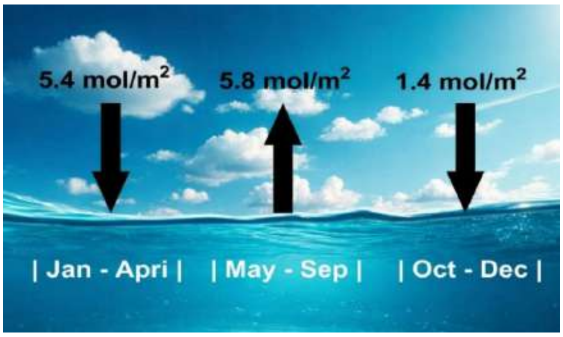


Figure.8. OACE climatology during 2017

Higher wind speed and lower ocean water temperature determine the magnitude of OACE and the flux direction is determined by the air-ocean pCO_2 difference. **Figure.9** (above) describes the partial pressure of atmosphere and sea water during the passage of Maarutha and Mora. During Maarutha passage, pCO_2 of the sea water decreases below the pCO_2 of atmosphere, resulting in influx (until end of April), while during Mora passage, pCO_2 of the

ocean water remains higher than pCO_2 of atmosphere, resulting in CO_2 efflux. Based on the OACE analysis, influx is observed during the post-monsoon period, which was identified from the Hud-Hud cyclone (during Oct-2014) analysis **(Figure.10)**

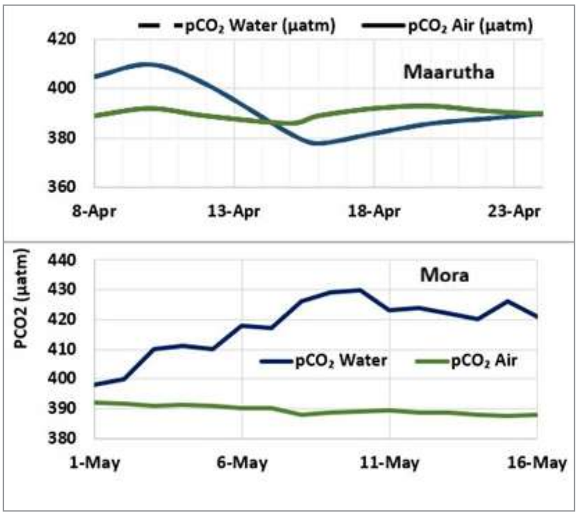


Figure.9. Partial pressure variations during Maarutha and Mora

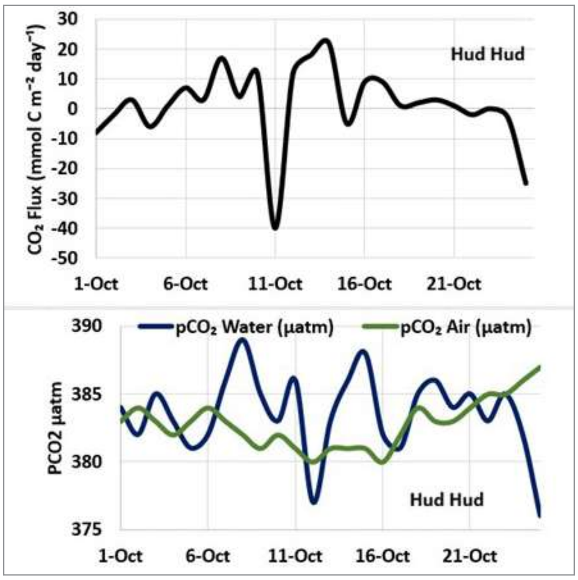


Figure.10. Partial pressure and flux variations during Hud-Hud

It is interesting to observe that, while the annual average influx during Jan-Apr is only ~3 mmole-C/m^2/day, the cyclone period influx is ~100 mmole-C/m^2/day, which is 33 times higher, essentially due to the influence of high winds. From the Hud-Hud cyclone observations (influx of ~40 mmole-C/m^2/day), the TC during the post-monsoon period (Oct-Dec), there is influx.

Although TC are short-lived, because of their large spatial extent (few 100's of kms in diameter), speed of transit and frequent occurrence (globally ~100 /year), they significantly contribute to the changes in atmospheric CO_2 budgets and influence ocean ecosystem. With specific reference to the BoB, ~5 cyclones are generated during pre-monsoon (peaking in April) and ~8 cyclones during post-monsoon (Oct-Dec). Considering average BoB cyclones of diameter of 500kms and transit period of 6 days, based on the observations of ~200 mmol-C/m^2 / day (8.8gms/m^2/day) for average wind speed of 15m/s and 78 cyclone-days, the quantity of cyclone period CO_2 influx is estimated to be ~10.4 million Tons. During the normal period, based on the climatology CO_2 flux within an estimated 0.7 million km^2 of BoB region (90E/15N-22N) the influx is estimated to be ~10 million Tons. Thus, the total CO_2 influx during normal and cyclonic period (total of ~20.4 MT) is prognosticated to be 8% of India's present annual CO_2 emissions, or 0.6% of global emissions.

Key recommendations -

a. Increased spatial deployment density of moored buoys with autonomous OACE measurements in the Indian seas for enabling precise budgeting of CO_2 flux.

b. For OACE quantification, as a potential alternate to NSF-OOI approach, monitoring pH changes in the ocean mixed layer upto 50m could be adopted.

c. Development of reliable, precise and cost-effective underwater pH sensors is essential for enabling long-term monitoring in the ocean.

Seawater pH has traditionally been measured using glass electrodes, that offered ±0.003 pH unit precision under laboratory conditions, but degrade in marine settings due to drift and salinity effects, making them unsuitable for long-term, in situ monitoring.

Autonomous sensors based on Ion-sensitive Field Effect Transistor (ISFET) technology that measures pH based on how hydrogen ions interact with an amphoteric metal-oxide surface altering the electrical conductivity of the transistor. These ISFET pH sensors manufactured by SeaFETs and Sea-Bird Scientific provide high precision (~±0.0005 pH) but exhibit long-term drift and require periodic recalibration, with additional maintenance and performance considerations.

The SAMI-pH of Sunburst Sensors is a colorimetric spectrophotometric sensor that provides slightly lower precision (±0.0007 to ±0.0014 pH) but long-term stability without recalibration, making it well- suited for extended autonomous deployments.

Based on the BoBOA data logs, over the past 13 years (till-date), the atmosphere and ocean pCO2 measurement system achieved a data return of only ~50%, while the pH sensor reported only ~30% **(Figure.11).** This low field data-return stresses the need for development of rugged sensors for monitoring the short-term pH variability during TC with reliability and precision.

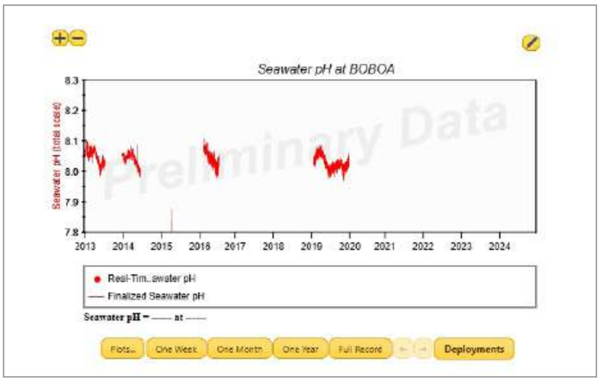


Figure.11. Data returns from pH sensor installed in BOBOA

ABBREVIATIONS

BATS	Bermuda Atlantic Time-Series Study
BoB	Bay of Bengal
CO_2	Carbon dioxide
DIC	Dissolved inorganic carbon
ECC	East India Coastal Current
HOTS	Hawaii Ocean Time Series
OOI	Ocean Observations Initiative
$MAPCO_2$	Moored Autonomous pCO_2
MLD	Mixed layer depth
MT	Million Tons
MoES	Ministry of Earth Sciences
NIOT	National Institute of Ocean Technology
NSF	National Science Foundation
OACE	Ocean-atmosphere CO_2 exchange
OCC	Ocean Carbon Cycle
pCO_2	Partial pressure of CO_2
RAMA	Research Moored Array for African-Asian-Australian Monsoon Analysis
SOCAT	Surface Ocean CO_2 Atlas

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