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Discovering the Deep-Ocean Hydrothermal Vents

The Institute of Marine Engineers (India)

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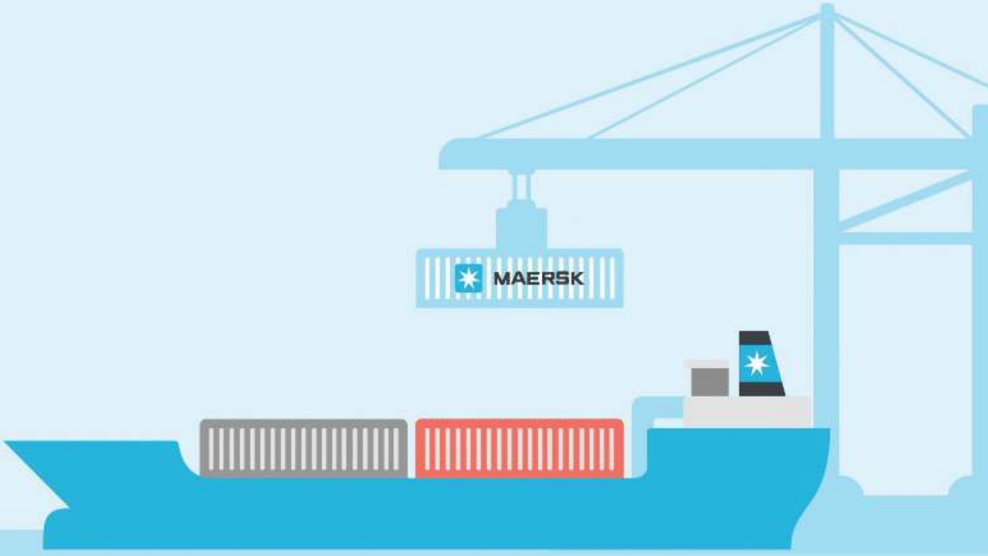

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EDITORIAL

We cannot solve our problems with the same thinking we used when we created them.

- Albert Einstein

The recently concluded COP27 at Sharm-el-Sheikh appears to be no great shakes. And the '*sharm*' towards deteriorating climate was also not so apparent, one could say. The L&D Fund (Loss and Damage Fund) could be the major takeaway. Since the Industrial Revolution, the rich (presently richer) countries have contributed to the accumulated emissions. While the policy of 'Greater polluters pay for the much needed intense corrections' could be a justifiable path to follow, the onus of juicing up mitigation measures cannot be tied to the supply of funds. To take the talks further, a brief view of few pointers:

Objective: keep average temperature rise below 1.5°C.

Reality check (based on UN Emissions Gap Report 2022): Expected rise is 1.8 °C (at 66% probability) and also if all voluntary pledges taken by various nations are kept and the assured targets are realised. Incidentally, the current rise is at 1.2-1.3°C, the highest since the Ice Age.

At these levels, the expected events (circa 2030): Greenland/West Antarctic Ice sheet collapse; boreal permafrost thawing; coral reef destructions; monsoon pattern changes; possible famines at some parts of the globe etc.

Continuing the COP27 conversation...

India is the most fitting example of a developing country in the climate canvas of the planet and will be the seventh most impacted due to climate change (2021 Global Climate Risk Index). The expectation is that developing countries (India) improve their per capita based on renewables. This is a tall order. We still need roads, schools, industries, healthcare to reach certain critical mass for development and India needs a lot of energy to reach this. The reliance on fossil fuels will persist but a judicious use at every stage would help.

India could take the cues by looking at formative technologies, mini formulations to uplift local (both rural & urban) living conditions etc., while also realigning the development plans (3 year/5 year/7 year plans etc.). Fuelling the renewables, particularly in the transport sector could prove to be beneficial in the long run, both for development and mitigation. India's approach model on balancing economic development and mitigation measures could settle as a paradigm to pursue for other developing nations.

Another significant takeaway from COP27 worth a mention is the '10 new insights in climate science' (latest) by Scientist, Prof. Rockstrom. [There will be more on this in the later issues]. His incisive observation is that 'success is still measured predominantly by GDP and affluence, rather than through improvements in resource use efficiency and advancing human well- being within the biosphere's constraints'.

In many ways, the funding towards mitigation (renewables etc.) could be a vitaliser for development (new jobs, new enterprises, better well-being etc.). This approach would at least show a departure from the thinking with which the humankind created these climate problems.

In this issue...

The origin of the universe has been a perpetual point for probing. While we have looked at the space in our solar systems and beyond, many answers could be found in our planet's depths. Dr Vedachalam takes us deep down the oceans for a tour of hydrothermal vents that maintain higher temperature ranges to sustain life etc. These vents were formed as early as when water appeared on earth and carry signs of life appearance about 4 billion years ago. Two discussions are thought provoking: The chemistry of mineral precipitations and how the vents support life. This is another colourful dive that Dr. Veda takes us, but this time deeper.

Following this is an article on mechanism based failure analysis. Prabhu Duplex extends the ideas of condition monitoring, predictive actions etc., with several ship machinery examples. In present times, connecting with such maintenance approaches will be facile and will be of value too. This would certainly be of interest to shipboard engineers and superintendents as well.

Hema Karnam concludes the maritime anomaly discussions. Part 3 highlights the methods and few research approaches. She briefly introduces the statistical methods, Bayesian network, which relies on historical data etc. The takeaway is that detection in seas have got more scientific and reliable. This original research attempt needs appreciation and we hope to have more on this as her research progresses.

Under Technical Notes, Sanjiv shifts gear to discuss basics of tribology. The MER December 1982 issue from archives carries some interesting items as always. There is a not-so-recent article on AI from one of the Conferences. We intend to feature the INMARCO contributions in the forthcoming issues and I assure there are a few interesting ones worth their salt.

INMARCO would have brought in the newsletter fragrance, **iMélange**, [Pronunciation: ʌɪ - meɪˈlɒ̃ʒ] and I hope you will enjoy this platform and extend your support as always. With the newsletter, here is the December 2022 issue for your reading pleasure.

Dr Rajoo Balaji
Honorary Editor
editormer@imare.in

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

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In This Issue

ARTICLES

COLUMNS

Cover pictures: RV Exploring a Hydrothermal Vent Field & 3.42 billion year old fossilised microbes (in hydrothermal vent)

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Fossilised Microbes: MARUM Center for Marine Environmental Sciences, University of Bremen, Germany. (Wikimedia Commons)
https://sciworthy.com/3-42-billion-year-old-fossilized-microbes-in-an-ancient-hydrothermal-vent/

TECHNOLOGIES FOR EXPLORING THE FASCINATING DEEP-OCEAN HYDROTHERMAL VENT ECOSYSTEM

N. Vedachalam

Abstract

The origin of life is a topic that spans and transcends many disciplines of science, eras, cultures, and even space. The unique features in the deep-ocean hydrothermal vents, cold seeps, whale falls, seamounts and oceanic trenches make these environments distinct from land and other marine ecosystems. Exploring and understanding the ecology and the metabolism of the mysterious deep-ocean dwellers has brought unprecedented opportunities for deciphering the origin and evolution of life in extreme environments in the deep biosphere, especially the hydrothermal vents. The article describes the deep-ocean technologies used for exploring and carrying out in-situ scientific investigations in the hydrothermal vents, hydrothermal vent activity and spreading rates, chemistry involved in black and white smokers, the chemosynthetic support of life and the fascinating biodiversity at the deep-sea hydrothermal vents due to the habitat enrichment and bacterial symbiosis from the vent fluids.

Introduction

Understanding how life arose on the Earth is a historical and reconstructive endeavour, but it is also very much a contemporary and ever-refreshing scientific undertaking. To date, various environments have been proposed as plausible sites for the origin of life on Earth. Geochemical investigations of graphitic carbons in early Archean sedimentary rocks indicate that life on Earth began 3.8 billion years ago.

The geological occurrences of graphite from the Isua supracrustal belt suggest possible existence of planktonic organisms 3.7 billion years before. Based on such information, the beginning of life on the Earth is inferred to be between 4.1 and 4.2 billion years. Based on such clues, various environments have been proposed as plausible sites for life's origin, including oceans, lakes, lagoons, tidal pools, submarine hydrothermal systems, etc.

Hypotheses such as prebiotic soup, hydro-thermal, and extra-terrestrial theories were propounded to describe the origin of life. Further, the origin of life is also supported by RNA World hypothesis and Metabolism-first principles. The RNA World hypothesis has gained increased acceptance in recent times, with several experimental studies indicating how hydrogen cyanide, known to exist on prebiotic Earth, could have been the starting point of many synthetic routes leading to the formation of RNA and protein precursors.

However, hitherto, it remains unclear what geochemical situations (elements and molecules that accumulate on a young planet) could drive all the stages of chemical evolution, processes that can transform them under the abiotic geochemical constraints into self-assembling, self-sustaining interactive systems with emerging patterns and behaviour, and begin to evolve into what could be considered as living entities.

The deep-sea environment creates the largest ecosystem in the planet with the largest biological community and extensive undiscovered biodiversity. Submarine hydrothermal vents are geochemically reactive habitats that harbour thermophilic microbial communities.

Geochemical investigations of graphitic carbons in early Archean sedimentary rocks indicate that life on Earth began 3.8 billion years ago

There are striking parallels between the chemistry of the H_2 – CO_2 redox couple that is present in the hydrothermal systems and the core energy metabolic reactions of some modern prokaryotic autotrophs. The biochemistry of these autotrophs (organisms that can produce its own food using light, water, carbon dioxide, or other chemicals**)** harbour clues about the kinds of reactions that initiated the chemistry of life.

Hydrothermal vents are one of the earliest types of environments in the deep oceans, formed as a result of volcanic eruptions, soon after water accumulated on earth

The hydrothermal-vent origin-of-life hypothesis can be divided into three steps, including (a) synthesis of amino acids and other essential organic compounds from the dissolved methane and other gases, initially at high temperatures, as they pass through a temperature gradient (>350° to -2°C); (b) synthesis of peptides and nucleotides by thermal dehydration and other high temperature reactions; and (c) synthesis of proto cells or RNA like molecules at some stage in the thermal gradient, and the conversion of these proto life forms into living organisms as the hydrothermal waters emerge from the vents.

Hydrothermal vents are one of the earliest types of environments in the deep oceans, formed as a result of volcanic eruptions, soon after water accumulated on earth. It features our planet and the oceans since the Hadean (>4 billion years ago).

These volcanic eruptions are concentrated where the Earth's tectonic plates collide or separate, resulting in hydrothermal venting, characterised by the ejection of hot, mineral- and chemical-rich fluids from the seafloor, typically at bathyal depths. These vents are important geological structures that concentrate minerals of economic significance, supporting remarkable biological communities with rare and endemic species, specially adapted to the conditions that hydrothermal vents present.

The vents' discovery in 1977 (8 years after man landed on the moon) while exploring an oceanic spreading ridge near the Galapagos Islands profoundly changed how we view the geological, geochemical and ecological history of the Earth. Thus, hydrothermal vent environments are believed to be intimately connected to the history of life, as they are deemed a highly probable setting for its origination and have a fossil history that extends to the first direct evidence of life on Earth.

Technologies for Exploration in Hydrothermal Vents

Deep-ocean exploration technologies have become increasingly multidisciplinary and are now a substantial international endeavour for understanding the origins, evolution and limits of life on Earth. Over the past few decades, remarkable developments in deep-ocean manned and unmanned robotic survey systems such as Autonomous Underwater Vehicles (AUV), intervention robotic systems like Remotely Operated Vehicles (ROV) and Human Occupied Vehicles (HOV), survey equipments such as side-scan synthetic aperture sonar aided by precision motion reference systems, truth-preserving in-situ sampling devices, deep-ocean simulator systems and ocean floor based long-term cabled observation networks (including NEPTUNE, VENUS, ESONET, MARS, DART, and DONET) have revolutionised deep-ocean research (**Figure.1**) [1].

The in-situ biological sampling systems has to work precisely in extreme deep-ocean environments characterised by high hydrostatic pressure and low temperature, and should effectively store, transport and reliably transfer the collected samples to laboratory bio-reactor systems [2].

The hydrothermal vent bio-sampler developed by the Jet Propulsion Lab (JPL) is designed to collect a large volume of hydrothermal vent samples with fluid temperature close to 400 ºC at abyssal depths [3]. The comparative capabilities of deep-ocean robotic vehicles are shown in **Table.1**. AUVs are used for carrying our wide area surveys, while ROV and HOV are capable of carrying our effective interventions.

Deep-sea research in extreme environments is inseparable from human wisdom, knowledge, experience and judgment, which makes HOV special compared to intelligent robot technologies (ROV & AUV). HOVs have the advantages of carrying scientists to deep-ocean areas for research in extreme environments for biological sampling, habitat analysis and in-situ experiments.

Scientists can continuously obtain real-time and in situ data, design experiments and perform fine operations based on actual dynamics in real time [4]. The discovery of the hydrothermal vent at the Galapagos Rift by HOV

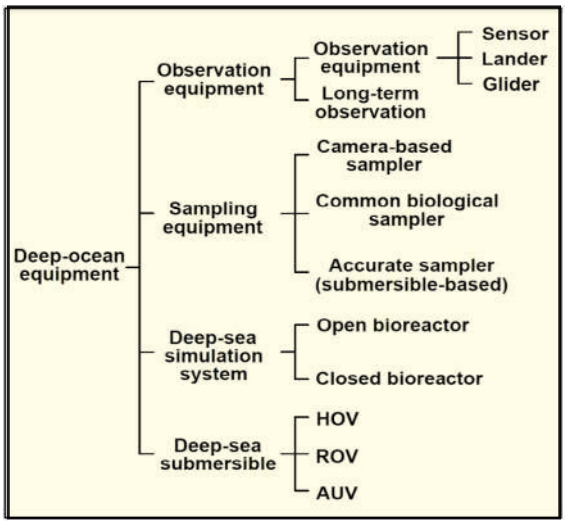

Figure 1. Ecosystem of deep-sea research equipment

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Table 1. Comparative capabilities of underwater robotic systems

Feature	ROV	AUV	HOV
Endurance	Unlimited	Limited	Limited
Spatial capability	Limited	>10s kms	< 10s kms
Connectivity	Tethered	Untethered	Untethered
Intervention capability	Limited	Maturing	Well proven

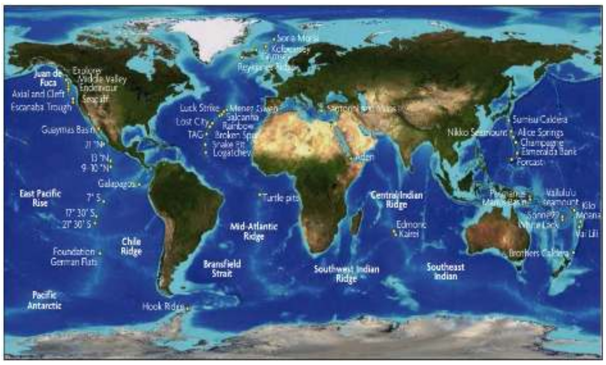

Figure.2. Location of oceanic ridges [6]

Deep Submergence Vehicle (DSV) Alvin in 1977 opened the prologue of biological research on deep-ocean hydrothermal vents [5].

The global distribution of the hydrothermal vents aligns with the sources of heat prevailing deep in the Earth's lithosphere, in general, magma upwelling at plate boundaries. Using the technologically advanced deep-ocean scientific exploration and scanning systems, ~25% of 40000-mile-long mid-ocean ridge (MOR) has been surveyed for evidence of hydrothermal plumes, ~ 5% of the total ocean floor area of the MOR has been imaged at a resolution sufficient to reveal the spatial distribution of individual hydrothermal vents, mineral deposits, biota and other significant small-scale geologic features (**Figure.2**).

As on date, ~572 hydrothermal vents are located at depths > 200m, 344 vents in mid-ocean ridges, 117 at back-arc spreading centers, 106 at volcanic arcs and 5 vents at intraplate hotspots. Deep-ocean AUVs were extensively used to survey and locate the hydrothermal vents. They include AUV ABE, Sentry, Hobalin, Autosub, Seal, Urashima, Tridog, Allan, Hugin and multi-cooperative AUV observation systems.

The 4500m depth-rated AUV ABE was used in ~191 benthic surveys in the MOR at 2000m water depths in the Juan de Fuca Ridge (JdFR) off North-West USA for detecting and mapping lava flows and to map the active hydrothermal vents in the spectacular Lost City hydrothermal vent field in the mid-Atlantic Ocean at 900 m water depth.

AUV SENTRY was deployed in the Galapagos rift hydrothermal vents in the Pacific Ocean, southern explorer ridge in the north-east Pacific, and in the Brothers volcano closer to the Kermadec Arc in New Zealand. AUV Autosub6000 was used in the 65 km long, 24h terrain-following survey carrying out high resolution imaging close to 5000m deep ocean floor in the Cayman trough's Beebe and Von Damm active hydrothermal vent fields hosting abundant vent-specific fauna [7].

The AUV Seal 5000 mapped the ecology in the Menez Gwen hydrothermal vents hosting chemosynthetic communities at 800 m water depths and generated high resolution maps of the fluid escape features and the gravitational mass movements in the Kerch seep area at 900m water depths. AUV Urashima was deployed for mapping the Iheya-North hydrothermal field off-Okinawa and in the Pika hydrothermal vent site in the southern Mariana Trough.

AUV Allan collected high-resolution visuals over the fluid escape mounds at 1000m water depth in the Santa Monica basin, offshore California. AUV Sentry was used to investigate the bio-geo-chemical interactions at the cold seep communities in the Blake ridge diaper off-South Carolina in the eastern USA.

AUV Hobalin observed seabed in Kogoshima bay and obtained image of seabed colonies and water properties in the south sea areas of Izu-Oshima Island of Tokyo. AUV Tridog autonomously observed 3000 m^2 of hydrothermal vent area and found unique tubular worm Lasellibrachia atsuma near the bubble. AUV Hugin identified bubble flow by near-bottom digital photography and recorded characteristics of animal communities in the seepage area. As an example, a high-resolution sonar image of the Pika hydrothermal field (**Figure.3**) in which white arrows show the loci of the hydrothermal plumes discharging into the water column [8].

Once a hydrothermal vent field is mapped using AUVs, instrumented ROVs and HOV are used for in-situ studies. HOV such as DSV Alvin, Shinkai, MIR 1&2, Nautilus, Jaiolong were deployed to collect vent fluids, sediment, and rock samples in various hydrothermal vent fields (**Figure.4**). DSV Alvin studied the propagation activities of mussels by transplant experiments in the hydrothermal areas.

Shinkai studied animal behaviour and population relationships near hydrothermal vents. Deep water ROV such as ROPOS II, Jason and Victor 6000 were used for acquired quantitative samples of faunal assemblages to estimate total biomass of a sulphides' edifice, spatial and temporal patterns of supply at hydrothermal vents, video recording and photographs of macroscopic observations [9] [10] [11].

Recently developed in-situ samplers (that maintain in situ pressures and temperatures) overcome the depressurisation effects (out gassing of compounds such as hydrogen and carbon dioxide) and sample processing delays as in ship-based samplers (that lead to redox reactions) and enable scientific studies on the autotrophic microbial incubations of the samples collected from the deep ocean.

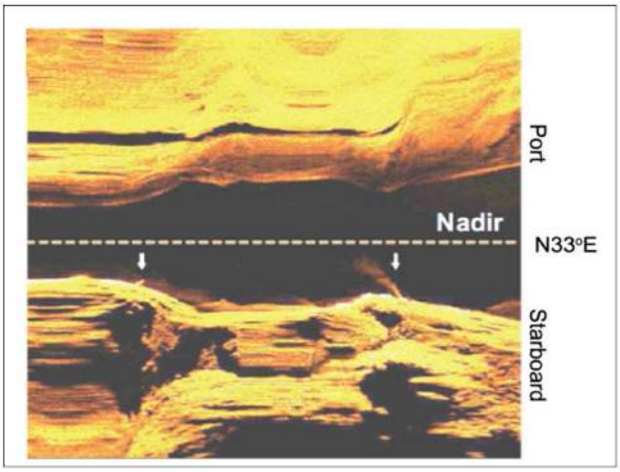

Figure 3. Sonar images at Pika hydrothermal vent field [8]

One such recent development is the ROV-powered incubator instrument (with integrated temperature sensor to continuously monitor fluid temperature during intake) and to carry out and compare results from in situ and shipboard RNA stable isotope probing (RNA-SIP) experiments to identify the key chemolithoautotrophic microbes and metabolisms in diffuse, low-temperature venting fluids from Axial Seamount.

The system was used in ROV Jason II (**Figure.5**) for collecting hydrothermal vent fluid from a vent at Axial Seamount, a submarine volcano located off the coast of Oregon. Each of the four incubation chambers was heated to a chosen set point temperature. Fluid was pulled into the insulated incubation chamber from the manifold of the hydrothermal fluid and particle sampler (HFPS) through a custom titanium shutoff valve, pulling hydrogen gas and buffering acid into the chamber as it filled.

Hydrothermal Vent Activity

Natural disturbances at the hydrothermal vents occur mainly at the local scale through volcanic eruptions or landslides, but may also result from tectonic events such as earthquakes. The spreading rate of the vents are categorised into ultraslow (140 mm/yr), slow (20-50 mm/yr), intermediate (50-80mm/yr), fast (80-140 mm/yr) and superfast (>140mm/yr) (**Figure.6**) [5].

The frequency of disturbance ranges from almost continuous at vents on submarine arc volcanoes with multi-year eruptions to very infrequent at vents located in ultraslow spreading settings. At spreading ridges, the frequency of volcanic eruptions is related to time-averaged magma supply and the spreading rate.

The longevity of the hydrothermal systems depends on the setting. Long-lived vent fields have deep and stable conduits for hydrothermal circulation, whereas venting in the aftermath of volcanic eruptions may be short-lived. The age of a vent (time since initiation of hydrothermal activity) differs from longevity (duration of most recent hydrothermal activity), since hydrothermal activity may wax and wane over time.

Age is inversely related to spreading rate. It ranges from ~100 years at 13º N vent field on the fast-spreading East Pacific Rise (EPR) to ~20000 years at the Trans-Atlantic Geo traverse (TAG) active field on the slow-spreading mid-Atlantic ridge (MAR), but not much is known about the longevity (**Figure.6**). Hydrothermal systems at volcanic arcs may be active for several 1000s of years, whereas others may have decadal spans of activity that are more intimately related to volcanic cycles.

As there are differences in the spreading rate in mid-ocean ridge magmatism, cracking and faulting, so too are differences in hydrothermal systems and deposits on ridges spreading at different rates. On spreading ridges, the range in expected spacing between vent fields is from 25 to 90 km, inversely proportional to the magnitude of the spreading rate (150–10 mm/yr) [6].

Venting Process and Chemistry

The requirements for hydrothermal systems include heat to drive fluid circulation and high-permeability pathways to facilitate fluid flow through crustal rocks.

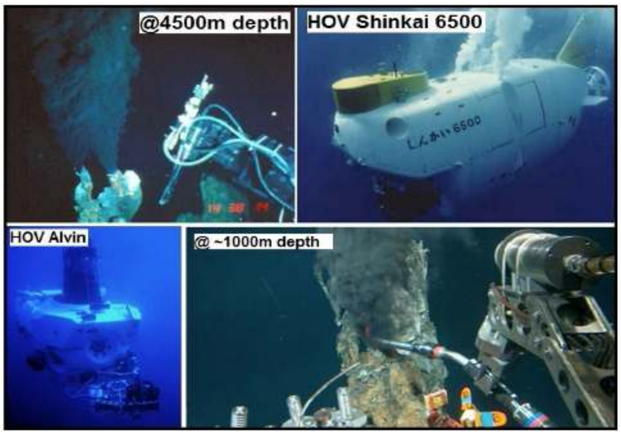

Figure 4. HOVs deployed in hydrothermal vent sampling

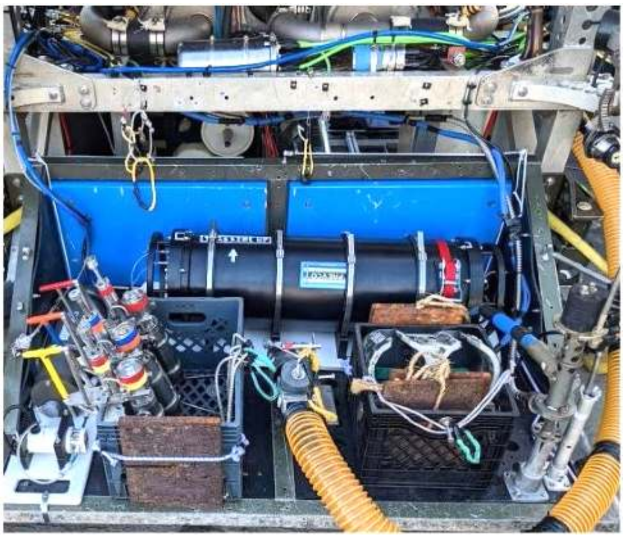

Figure 5. PMEL's hydrothermal fluid and particle sampler

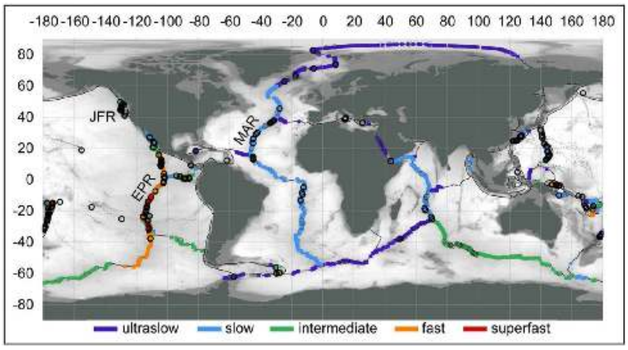

Figure 6. Location of hydrothermal vent fields (in circles) and the spreading rate (indicated by coloured lines) [6]

Sea water does not boil as its boiling point increases with the hydrostatic pressure (310°C, 410°C and 480°C at 1000m, 3000m and 6000m, respectively)

On mid-ocean ridges (MOR), vents and deposits form at sites where ascending magma introduces heat into the permeable upper crust, and at sites where deep cracks and faults provide permeability and fluid access to heat sources at depth.

By the time hydrothermal fluids reach the seafloor, they can have temperatures of around 350–400°C, have interacted with rocks in the sub-seafloor, and represent near-neutral, complex mixtures laden with chemically-reduced dissolved minerals (typically iron, zinc and copper sulphides, silica, anhydrite, barite) and gases (hydrogen sulphide, hydrogen, methane). The interaction of the escaping hydrothermal fluids with cool water at the ocean bed results in mineral precipitation, producing characteristic chimney structures that exhibit zonation relating to the conditions under which various mineral phases precipitate, particularly due to the temperature. Sea water does not boil as its boiling point increases with the hydrostatic pressure (310°C, 410°C and 480°C at 1000m, 3000m and 6000m, respectively).

The morphology of the hydrothermal vent deposits can be highly variable depending on the rate of ocean floor spreading, fluid flow dynamics, internal plumbing conditions and duration of venting. Therefore, hydrothermal vent precipitates can also manifest as non-chimney structures (could be tens of meters tall), such as complex sulfide mounds (**Figure.7**).

The hydrothermal fluids exit the chimney and mix with the cold seawater. In a black smoker vent, the metals carried up in the fluids combine with sulphur to form black minerals called metal sulphides, and give the hydrothermal fluid the appearance of smoke. These chimneys grow at a rate of ~30 cms /day. They are fragile and often collapse if they grow too big.

White smoker fluid is usually cooler (250-300°C) and flows more slowly than the **black smoker fluid**. White smoker chimneys are generally smaller. The white colour comes from minerals that form when the fluid exits the chimney and mixes with seawater. Unlike the black minerals in black smokers, these minerals don't contain metals.

Therefore, the black minerals form beneath the seafloor before the fluid exits the chimney. Other types of compounds, including silica, remain in the fluid. When the fluid exits the chimney, the silica precipitates out. Thus, white smokers are chimneys formed from deposits of barium, calcium, and silicon, which are white. Another chemical reaction creates a white mineral called anhydrite. Both of these minerals turn the fluids that exit the chimney white (**Figure.8**).

Life in Hydrothermal Vents

Till 1977, it was believed that the high hydrostatic pressure and low temperature environments constrain the size of benthic organisms, and deep-sea environments were food-limited. From the scientific investigations at hydrothermal vents, species like crabs, shrimps, fish, and octopus, as well as sessile creatures like tubeworms, barnacles, limpets and feather stars were discovered (**Figure.9**).

Samples collected and measurements carried out at various hydrothermal vents with precisely placed probes demonstrate close correspondence between distributions of individual species and temperature, pH, oxygen, H_2S, and various metal compounds. **Active vents support greater biodiversity due to the habitat enrichment and bacterial symbiosis from the vent fluids.**

Local environmental conditions in vent habitats can be extreme and variable, and exert a strong influence on the species occurrence. The undiluted hydrothermal fluids exit the seafloor at temperatures ~400ºC, and often

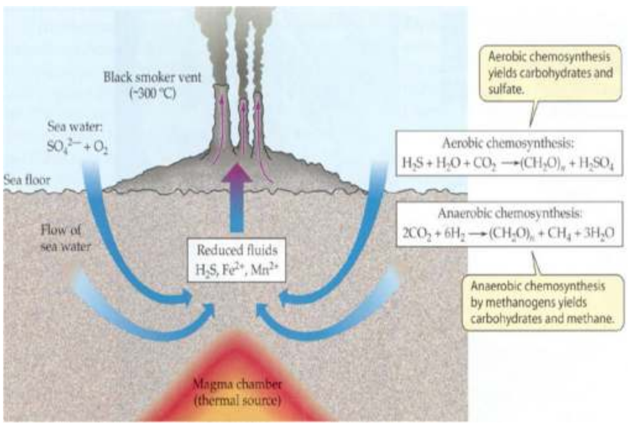

Figure 7. Chemistry and composition in black smoker vents

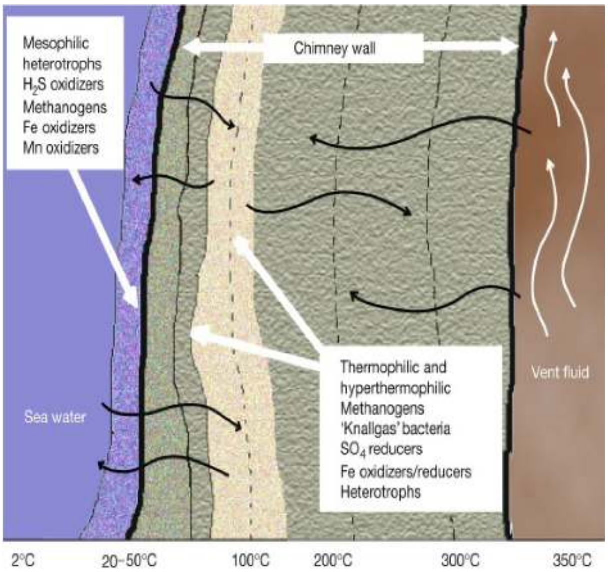

Figure 8. Chemical process around the chimney and walls

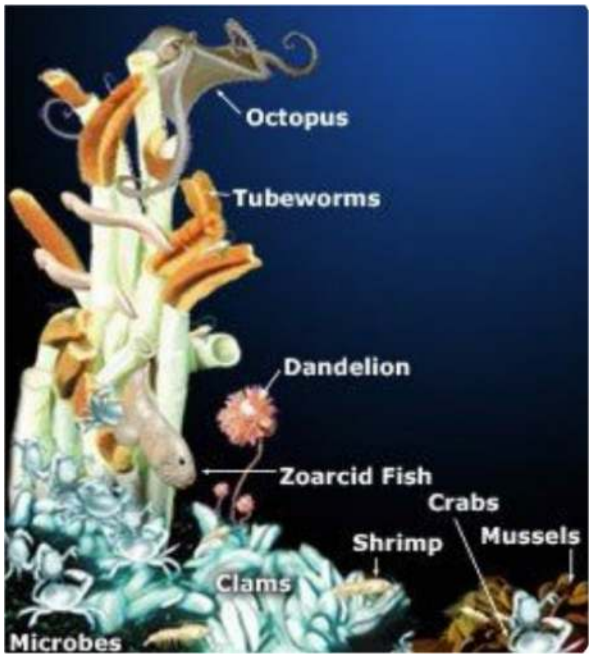

Figure 9. Hydrothermal vents bio-ecosystem

are characterised by low O_2 levels, low pH, and elevated concentrations of toxic metals. Only where the fluids mix with ambient seawater are the conditions favourable for vent communities.

At the ocean interface, microbial chemosynthetic production, fuelled by reducing compounds such as H_2S or methane, provides the trophic base for vent ecosystems. The location and flux of hydrothermal fluids constrain organism distributions, depending on the species' physiological tolerances and their nutritional requirements.

Thus the presence of life-forms under these extreme environmental conditions (including complete darkness, high hydrostatic pressure and food-limited environment) brought to light an incredible truth that life can exist and flourish without the process of photosynthesis, but solely with the support of chemical energy derived through a bacteria-mediated process known as chemosynthesis for the synthesis of proteins and carbohydrates using the organic compounds that are transferred from the hydrothermal vents to the hydrosphere. The ecosystem harbor fascinating life with symbiotic relationships involves lithoautotrophic microorganisms that use chemical energy to support metazoans [12].

The key to the high productivity in the hydrothermal vent ecosystem is the chemoautotrophic bacteria that live freely or form symbioses within specialised tube worms, clams, and mussels. These bacteria utilise H_2S to synthesise organic compounds that are passed on to the symbiont hosts. The hosts are characterised by reduced guts and little or no feeding structures. For both members of the symbiotic partnership, there are clear advantages.

Samples collected and measurements carried out at various hydrothermal vents with precisely placed probes demonstrate close correspondence between distributions of individual species and temperature, pH, oxygen, H2S, and various metal compounds

The host provides a physically stable habitat in the immediate proximity of H_2S and the bacteria provides a rich food supply to the host. The transient nature of vent environments, which generally persist for time scales of only decades, means that organisms must be able to colonise, grow quickly, and reproduce before vent flow ceases [13].

Where the hydrothermal fluids mix with the oxygenated seawater, they support these lush communities fuelled by microbial chemoautotrophy. Hydrothermal vent communities can inhabit sulfide-rich habitats because of evolution of detoxification mechanism that often involve microbial symbionts. Detoxification of sulfide through binding to blood-borne components is known in chemosynthetic vestimentiferans and vesicomyid clams, and is particularly well-characterised for the **tube worm** Riftia pachyptila.

Tube worms grow up to 2m long and 10cms in diameter (**Figure.10**). They never leave their tubes, which are made of a hard material called chitin. The tubes help protect the worms from the toxic vent chemicals and from predators such as crabs and fish. Tubeworms do not eat. They have neither a mouth nor a stomach. Instead, billions of symbiotic bacteria living inside the tubeworms produce sugars from carbon dioxide, H_2S and oxygen.

> ***Where the hydrothermal fluids mix with the oxygenated seawater, they support these lush communities fuelled by microbial chemoautotrophy***

The abundant respiratory haemoglobin present in the plume of Riftia is capable of binding oxygen and sulfide simultaneously with very high affinities. The blood transports the respiratory haemoglobin with the tightly-bound sulfide to the internal symbiotic bacteria, providing an electron donor for bacterial chemoautotrophy, while also protecting animal tissue by sequestering the toxin as a bound form [14].

Colonies of Riftia are anchored on the rocks where hydrothermal fluid (12–15°C) issues out onto the sea floor. At the base of their tubes, hydrothermal fluid is enriched in H_2S and CO_2, but is devoid of oxygen. The respiratory plume is extended into the ambient (2°C), oxygen-enriched bottom water.

Riftia's unusual micro-habitat is the interface between the hydrothermal fluids and the ambient bottom water where essential metabolites can be taken up by the plume and transported to internal bacteria for metabolism. The steep thermal and chemical gradients provide access to the reduced compounds needed to fuel growth and the oxygen needed to burn the fuel.

Octopuses are typically 1m long with heads about the size of orange. Living among or even under clumps of mussels, they are top predators, eating crabs, clams, and mussels. The ***zoarcid***/white fishes are 60cm long are also top predators around vents. They eat everything from tubeworms to shrimp. Despite their huge appetites, these fishes are slow and lethargic. They spend a lot of time floating around clumps of tube worms.

Clams colonise hydrothermal vents at a period later than mussels. Each clam has a big muscular foot that it wedges into cracks in the ocean floor. A clam also uses its foot to move around. Like mussels, clams depend on symbiotic bacteria that live in their gills that use the chemicals in the hydrothermal fluid to produce sugars. Despite their thick shells, clams are eaten by crabs and octopi.

Figure 10. Tube worms in the vent area [14]

Dandelions are fuzzy-looking balls made up of a colony of numerous individual animals that hold onto each other. The animals in these colonies are related to the Portuguese-Man-O'War and other jellyfish. They use long whisker-like tentacles to anchor themselves on to rocks and to move around. The dandelions are scavengers. They are some of the last animals to colonise vent sites. Presence of dandelions around a vent site indicates that the hydrothermal vents are no longer active and most of other organisms in the area are dying.

Mussels are very late to colonise hydrothermal vent sites. They clump together in cracks in the seafloor. Symbiotic bacteria live in the mussels' gills. Like the microbes living inside tubeworms, these bacteria use energy from chemicals in the vent fluids to produce sugars. The sugars provide nourishment for both the mussels and the bacteria. Mussels can also filter food from the water, so if hydrothermal fluid stops flowing out of the vent, mussels can survive for a short period of time. Deep-sea mussels have enormous gills, with surfaces up to 20 times larger than that of similarly-sized edible mussels. Approximately 1000 billion symbiotic bacteria live in and on the gills of these mussels, which is equivalent to the number of bacteria found in 1 kg of deep-sea sediment or 1000 liters of seawater.

The ***microbes*** in the vent ecosystem can be psychrophilic (able to grow best below 15°C), mesophilic (25°C and 40°C), thermophilic (above 45°C) and hyperthermophiles are thermophiles that grow best at temperatures >80°C. The mesophilic microbes can be free-living, growing in the cold nutrient-rich sea water surrounding deep-sea vents in areas such as the buoyant plume that results as the hydrothermal fluid rises into the water column and disperses laterally or microbial mats covering sediments and rocks. Other mesophilic microbes at vents include epibionts that attach to the invertebrates colonising the vents, or endosymbionts found in specialised intracellular compartments in the invertebrates. Thermophilic microbes are restricted to areas where there is close contact with the high-temperature hydrothermal fluid. Hyperthermophiles microbes are found both within the walls of black smoker chimneys and where the hydrothermal vent fluids mix with the surrounding seawater.

Classification of the ***hyper-thermophilic microbes*** has provided new insights into evolution and the origin of life. Two of the hyper-thermophilic genera are classified by ribosomal RNA analyses as Archaea, which are the second domain of prokaryotic life, in addition to the bacteria. By phylogenetic analyses, the hyper-thermophilic archaea and the two hyper-thermophilic bacteria are the most slowly evolving within their domains, suggesting that life may have first evolved when the Earth was much hotter than it is now. Such a thesis is controversial, but indicates that extant life forms are largely the result of temperature adaptations to lower (below hyper-thermophilic) temperatures [15].

Benthic Observatories

Over the past two decades, a number of benthic cabled observatories have been established from shallow to deep oceans for understanding various subsea processes on long-term (**Figure.11**). They include the Monterey Accelerated Research System (MARS) located at ~900m water depth in the Monterey Bay, comprising of 8 nodes, with the main node connected to the shore through a 52-km-long power and fiber-optic cables; the Ocean Networks Canada's Victoria Experimental Network Under the Sea (**VENUS**) coastal observatory in the Vancouver Island's Saanich Inlet and connected in real-time through high-speed fiber-optic cable; the North-East Pacific Time-series Undersea Networked Experiments (**NEPTUNE**) comprising of a network of over 30 subsea observatories covering the 200,000 km^2 JdFR tectonic plate, Northeast Pacific.

It draws power through two shore stations and exchange data through the 3000 km subsea fiber-optic cables. Each observatory, and cabled extensions, hosts and power many scientific instruments on the surrounding seafloor, in seafloor boreholes and buoyed through the water column; the University of Hawaii's **ALOHA** Cabled Observatory located 100km north of the island of Oahu, Hawaii in the North Pacific Ocean provides real-time oceanographic observations from a depth of ~4800 m through a subsea submarine fiber-optic cable [16].

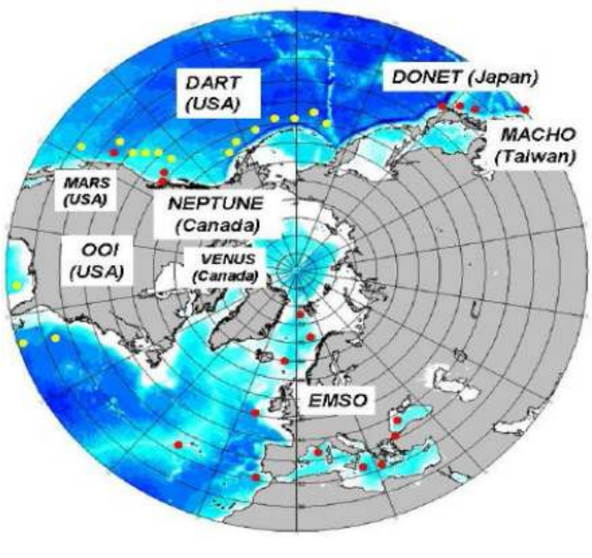

Figure 11. Location of major benthic observatories

The Lofoten-Vesterålen Ocean Observatory (LoVe Ocean) located off-Norway is a multi-purpose cabled observatory network with scientific nodes forming a westward transect comprise of an electro-optic subsea cable transmitting 3kV and three subsea distribution units, distributing 230V and fibres to the scientific nodes located up to 2500m water depth.

The Ocean Observatories Initiative (OOI) network spans the JDFR tectonic plate, with two cables extending from a shore station in Pacific City, Oregon. The underwater network includes ~900 km of high power (8 kW) and bandwidth (10 Gbps) telecommunication cables. One of the branches extends ~480 km due west to Axial Seamount, the largest volcano on the JDFR.

The second branch extends 208 km southward along the base of the Cascadia Subduction Zone located at 2900 m water depth and then turns east extending 147 km to 80 m water depth offshore Newport, Oregon. The cabled array also provides power and bandwidth to the Endurance Array at two locations. The Taiwan Marine Cable Hosted Observatory (MACHO), the US Deep-Ocean Assessment and Reporting of Tsunamis (**DART)** and Japan Dense Ocean floor Network System for Earthquakes and Tsunamis (**DONET)** were established for the purpose of ocean floor seismic and tsunami monitoring.

For carrying out long-term monitoring of hydrothermal vents, there are currently three MOR ocean observatories including, the Azores –Component of the European Multidisciplinary Seafloor and water column Observatory (EMSO), the Endeavour node of Ocean Networks Canada (ONC) and the Axial Seamount array of Ocean Observatory Initiative (OOI) (**Figure.12**). The EMSO Azores, part of the EMSO-European Research Infrastructure Consortium (ERIC) is located on the slow-spreading MAR, at the summit of a magmatically robust central volcano hosting the Lucky Strike hydrothermal field.

The two other observatories include submarine high power and bandwidth cables spanning the intermediate spreading JdFR in the NE Pacific. The ONC-Endeavour, located on the intensely hydrothermally-active Endeavour Segment, is significantly influenced by seismicity, extensional tectonics and faulting. The OOI-Axial Seamount, located on the magmatically robust and volcanically active Axial volcano is operated by the University of Washington for the US OOI, as part of the OOI Regional Cable Array.

All three observatories support research aimed at understanding second, to daily, to multi-decadal geophysical and geochemical processes occurring at these submarine volcanoes and their vent systems, and, in turn, how these processes affect the water column and drive biological responses in time and space, below, at, and above the seafloor. The multidisciplinary observatories host sensors to characterise crustal dynamics, hydrothermal circulation, fluid dynamics and composition both below and above ground, and biological activity.

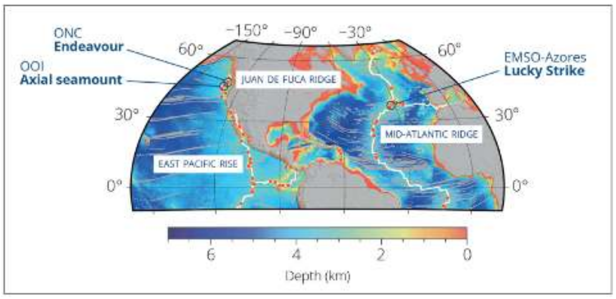

Figure 12. Location of the three currently operating seafloor and water column MOR ocean observatories in the Pacific and Atlantic oceans [16] [17]

The EMSO-Azores sits atop an active volcano close to the Azores Triple Junction on the northern part of the Mid-Atlantic Ridge (MAR). The volcano hosts Lucky Strike, one of the largest active ridge-related hydrothermal vent fields. This basalt-hosted field, situated at an average water depth of 1700 m, contains over 20 active hydrothermal edifices distributed around a fossilised lava lake, and overlying a magma chamber at ~3 km depth below seafloor.

The autonomous instruments deployed at Lucky Strike include 4 short-period Ocean Bottom Seismometers (OBS), 2 pressure gauges, a physical oceanography mooring, a seabed array of 4 cabled hydrophones that supports micro-seismicity and marine sound studies at the Tour Eiffel site (**Figure.13**), a vast array of temperature probes distributed in hot and diffuse vents through the hydrothermal field, several bottom current meters and over 20 autonomous faunal colonisation devices. All seafloor system components are recovered, serviced onboard and redeployed by either the ROV Victor 6000 or HOV Nautile.

With reference to ONC-Endeavour (**Figure.14**), the hydrothermally active Endeavour Segment, located on the northern part of the intermediate-spreading JdFR is 10 km long, with a 1 km wide axial valley that has rift walls reaching 200 m. Endeavour segment hosts five major hydrothermal vent fields that are underlain by magma lenses at depths of ~2-3 km with micro-seismic activity linked to hydrothermal circulation between the magma lens and the seafloor. *Axial* Seamount is a seamount and submarine volcano located on the JdFR, ~480 km west of Cannon Beach, Oregon.

These benthic hydrothermal vent observatories are located in the highly dynamic MAR and back arc spreading centers, where seafloor volcanism and tectonic activity are acting predominant. Hydrothermal circulation within these environments is responsible for significant transfer of heat and chemical constituents between the ocean lithosphere and the overlying hydrosphere, thus controlling the thermo-mechanism state of crust, its formation and deformation, rock alteration, and influencing element balances in the ocean.

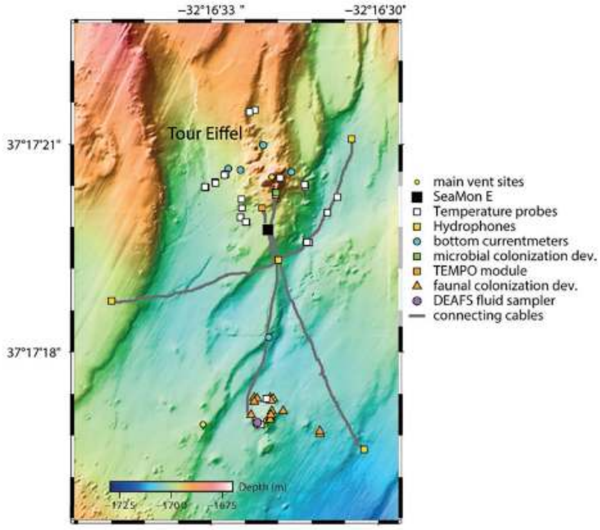

Figure 13. Detail of the instrumentation at Tour Eiffel in Lucky Strike vent zone [17]

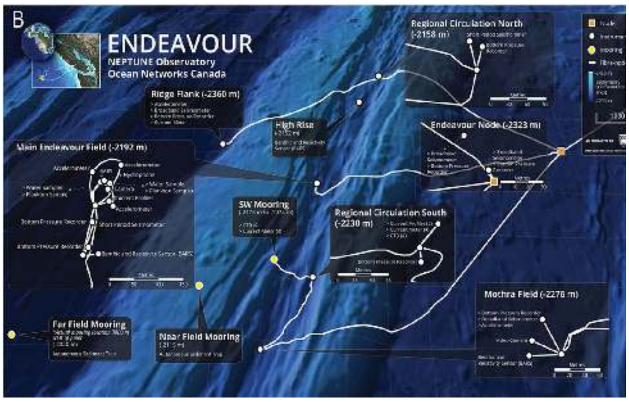

Figure 14. Details of the instruments' locations at the Endeavour node of the JdFR [17]

Challenging physiochemical conditions at the vent sites constrain faunal diversity, whereas highly diverse prokaryotes exploit a broad range of habitats. Thus, the studies on the hydrothermal vent ecosystems (**Table.2**) broaden our understanding of the potential origins of life on the planet and aspects related to climate change.

Conclusion

Hydrothermal vents are among the most fascinating environments that exist in the planet. They have been a feature of our planet since the Hadean and their history is intricately weaved into that of life on Earth. The physicochemical conditions that vents provide are central to their ability to sustain highly productive ecosystems. Thus, they are the home to highly productive communities of specially-adapted fauna, supported by chemical energy emanating from the Earth's subsurface. The article provided an overview of the **technologies** that are in place for hydrothermal vents studies, **vent locations, geothermal conditions, biogeography** and their **unique biodiversity**.

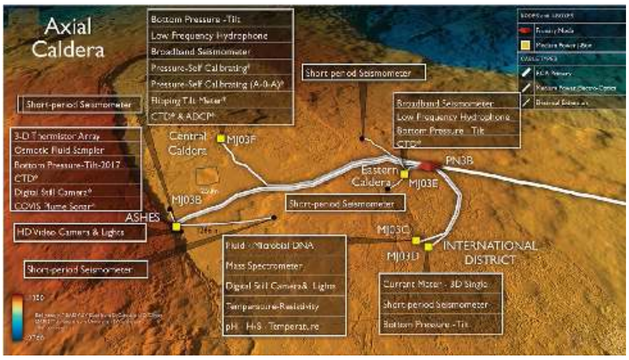

Figure 15. Details of the instruments' locations within the Axial Caldera [17]

The remarkable developments in the deep-ocean manned and unmanned robotics and in-situ sampling tools have enabled biological sampling, habitat analysis and in-situ experiments in extreme environments. The recent developments in hadal depth HOV such as Deep Sea Challenger, Triton and Fendouzhe designed for carrying out expeditions in ultra-deep waters such as in the New Britain trench (8228m) and Mariana trench (10908m) could be of use in hydrothermal vents located at hadal depths.

Over the recent years, the data from the deep-ocean benthic observatories, specifically long-term time-series acquired at the sites located 9º N-13º N along the EPR have greatly enabled our understanding of the ridges, and more particularly vent ecosystems dynamics. The Integrating Multidisciplinary Observations in Vent Environments (IMOVE) Working Group formed to advance multi-disciplinary research within and across the three MOR observatories supports multi-disciplinary research at the hydrothermal vents hosted in a basaltic upper crust, and overlying magma chambers at varying depths.

These magmatic sites are visited very year as part of maintenance cruises allowing systematic surveys and sampling and information of the different scales of biological and environmental data. The data provided a basis for further expanding existing data and for identifying Essential Ocean Variables (EoV) and Essential Biological Variables (EBV) that needs to be measured to improve our understanding on the hydrothermal vent processes fluid flow geometry, fluxes, variability,

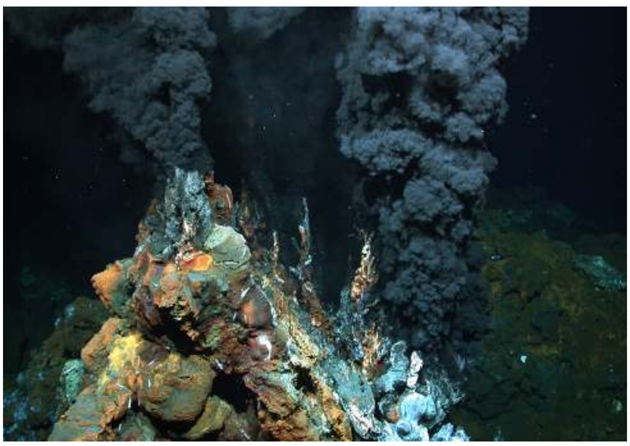

Table 2. Studies on various areas of vent

Parameter	Significance
Subsea floor	Ground deformation, heat transfer, fluid-rock interactions affecting fluid flow geometry, fluid composition and crustal stress and permeability, fluid residence times and recharge, and microbial community composition
Interface at the ocean floor	Thermo-chemical exchanges and mixing impact fluid flow characteristics, microbial and vent species distributions and biomass, &energy flow
Water column	Oceanographic forcing, including currents, tides and their interactions with the local topography, drives plume dispersal, hydrothermal fluxes and exports to the ocean, faunal distribution, behaviour and larval dispersal, and influences species connectivity

local oceanographic currents and associated biological responses.

Still questions remain regarding the evolution of biological communities through time, including non-directional change (i.e., change in species composition, symbiosis and abundances due to immigration, extinction, competition, predation etc) as well as directional change (i.e., Succession after neutral and /or anthropogenic disturbance).

To foster our understanding on these areas, the next step should be to integrate across disciplines to better constrain the overall ecosystem functioning, from geological processes to biological communities' distribution and responses. Establishment of more hydrothermal vent observatories (such as the ones proposed in locations including the Azores Archipelago and the Northeast Pacific from the Cascadian Margin to the Juan de Fuca Ridge) with advanced geo-chemical, biological and IOT-enabled sensor technologies will promote large-scale interdisciplinary studies, placing the ridge environment and its influence at the heart of the global ocean.

ABBREVIATIONS

ABE	Autonomous Benthic Explorer
AUV	Autonomous Underwater Vehicles
DART	Deep –Ocean Assessment and Reporting of Tsunamis
DONET	Dense Ocean floor Network System for Earthquakes and Tsunamis
DSV	Deep Submergence Vehicle
EBV	Essential Biological Variable

EOV	Essential Ocean Variable
EPR	East Pacific Rise
ERIC	European Research Infrastructure Consortium
ESONET	European Sea floor Observatory NETwork
EMSO	European Multidisciplinary Seafloor and water column Observatory
HFPS	Hydrothermal Fluid and Particle Sampler
HOV	Human Occupied Vehicle
IMOVE	Integrating Multidisciplinary Observations in Vent Environments
IOT	Internet of Things
JdFR	Juan de Fuca Ridge
JPL	Jet Propulsion Laboratory
LoVe	Lofoten-Vesterålen Ocean Observatory
NEPTUNE	North-East Pacific Time-series Undersea Networked Experiments
MACHO	Marine Cable Hosted Observatory
MAR	mid-Atlantic ridge
MARS	Monterey Accelerated Research System
MOR	Mid-Oceanic Ridge
OBS	Ocean Bottom Seismometer
ONC	Ocean Networks Canada
OOI	Ocean Observatory Initiative
PMEL	Pacific Marine Environmental Laboratory
ROV	Remotely Operated Vehicle
RNA	Ribonucleic acid
SIP	Stable Isotope Probing
TAG	Trans-Atlantic Geo traverse
VENUS	Victoria Experimental Network Under the Sea

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About the author

Dr N. Vedachalam is currently Scientist G in Deep Sea Technologies division of National Institute of Ocean Technology (NIOT), Ministry of Earth Sciences, India. He is the technical lead for India's first indigenously-developed deep-water manned scientific submarine MATSYA 6000. He holds a Bachelor's degree in Electrical and Electronics engineering from Coimbatore Institute of Technology (1995) and PhD in Techno-economics of marine gas hydrates from College of Engineering - Anna University, India. His 27 years of experience include industrial power, process, offshore and subsea domains at Aditya Birla group, General Electric & Alstom Power Conversion in France. Technical exposure includes development of multi-megawatt subsea power and control systems for Ormen Lange subsea compression pilot; Ocean Thermal Energy Conversion and wave energy systems; subsea renewable power grids; unmanned and manned underwater vehicles; ocean observation technologies and industrial systems. His research interests include energy, subsea robotics and reliability. He has more than 100 publications in indexed journals, holds an international and two national patents in subsea robotics and subsea processing. He is a recipient of the national meritorious invention award in 2019 for the development and usage of underwater robotic vehicles. He is a member of Indian Naval Research Board, member of Bureau of Indian Standards and was the Secretary of IEEE OES - India Chapter. He is a regular contributor to MER.

Email: veda1973@gmail.com

MECHANISM BASED FAILURE ANALYSIS

Prabu Duplex

1. Introduction

Despite the range of maintenance activities performed within the maritime industry, unexpected failures are unavoidable in practice. However, if a failure has serious consequences in terms of costs, safety, environmental effects or consequential damage, measures are usually taken to prevent such a failure from occurring again in the future. Also, less critical failures can be extremely troublesome when they occur on a regular basis. In such cases it is essential to identify the root cause of the failure, as one can then find a solution for the problem, either by reducing the loads on the system or by increasing the load carrying capacity. In this work, a method to analyse failures and their effects and causes is discussed. This can be used to analyse past and possible future failures. The method will guide the failure analysis and ensure that a structured approach is adopted. A procedure will be proposed for a mechanism-based failure analysis that adopts the structured approach, while at the same time making full use of the knowledge of loads and failure mechanisms.

There are several methods available that can be used to perform a structured analysis of failures. The main goal of all these methods is the prevention of failures, especially those failures which have serious consequences. The methods can be divided into two separate categories.

The first category covers those methods that are applied during the design phase of the system and before it has entered service and before any failures have occurred. These methods, which include the failure Mode, effects and criticality analysis (FMECA) and the fault Tree analysis (FTA), aim to identify possible future failure modes. If the risks associated with certain failure modes are perceived to be too high, a modification of the design can be considered or appropriate maintenance tasks can be defined (e.g., periodic inspections).

These methods, which include the failure Mode, effects and criticality analysis (FMECA) and the fault Tree analysis (FTA), aim to identify possible future failure modes

The second category concerns the methods used after a failure has occurred. These methods focus on finding a way of preventing additional failures from occurring, either by looking for the root cause of the failure (e.g. root cause analysis) or by selecting the failures with the highest priority (e.g. Pareto and degrader analysis).

Executing a sound failure analysis in a maintenance context requires that the following conditions are met:

1. a concise and structured approach is followed,
2. a proper selection is made of relevant failures to be investigated,
3. the analysis is executed to a sufficiently deep level. The existing methods discussed in the previous paragraph individually do not meet all these requirements [1].

Therefore, in this section, a procedure is proposed that meets all the requirements, and at the same time optimally utilises the knowledge on loads and failure mechanisms. The procedure, which is called the Mechanism based failure analysis (MBFA), combines the methods introduced in the previous section. A stepwise guideline for performing a failure analysis is shown in **Figure 1**.

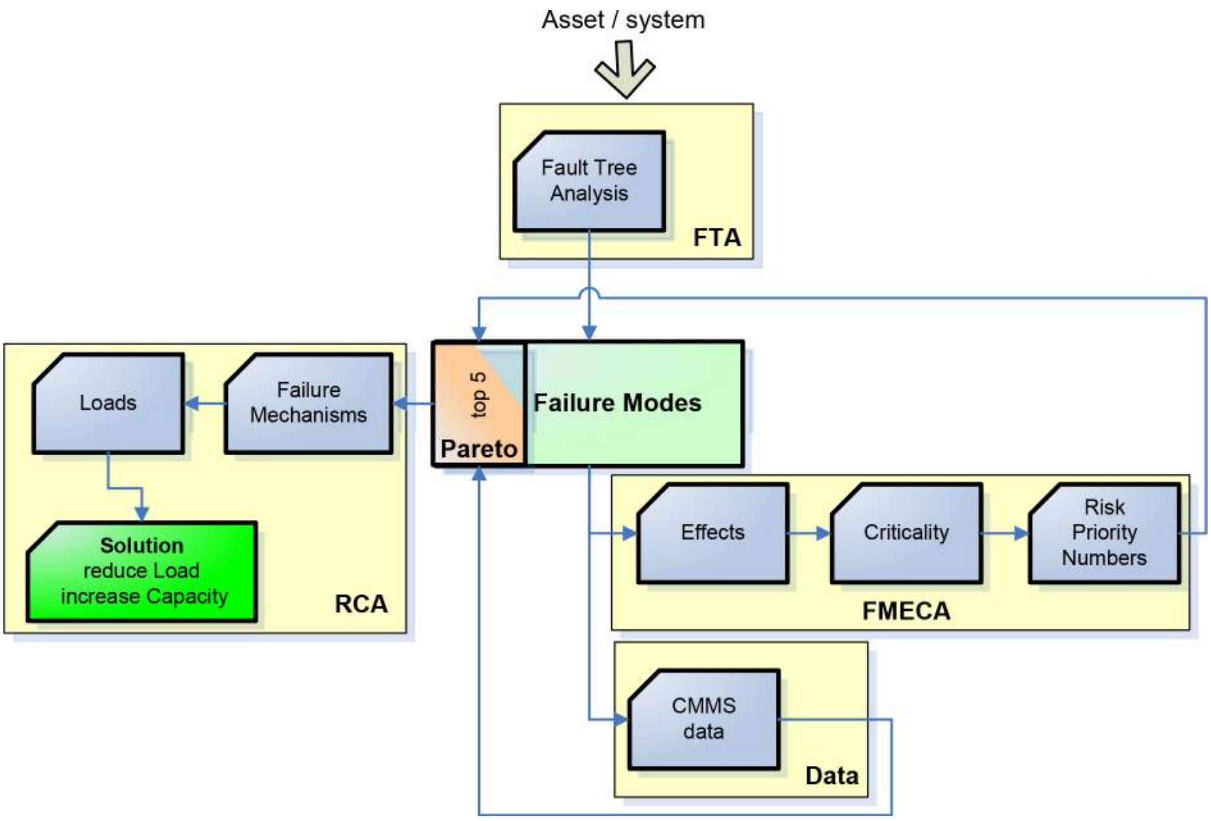

Figure 1. Failure analysis process (Tinga 2012 [1])

Starting from a failed asset or system to be analysed, firstly a fault tree analysis is performed to identify all possible failure modes that could lead to the system (functional) failure. After the completion of this overview, it is required to identify the most critical failure modes, since generally solving all possible failure modes is not feasible. To be able to perform a Pareto analysis, which determines the top 5 or 10 most critical failure modes, data must be generated on which the sorting process in the Pareto analysis can be based. Two options are available to generate this quantitative data:

(i) collect failure data from the computerised maintenance management system (CMMS) or **(ii)** perform a FMECA analysis and calculate risk priority numbers (RPN) for all failure modes. Based on either the CMMS data or the RPN values, the Pareto analysis will yield the top 5 cost drivers or performance killers.

Then for the critical failure modes, a root cause analysis must be performed. It is essential that the level of detail of this RCA is such that the failure mechanisms and the internal loads for each failure mode can be assessed. Moreover, the relation between the governing loads and the usage of the system must be identified, which implies that any excessive load can be linked to a certain usage condition. Monitoring data on loads and usage could be very useful in this assessment. Finally, the solution for the problem, i.e. prevention of similar failures in the future, must be found. Since the failure mechanism and governing loads have been determined, it is generally rather easy to decide whether the loads or the capacity of the system constitute the root cause.

For capacity problems, a modification of the system should be considered, while for loading problems the usage and associated loading of the system should be reduced. If changing the usage profile of the system is not feasible, the (frequent) failures must be accepted, but setting up a monitoring program for the usage, loads or condition may aid to make the failures predictable. In line with these principles, this article describes a Mechanism based Failure Analysis on 4-stroke marine diesel engine.

2. Problem Definition

The first step in the analysis is the problem definition, starting with the specification of a (functional) failure. The system boundary is set to include only the failure mechanisms that are affected by, or caused by the vessel's diesel engine.

3. Fault Tree Analysis of Diesel Engine

Types of Failure Cause

The next step in the failure analysis procedure is the execution of a fault tree analysis to identify all failure modes that could possibly lead to the diesel engine failure. The resulting fault trees are shown in **Figures 3 to 8**. Basically the branches appear in this fault tree, are associated to engine failure conditions generally observed in the maritime industry. For each condition, several lower level failures have been identified and ultimately a number of basic failures are obtained, as represented by the coloured circles at the lower end of the fault tree. The meaning of the different colours are explained in **Figure 2**. In the fault tree analysis, a distinction is made between four types of failure causes (Tinga, 2012).

4. Priorities in Failure Modes

The Risk Priority Number approach was used to determine the priority between failure modes as shown in **Table 1**. In this analysis, a qualitative approach was considered for diesel engines. A future improvement can be made by performing a Pareto analysis on failure data in CMMS as shown in **Figure 9**. It is to be noted that methods such as FMECA are generally applied before the system enters service and thus before any failure has occurred. They are used to get insight in the possible risks and aim to govern the system design process.

For systems that are already operative, the data collected on failures during service provides very useful additional information that can be utilised to further improve the system or its operation [1]. The Pareto analysis can be used to prioritise such improvement efforts for complex systems. In general, systems show different failures, but not all failures are equally harming the operation of the system. The Pareto analysis provides a structured methodology to filter out the most important failures. It is based on the observation that 20% of the failures are responsible for 80% of the maintenance costs, or 80% of the total downtime of the system. Such failures should therefore be aimed at, in improving the system. However in this work FMECA analysis is considered to give insight on the methodology.

The Pareto analysis provides a structured methodology to filter out the most important failures. It is based on the observation that 20% of the failures are responsible for 80% of the maintenance costs, or 80% of the total downtime of the system

Failure cause	Colour code (in FTA)
1. **Insufficient load-carrying capacity of the system or part** This is often caused by applying parts that do not comply with specifications. Example: applying a seal from a different material than specified, resulting in excessive wear or degradation.	Insufficient load-carrying capacity
2. **Human Error** often caused by disregarding regulations, by the absence of clear regulations or by inadequate training. example: applying the wrong type of lubricant.	Human error
3. **Excessive load on the system due to avoidable (mis)use** The usage of the system deviates from the design specification, but can rather easily be changed to comply with the specifications. Example: if a valve is closed, a large pressure difference exists across the ball (and seals). if the valve is opened too slowly, a high velocity gas flow will appear due to the small orifice that is available, leading to erosion of the seals.	Avoidable load (misuse)
4. **Excessive load on the system due to unavoidable (mis)use** The usage of the system deviates from the design specification, but adaptation of the usage is unacceptable or impossible. example: low ambient temperatures yield freezing of water in the cover tube, leading to blockage of the stem.	Unavoidable load

Figure 2. Types of failure cause & colour coding

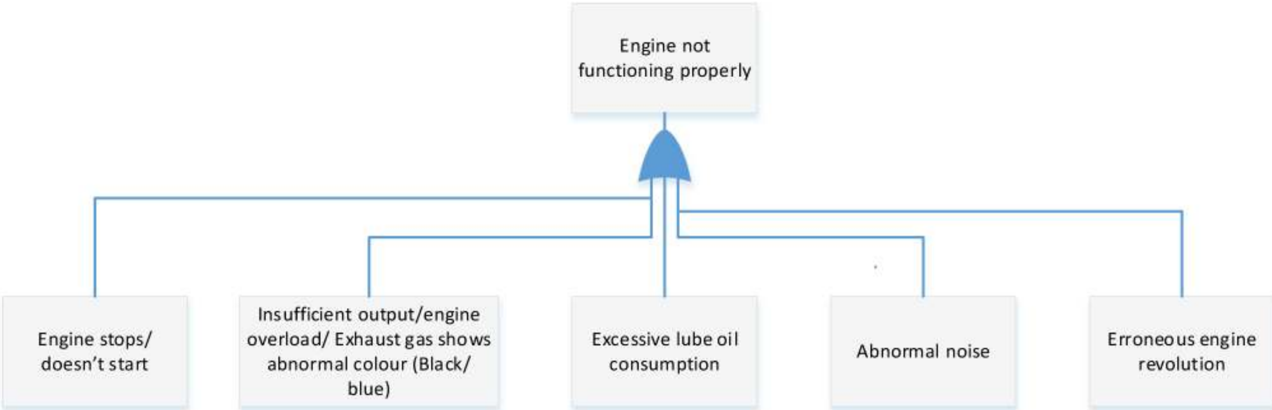

Figure 3. Events related to Engine malfunction

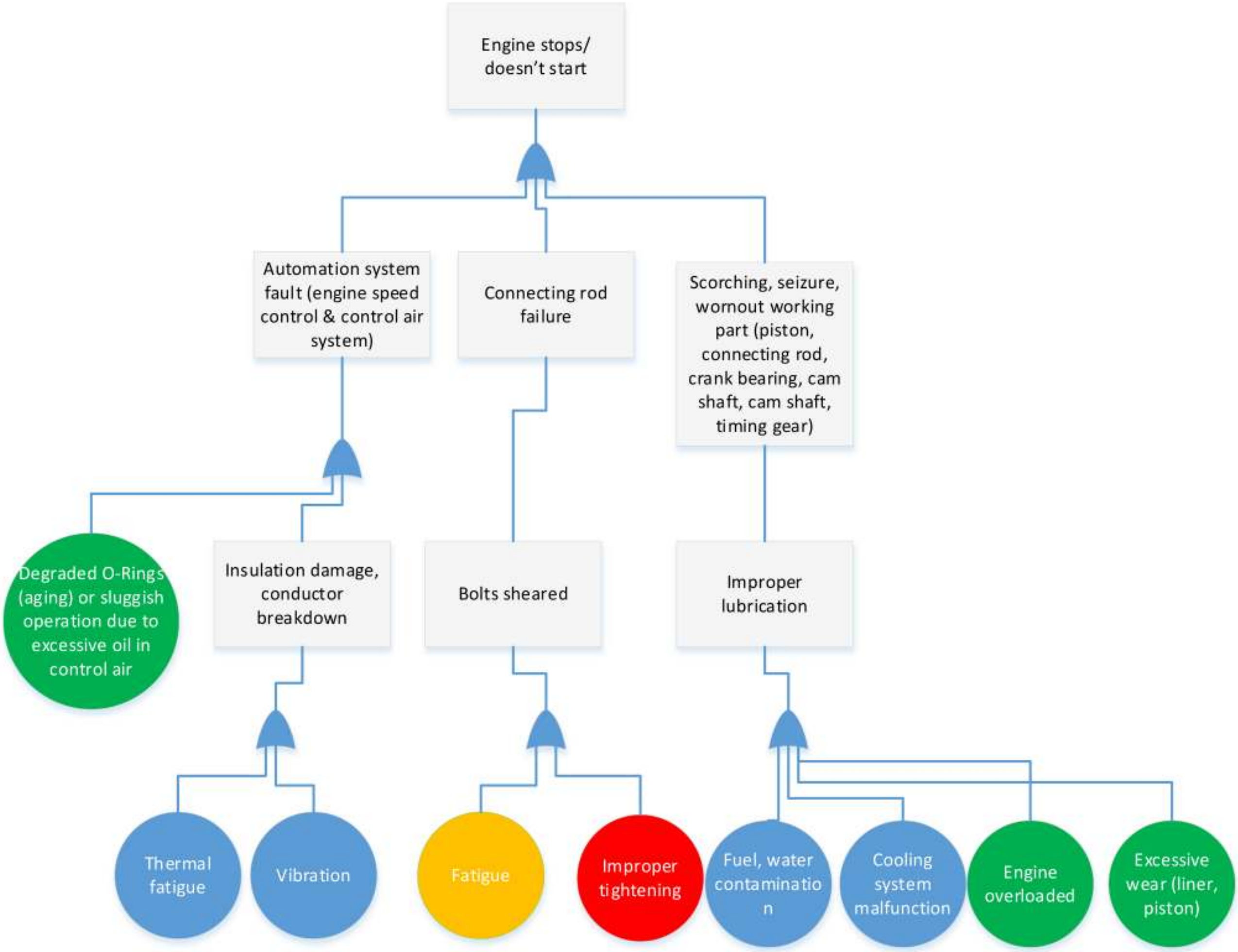

Figure 4. Events related to engine stop/ does not start

Remarks on FMECA

- Failures leading to immobilisation of the ship, and need external help or cause environmental hazard that leads to suspension of its operatory license are considered as critical failures.
- Fire is more hazardous than analysing ship propulsion system in general. It is a random process initiated by increased vibration and temperature level in certain engine sub system.
- Transmitting gears, reduction gears, crank shaft, tail shaft, intermediate shaft doesn't have extensive failure record.
- Crank case explosion is not registered in these engines.
- Pump related failures (jacket cooling water pump, lube oil pump), can be attended by spare pumps or by staff.

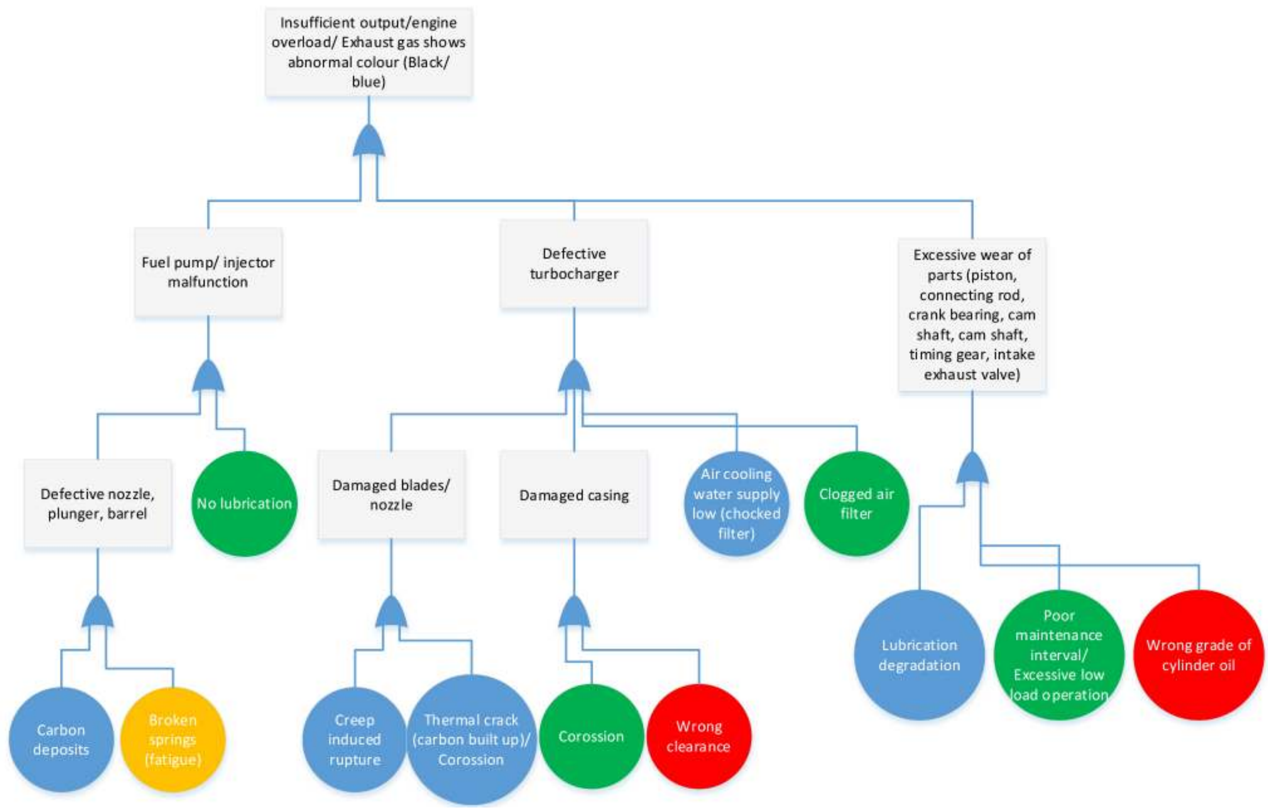

Figure 5. Events related to insufficient engine output/ overload/ abnormal exhaust gas

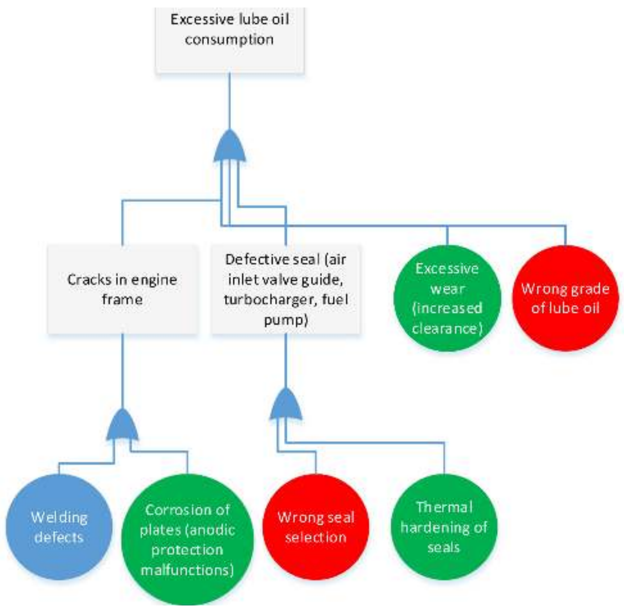

Figure 6. Events related to excessive lube oil consumption

- Electrical faults can be handled by back up mechanical systems and technicians. Few electrical (speed control systems) components are prone to frequent failures. Even though they rank less in priority than others, and cheap to replace, the inherent damage it causes to engine in general needs to be considered.
- Engine operation in resonance RPM is uncommon

Failures leading to immmobilisation of the ship, and need external help or cause environmental hazard that leads to suspension of its operatory license are considered as critical failures

- Pumps (jacket cooling water pump, lube oil pump) are redundant in nature, and small failures such as seals, shaft, impeller failures can be over hauled onboard.
- Components affected by low load operation needs to be assessed

5. Failure Mechanisms

From the Risk Priority analysis as shown in **Table 1**, it can be observed, the top failure modes with the highest RPN values are as follows:

1. Piston assembly, liner, turbocharger and valves (including rings, cylinder liner, inlet & exhaust valves)
2. Fuel pumps & injectors
3. Lubrication oil

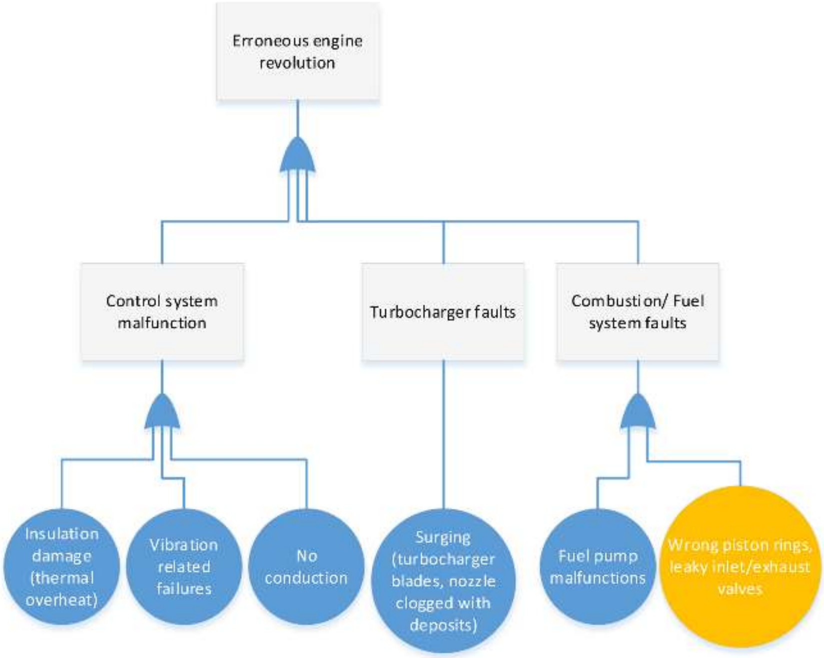

Figure 7. Events related to erroneous engine operation

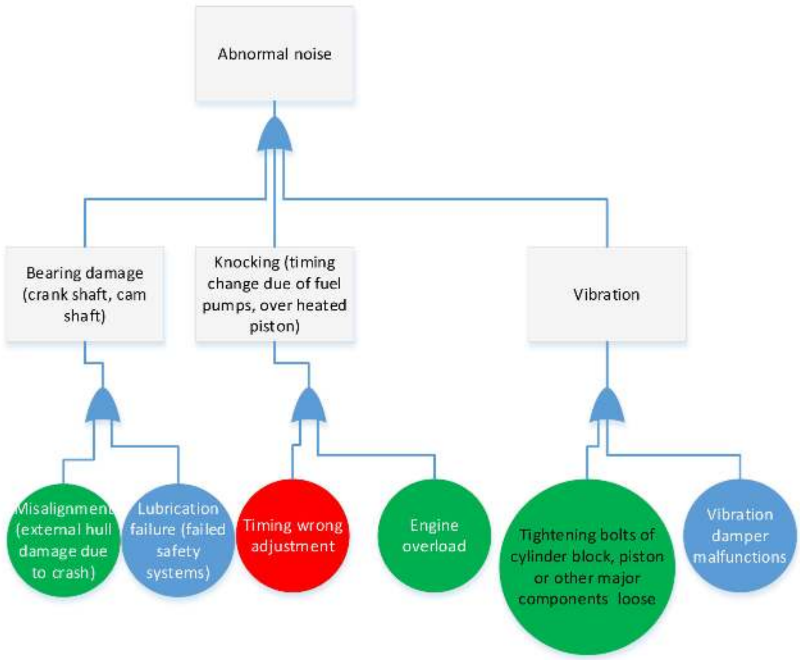

Figure 8. Events related to abnormal noise

The common failure mechanisms, if engine is operated in OEM prescribed conditions, are recession (abrasive & adhesive wear) and high temperature corrosion

5.1 Piston Assembly, Liner, Turbocharger and Valves

Inlet & Exhaust Valves

1. Valves are subjected to very demanding conditions such as, extremely high temperatures, time variable mechanical loads and corrosion.
2. The common failure mechanisms, if engine is operated in OEM prescribed conditions, are recession (abrasive & adhesive wear) and high temperature corrosion. The recession caused by the wear eventually, reduces the inability of the valve system to seal against the pressure, and results in failure due to guttering.
3. Impact during valve closure generates plastic deformations on the contact surfaces, which lead to the formation of circumferential ridges and valleys around the axis of the valve. This yields to surface cracking and eventually loss of material.
4. If the engine is operated outside OEM prescribed limits, fatigue failure of valve stem is expected. For example excessive carbon built up in low load conditions, overheats the components. There by high temperature corrosion and subsequent fatigue failures can be expected.
5. If valve seat and valve misaligns, it will produce a non-uniform wear pattern and will cause premature failures.
6. To make uniform wear these valves are actuated by roto caps. This will rotate the valve in each valve closing cycle, and developing uniform wear. Due to lube oil contamination, the equipment malfunctions most of the time and creates premature failure.
7. Finally, the inlet & exhaust valves are made up of different materials. The most common mistake done by technicians is to interchange these. Eventually inlet valve can't operate under extreme exhaust temperatures. There by it will fail.

Cylinder liner

1. The liner wear is a complicated process due to the changing oil lubrication regimes (from dry to fully lubricated). Liner can experience extreme wear when soot accumulates in the oil and the cylinder surfaces.

Table 1. Risk Priority Table for the Caterpillar C32 diesel engine

No.	Components	Failure modes	Failure effects	C	P	D	RPN
1	Bearing (main, small end big end bearings)	Misalignment		7	3	7	147
		Seizure	Seizure of engine	10	3	7	210
		loosening of bolts	Excessive vibration	8	6	8	384
2	Piston assembly (rings, piston head, cylinder liner), turbo charger	Turbocharger vibration	Loss of engine load carrying capacity	10	8	8	640
		Jammed rings	Loss of ship speed, collision hazards	10	8	8	640
		Broken rings	Vibration	10	8	8	640
		Excessive clearance in ring / grooves	Air pollution, excessive emission, black smoke	10	8	8	640
		Non uniform wear pattern of liner		10	8	8	640
3	Inlet & exhaust valves	Recession	Loss of combustion, air pollution, excessive emission	8	8	8	512
		Breakage		8	7	8	448
4	Gear wheel train	Excessive back lash	Improper combustion	7	2	8	112
		Vibration		7	2	8	112
5	Gear box	Vibration, excessive noise	Excessive engine vibration	7	2	8	112
6	Electric component	Vibration	Partial loss of control	7	2	8	112
7	Fuel injectors	Sticky components	Erratic engine speed, ship speed loss, excessive emission, black smoke	10	8	8	640
		Excessive wear		10	7	8	560
8	Fuel pump	Sticky components	Erratic engine speed, ship speed loss, air pollution, black smoke	10	8	8	640
		Sluggish operation		10	8	8	640
9	Heat exchanger	Fouling	System contamination, corrosion hazards	8	5	2	80
		Intermixing of fluid		8	6	2	96
		Leakage		7	6	2	84
10	Engine control unit	Short circuit	Loss of ship speed, manoeuvring capabilities, air pollution	8	6	5	240
		Loosening of contacts		8	9	5	360
11	Auxiliary control systems	Short circuit	Functional loss of subsystems	7	8	5	280
		Loosening of contacts		7	8	5	280
12	Attached pumps	Casing wear	Engine can't be operational, excessive vibration	7	7	6	294
		Bent shaft		7	7	6	294
		Bearing failure		7	7	6	294
		Seal loss		7	8	6	336
		Impeller damage		7	8	6	336
13	Starting system	Sticky components	Starting and reversing problems	8	8	6	384
		Excessive clearance		8	7	6	336
14	Crank shaft, cam shaft	Cracks	Engine failure, expensive replacement costs	9	5	8	360
		Bent shaft		9	5	8	360
		Slippage		9	5	8	360
15	Lube oil	Loss of additives	Increase wear rate, corrosion of components	9	8	6	432
16	Connecting rod	Bent shaft	Engine failure	8	7	6	336
		Over heating		9	4	8	288

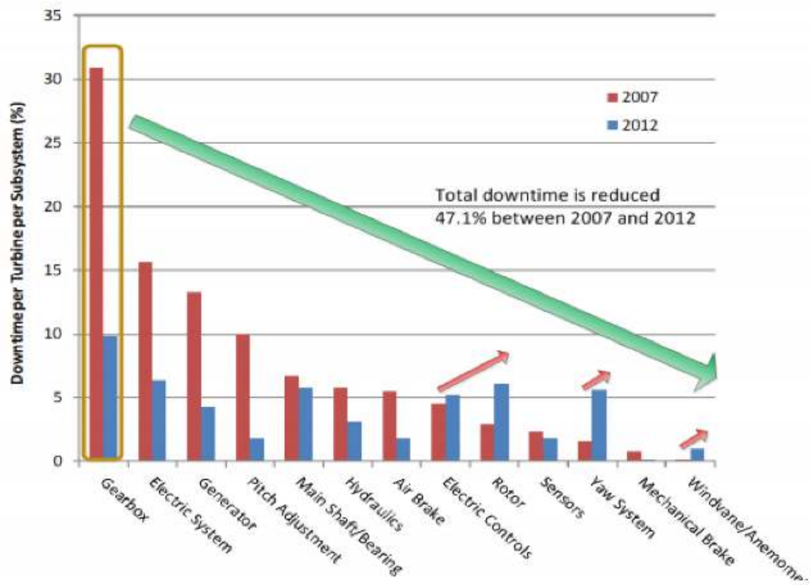

Figure 9. Down time of frequent failures

- The jacket water cooling system if not maintained properly will inhibit scaling and corrosion, in the cylinder unit. This will subsequently lead to overheating and corrosion of liner surfaces, thereby degrading the metallurgical properties.

Turbocharger

1. Shaft fracture caused by eccentricity of rotor, because of excessive carbon deposits in low load operations. The shaft will then be loaded asymmetrically, leading to fatigue fracture.

The latter occurs mainly when operating the engine outside its design range, i.e. at low load operation (<50%). The most common features are:

- Soot acts as an abrasive surface when it accumulates on the piston rings. It's hardness is found to range from low to more than the piston ring and much higher than the liner.
- Soot accumulation in the oil increases the oil viscosity thus reducing its flow through the oil lines and to the liner surface.
- Soot clogs the liner induced roughness (honing) and the oil does not stay thus leading in metal to metal contact
- Soot absorbs and deactivates the oil additives which reduce wear

2. If engine is operated in its designed load conditions, abrasion, adhesion wear occurs at cylinder liner and piston ring interface.

- Excessive wear leads to leads to blow past (improper sealing of combustion chamber), which leads to overheating of combustion chamber, and impose non-uniform thermal loads on the components (piston, liner). Due to these loads, cracks will be initiated in the cylinder liner, and the surface will deteriorate over a very short period.
- Excessive wear leads to thinning of material and thereby it can't resist the hoop stress.

The liner wear is a complicated process due to the changing oil lubrication regimes (from dry to fully lubricated). Liner can experience extreme wear when soot accumulates in the oil and the cylinder surfaces

2. Turbine blades are exposed to high temperatures. There will be a very slow deformation at high temperature (creep), and if it is not replaced it will lead to premature failures.
3. The gas passages have very fine clearances, therefore if it is aligned properly extreme vibrations due to misalignment (manual error) impose high loads and subsequent damage.

Piston Assembly

1. Overheating leads to oxidation of fuel and subsequent carbon deposits in piston grooves. Due to this piston rings will cease to rotate and there by cause incomplete combustion and additional thermal loads, eventually material property degrade and it will fail.
2. Due to increased clearance in piston ring grooves, rings will be subjected to axial impact loads and over stretching, which eventually leads to breakage.
3. Other common failures are fixing wrong piston rings in groove (top ring is made of different material), and using improper tools for fixing.
4. There are a few rubber O-rings in piston lubrication passages. High fluctuations of operational temperature cause thermal shock and subsequent fracture, if operational conditions are not met.

5.2 Fuel Pumps & Injectors

1. The components are almost identical in fuel pumps and injectors. These are high precision components. If these components are not replaced in the prescribed

intervals, the atomisers will wear out. Wear is the most common phenomena in nozzles, plunger and barrel interfaces.

2. Under low load conditions, the combustion will be incomplete. Therefore carbon deposits will be accumulated in the periphery of nozzle holes, thereby it will change the atomising pattern. Eventually it will overheat the nozzle and lead to subsequent failure. High temperature corrosion is also found in some cases.
3. There are more O-rings in fuel pumps and valves. This failure behaviour is very similar as mentioned under piston ring category.

> *Oil properties are not monitored in a real time. Therefore contamination deteriorates the chemical and load carrying capacity (loss of hydrodynamic film) of lubricants*

5.3 Lubrication System

1. In four stroke engines, the bearing lubrication and cylinder lubrication will be done by the same system. Therefore if a fuel injector, malfunctions it will contaminate lubrication system with in a shorter period. Oil properties are not monitored in a real time. Therefore contamination deteriorates the chemical and load carrying capacity (loss of hydrodynamic film) of lubricants. It subsequently damage all bearings in the system. It is quite expensive therefore company supplies in a shorter quantity. In case of contamination it will incur additional cost to procure and supply to ships.
2. Other sources of contamination are seal damage in attached fuel pump, and exhaust gas seals in turbocharger and exhaust valve cooling system. Seal surfaces damage due to normal wear and additional vibration loads in case of engine malfunction.

6. Loads and Relation to Failure

For every failure mechanism, the governing load that eventually causes failure can be determined. Reduction of this load will yield an increase of the system service life, whereas monitoring of this load enables the prediction of upcoming failures.

6.1 Piston Assembly, Liner, Turbocharger and valves

Piston Assembly

Combustion gas pressure exerted in the grooves (wear is proportional to gas pressure and sliding distance), balanced by lubrication film (function of piston velocity). Temperature is crucial factor in abnormal operational conditions. Coefficient of friction is influenced by the increase of temperature. Generally with the rise of ambient temperature, the coefficient of friction of the material surface would be changed. Such change varies for different materials.

Operating engine under prescribed load vs speed range, enables proper gas pressure, temperature and lubrication properties. Low speed conditions needs to be avoided for extended run (velocity affects hydrodynamic properties of lubrication oil). If extended low speed operations are intended derating engine or changing propeller to match the engine must be considered.

Valves

Combustion gas pressure exerted in valve head and closing velocity (wear is proportional to gas pressure and closing velocity). The load conditions explained for piston applies to valves also.

Turbocharger

Temperature is the governing load. Monitoring and maintaining it will enable long life by reducing carbon deposit, creep and associated failures.

6.2 Fuel Pumps & Injectors

Temperature and lubrication properties are the governing loads. Monitoring and maintaining them will enable long life.

6.3 Lubrication Oil

TBN content, additives, are the key performance parameters. Governing load is the acidity due to sea water intermix, temperature (affects viscosity) and contaminants. This can be avoided by proper maintaining of temperature (lube oil coolers and cooling systems), and using OEM prescribed lubrication oil.

6.4 General Remarks

In case of diesel engines operated at varied load conditions, clear operational instructions needs to be followed to increase or decrease engine speed so that, temperature fluctuations (thermal loads) are with in prescribed limits. Operational parameters like jacket water cooling temperature and lube oil temperatures needs to be maintained properly, so that thermal load fluctuations will be minimum. In case of unavoidable misuse such as low-load operations, OEMs need to be contacted for a better solution (derating). If that is not possible failures needs to be accepted, and the equipment needs to be monitored by usage or condition monitoring.

7. Solution Propositions

7.1 Piston Assembly, Liner, Turbocharger and Valves

Valves

Precautions needs to be taken while installing the valves. Rotocaps needs to be checked periodically for it functioning. If extended low load operation is intended, valves needs to be sampled in random to assess its life and carbon deposits. Wear rate (recession) should be measured and recorded at regular intervals.

Piston Unit

Care should be taken while installing the piston rings (direction, sequence). The clearances needs to be checked periodically, and the rings has to be changed as per maker instructions. The same holds true for piston crown.

Cylinder liner

Cooling water additives to be added and inspected periodically to keep the liners corrosion free. Uneven wear pattern in the liner needs to be inspected and reconditioned at manufacturer prescribed intervals. Liner needs to be changed if the internal diameter increases beyond the maker prescribed levels.

If extended low load operation is intended, then the combustion temperature should be maintained by adjusting jacket cooling water system.

Turbochargers

The overhaul of turbochargers needs to be done only by authorised persons from the workshop. More over the accumulated soot needs to be cleaned by OEM prescribed methods (water wash) at regular interval. Feasibility to install vibration sensors needs to be explored.

7.2 Lubrication System

This has a direct influence on piston rings, cylinder liner wear rate. Therefore its chemical compositions and physical properties should be assessed (accumulation of soot, iron, TBN number, viscosity, water content and other additives) in a very close interval on-board. In addition to that periodically it has to be sent to lab for a detailed inspection.

7.3 Fuel Pumps & Injectors

Fuel pumps needs to be pressure tested/ replaced at OEM prescribed intervals. Cooling and lubrication system if present needs to be checked frequently for its effectiveness. Fatigue failure of springs can be controlled by replacing them at regular intervals or redesigning.

> *Mechanism based Failure Analysis can be applied to solve problems in the real world*

8. Conclusion

Mechanism based Failure Analysis can be applied to solve problems in the real world. It demonstrates that analysing the failure mechanisms and associated loads can help solve those problems in a relatively straightforward manner. It is to be noted that obtaining details on failure mechanisms from information systems like CMMS appears to be crucial to protect from future failures. Maritime companies can take forward this analysis and review their asset management philosophy. This helps the ship management firms to improve the reliability and availability of equipment and secondly to reduce maintenance costs.

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About the author

Prabu Duplex had sailed as a marine engineer between 2005- 2013. He graduated with a Professional Doctorate in Engineering (PDEng), undergoing a programme at the University of Twente, in the Netherlands. He also worked in a research group called 'Dynamics Based Maintenance (DBM),' which actively focuses on developing innovative predictive maintenance methods for a wide range of industries. His work involved developing physics based mathematical models to predict the life time of diesel engines components in maritime propulsion systems. He also has a Master's degree in Naval Architecture. Presently, he is working as a junior reliability engineer in a Polish based firm info-marine which offers predictive based maintenance solutions for merchant navy. He is open for careers in design or research activities in naval, wind, offshore or predictive maintenance domains.

Email: prabumn@gmail.com

MARITIME ANOMALY DETECTION: CLASSIFICATION OF RECENT RESEARCH APPROACHES (PART 3): RESEARCH APPROACHES, DISCUSSIONS & CONCLUSION

Hema Karnam Surendrababu

1.b. Methods/Techniques based Classification

The literature that was surveyed for the current research study of maritime anomaly detection can also be classified into different categories based on the types of methods used for anomaly detection and is summarised in **Table. 2**.

i. Machine learning (ML) and clustering-based methods

Machine learning is a type of Artificial Intelligence (AI) technique that is used to predict values based on historic data. It can be further classified into supervised, unsupervised, or semi supervised. In supervised ML algorithms, the algorithm is trained with labelled datasets, where both the input and the corresponding output values are clearly defined. In the unsupervised category, the ML algorithm trains on unlabelled data sets and identifies patterns in the data to classify data into different groups, whereas the semi supervised is a hybrid of the preceding approaches. An example of unsupervised algorithm is 'clustering', wherein metric data based on similarity is classified into different clusters.

> *Machine learning is a type of Artificial Intelligence (AI) technique that is used to predict values based on historic data*

To detect anomalies, normality models are constructed for the observed ship trajectories using ML algorithms, and outliers from the models are classified as anomalies. Vessel motion patterns are automatically modelled using an unsupervised ML algorithm as described in [31]. Using this approach, maritime traffic models that represent vessel behaviours in terms of waypoints such as port areas, entry and exit points, turning points etc. are built. Sea lanes and routes are delineated, using object oriented programming. Once the normality of traffic patterns is learned, any outliers from these models are categorised as anomalies.

Another ML approach to detect maritime anomalies is discussed in [32], where a supervised method such as Support Vector Machines (SVMs) is used to detect abnormal U turn events and unusual stopping behaviours of vessels. The SVMs classify the training data into different clusters using hyperplanes or a decision boundary that helps separate the data into normal vessel behaviour and anomalies. In addition to SVMs, the approach also uses visual analysis to detect abnormal vessel behaviour.

In the approach discussed in [33], vessel trajectories are clustered using a similarity metric with respect to spatial and directional variables of AIS. Once the vessel trajectories are clustered, a naïve Bayes' classifier is used for classification of anomalous tracks from the normal vessel sailing patterns of the historic data.

An unsupervised clustering technique such as the OPTICS algorithm as described in [34] is used for trajectory learning to learn normal motion patterns of vessels and model major sea lanes and stop areas. In this approach, a probabilistic framework is used to model the maritime patterns and transitions which is subsequently used for path prediction, and statistical maritime anomaly detection.

To detect anomalies, normality models are constructed for the observed ship trajectories using ML algorithms, and outliers from the models are classified as anomalies

A two-level approach to detect anomalies in vessel routes is presented in [35], where an unsupervised Density-based Spatial Clustering of Applications with Noise (DBSCAN) technique is considered with speed and directional attributes to distinguish anomalies and normal vessel data. The DBSCAN technique uses a clustering method to classify abnormal and normal vessel data. Due to the unclassified data instances and high noise produced in the labelling step, a further processing is carried out in the second phase where subject matter experts refine the unclassified instances and erase the noisy results. Subsequently, a Hadoop MAP reduce algorithm is used to achieve higher accuracies in anomaly detection and reduce the computational complexity of the algorithm.

In a similar approach to [35], a clustering approach such as DBSCAN technique that incorporates speed and direction attributes of the AIS data for extracting normal vessel patterns is used in [36]. The framework described in [37] is different from the previously described approaches in that, the contextual information that is usually not included for distinguishing between anomalies and normal data is included in this approach.

ii. Neural Networks (NN) based methods

In the NN based approach, which is a type of deep learning technique, models are built on labelled datasets and defined rules that adjust the weighting parameters of the network to predict outputs accurately. A multiclass Artificial Neural Network (ANN) based approach that is used to detect and distinguish between intentional on off switching of the AIS transponder and AIS message dropouts due to channel effects is described in [38]. Various kinematic features such as speed, course, latitude, and longitude extracted from the historic AIS data are used to train the ANN models.

In the NN based approach, which is a type of deep learning technique, models are built on labelled datasets and defined rules that adjust the weighting parameters of the network to predict outputs accurately

In [39], an unsupervised Self-Organizing Map (SOM) application that is used to detect abnormal vessel movement is described. In this approach, various retraining strategies that achieve higher precision for distinguishing normal and abnormal maritime vessel movement data are investigated. An SOM is a neural network-based method, but additionally has a feature that can distinguish anomalous and normal vessel trajectories by scaling the trajectories differently according to different maritime traffic observation areas as described in [39]. Different strategies for training the SOM are presented in this approach, that can potentially ensure higher model precisions and less training time for the model.

A deep learning based probabilistic Variational Recurrent Neural Network (VRNN) framework is described in [40] to address abnormal vessel behaviour such as abnormal U turn, route changes and deviations from standard maritime routes. Other factors predicted by this model include vessel type identification and trajectory reconstruction. In this approach, an embedding block that uses a VRNN converts irregularly sampled AIS data into regularly sampled AIS data streams. Additionally, this model also uses latent variables (roots) that represent the AIS data, and which can essentially capture information on the vessel movement.

iii. Statistical Parametric and Non-Parametric Methods

In the **statistical based methods**, parametric techniques assume that the normality models have a predefined structure, and the parameters for these models are estimated based on these assumptions. In the **non-parametric approach**, no such assumption is made with respect to the underlying data distribution. In a non-parametric approach, an adaptive kernel density framework or the Parzen window method [KDE] is employed in [41] to extract motion patterns which are subsequently used for Anomaly detection and future vessel motion prediction. A parametric density model is employed in [11] where a Gaussian Mixture Model is used to model the probability density function of the position velocity vector to obtain normal vessel patterns. Any deviations from this normality are useful in detecting kinematic anomalies.

> *It needs to be emphasised, that currently there is no publicly available and usable AIS database that can be leveraged for Maritime Anomaly detection in the Indian Ocean Region (IOR)*

A conformal anomaly detection method is described in [42]. Conformal anomaly predictors aid in detecting non conformal object behaviour (outliers or anomalies) using a non-conformity measure. In this approach, KDE model is used as a non-conformity measure to distinguish between normal vessel trajectories and anomalous trajectories. In a similar approach described in [43] conformal based prediction methods are used for online learning and anomaly detection.

A hybrid approach is described in [44], where a Self-Organizing Map (SOM) is used as a clustering algorithm based on a neural network. Once the data is clustered, a GMM is used to identify normal and anomalous behaviours by calculating the probability measures for the observed data and comparing it to a threshold value.

iv. Bayesian Networks

The usage of Bayesian Networks for anomaly detection was discussed in [13]. Using this approach, a wide variety of anomalies are detected which include vessels travelling in unusual patterns, vessels that make no landfall, vessels behaving against their ship type etc. Positional anomalies such as deviation from standard route and zone entry, that are detected from the AIS transmissions are discussed in [15]. A Bayesian Network approach is used for calculating the probabilities of possible destinations based on historic data. Based on the observed vessel data and the computed probabilities, the hypothesis of whether a ship is travelling to its stated destination or not is tested and validated. This approach also describes methods to detect zone entry anomalies that occur when a ship is said to have entered a restricted zone.

Table.2. Methods Based Classification of Maritime Anomaly Detection

Method used	Author & Publication Reference	Year of Publication	Detected Anomaly
Machine Learning /Density Based Clustering	M. Vespe et. al, [32]	2012	Route deviation Zone entry
	D. Handyani et.al, [33]	2013	Abnormal U turn, Abnormal stops
	N.L. Guillarme, et. al, [35]	2013	Route deviation
	X. Wang et. al, [36]	2014	Speed and directional anomalies
	B. Liu et. al, [37]	2014	Speed and directional anomalies
	A.N Radon et. al, [38]	2015	Route deviation Speed anomalies
	R. Zhen et. al, [34]	2013	Route deviation
Neural Networks	J. Venskus et. al, [40]	2019	Route deviation
	S. K. Singh et. al, [39]	2020	Unexpected AIS activity
	D Nguyen et. al, [41]	2021	Route Deviation Abnormal U turns
Statistical (Parametric and Nonparametric)	B Ristic et. al, [42]	2008	Route deviation
	M Riveiro et. al, [45]	2008	Route deviation
	R. Laxhammar et. al, [44]	2010	Route deviation
	J. Smith et. al,[43]	2014	Route deviation
Bayesian Networks	S. Mascaro et. al, [13]	2010	Route deviation
	R. Lane et. al, [15]	2010	Route deviation Zone entry Unexpected AIS activity

However, given the wealth of AIS data that is transmitted, AIS can also be used as a powerful tool with potential applications in maritime surveillance and environmental monitoring as has been reported by the vast number of research groups working in this area

1. Discussion

As evident from the discussion in the preceding sections and **Table. 1** and **Table.2**, the current review of the recent research approaches used for maritime anomaly detection reveals that the focus of a majority of the research approaches is on detecting positional and kinematic anomalies while not many approaches explore the more complex anomalous vessel behaviours such as spoofing and loitering. More specifically, ship spoofing using AIS data, which is becoming a widely reported threat globally as described in [8], both from a maritime safety and security perspective has only been marginally studied in publications [25] [26] [27][28]. Additionally, only a handful of research publications have studied anomalies such as loitering [29] [30], and close approach rendezvous at high sea [22] which could be potential indicators of piracy, drug trafficking etc.

It needs to be emphasised, that currently there is no publicly available and usable AIS database that can be leveraged for Maritime Anomaly detection in the Indian Ocean Region (IOR). Therefore, to automate the Maritime Anomaly detection process, and create a mapping between the detected anomalies to suspicious vessel behaviours and other illegal activities in the IOR, there is a need to establish a publicly available AIS database for the IOR region.

2. Conclusion

The AIS was initially developed from a safety perspective as a collision avoidance and monitoring tool for effective traffic management in the maritime domain. However, given the wealth of AIS data that is transmitted, AIS can also be used as a powerful tool with potential applications in maritime surveillance and environmental monitoring as has been reported by the vast number of research groups working in this area. From the survey of the current literature, it can be concluded that the detected anomalies are mostly homogeneous in nature with a majority of the research approaches focusing on the detection of kinematic anomalies. However, to detect more diverse type anomalies, complex anomalous vessel behaviours need to be extensively studied given that these behaviours translate into critical and actionable intelligence for maritime surveillance. Additionally, to advance the Maritime Anomaly Detection research in the IOR, the current need of the hour is to establish an AIS database that can be accessed in the public domain.

With respect to the methods used, the current survey reveals that many of the methods are offline based approaches, with very little work focusing on real time detection of maritime anomalies. Hence there is a need to develop more approaches that focus on real time surveillance.

Although many of the classified approaches use AIS data for anomaly detection, additional focus on approaches that integrate the data from other sensors such as RADAR, Long Range Identification and Tracking (LRIT), AIS satellite data and also contextual data such as weather, seasons, days of the week etc., that utilise a data fusion approach has the potential to significantly improve the maritime anomaly detection process.

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About the Author

Hema Karnam Surendrababu is currently a PhD scholar at the National Institute of Advanced Studies (NIAS), Bengaluru (affiliated to The University of Trans-Disciplinary Health Sciences & Technology, Bengaluru, India). She works as a part of the International Strategic and Security Studies (ISSSP) Group at NIAS. Her research experience comprises of Signal/Image Processing and Cyber security. Her current research focus is on the usage of Artificial Intelligence techniques for Maritime Anomaly Detection.

Email: hemaskarnam@nias.res.in


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Bunker Sample History Logs
MARPOL Seal Logs
Sewage and Graywater Record Book
Type approvals received
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ARTIFICIAL INTELLIGENCE AND ROBOTICS IN MARITIME FIELD

T. Mohan

Abstract— **Artificial intelligence (AI) is becoming increasingly inevitable for the maritime industry and is going to play an important role in the near future. The influence of automation in the maritime activities along with the demand for more autonomous shipping has led to an increase in the demand for AI. Predictive maintenance, intelligent scheduling, and real-time analytics, will drive AI along with Machine Learning & Robotics to play a more important role in Maritime Field.**

Keywords—Machine Learning, Artificial Neural Networks, Internet of Things, Cognitive analytics, Digital Twins, Predictive maintenance, Robotics

Introduction

The jargon of modern times in industry and business is Artificial Intelligence. This AI technology is vital to the digital transformation happening today as organisations are trying to capitalise on the exponentially growing amount of data that being generated and collected. This vast ocean of data has necessitated intense research into the means this data can be processed, analysed and utilised for further action.

Maritime Applications

With more and more new sensors and internet of things (IOT) devices on ships, more data being generated but only little of that data is actually being put to good use. According to surveys, very little of all shipboard generated data are analysed in a meaningful way. Ship owners, Regulatory entities and machinery manufacturers are increasingly interested in harnessing the value of data being collected on board ships. The possibilities are detection of mechanical anomalies in real time, categorising these anomalies into minor, intermediate or serious, showing these anomalies in 3D displaying which component inside the machine is causing the anomaly and the automated model building can predict when failure might occur. Classification societies can create a notation for the ships using these technologies and grant considerable extension of time for survey.

Machine learning and cognitive analytics tools provide all of these capabilities, detecting anomalies in machine operations and predicting failure with high degree of accuracy. Machine learning will be a game-changer for the maritime sector. The ability to apply machine learning tools to shipboard generated data is now more widely available. The progression of analytics from descriptive (what happened?) to diagnostic (why did it happen?) to predictive & prescriptive (when is it likely to happen and what can be done to prevent it?) is changing the way the industry can harness the value of machine learning tools in data analysis.

Additionally, machine learning empowers fleet managers to reduce unplanned out-of-service time, protect against malicious threats, and provide cognitive query of relevant vessel-operating information from a variety of sources. This further allows for savings in maintenance and capital cost replacements, extending the life of critical shipboard assets. Operators in the maritime space are increasingly interested in this new technology for following reasons:

(i) Cognitive analytics provide the capability to ingest the terabytes of data that are already being generated, and find the insights contained within to save money and reduce off-hire.

(ii) Cognitive analytics allow more intelligent planning of major maintenance periods such as special surveys and dry-dock periods, spare parts and consumables inventories, and support to seagoing staff in assessing whether maintenance needs to be performed in-voyage, in a port turnaround, or over a longer period of time.

(iii) Ship-owners and operators find value in developing a deeper understanding of shipboard machines rather than leaving it to yard periods or warranty and insurance claims.

For an industry that has used some of the same systems for years, artificial intelligence and machine learning offer an opportunity for revolution in shipping. The commercial shipping industry runs on a lot of data; every ship has a manifest, every container has an identification number, every box has a packing slip. AI advancements in gathering and analysing that data could allow the shipping industry to plan further out and more accurately, particularly for busy times of the year that are known to be a challenge. The result could be not just greater efficiency for the industry, but significant cost savings.

Machine Learning

Artificial Intelligence is a concept of building machines which are capable of thinking like humans using the digital binary logic of computers. The field of research which has been more fruitful in recent years is what has become known as "machine learning". The concept of machine learning is that rather than have to be taught to do everything step by step, machines, if they can be programmed to think like humans can learn to work by observing, classifying and learning from its mistakes.

Given data, a machine learning algorithm can recognise patterns and learn from data to make predictions about new data, all through the use of clever statistics. In short, if you have data and a pattern in the data, your machine can learn. As in much of engineering, however, there is obviously more to machine learning than that simple explanation when it comes to execution and delivery. Within the field, there are three types of machine learning algorithms: supervised learning, unsupervised learning and reinforcement learning. Supervised and unsupervised are currently the most popular learning methods. They differ as follows:

- **Supervised learning:** In this method, the algorithms are trained by entering an input and a desired outcome to create labelled examples. The machine is able to find errors by comparing the actual outcome with the outcome that it knows should be correct based on the information originally entered. An example would be an algorithm for identifying credit card fraud. The machine can spot unusual charges by comparing them to the expected transactions.
- **Unsupervised learning:** As opposed to supervised learning, unsupervised learning does not have "right" answers – or historical labels – to compare the information to. Rather, the algorithm must look at the information provided and draw its own conclusions. This method is helpful for finding attributes by which to sort groups, such as identifying what consumers can be targeted by the same marketing campaign.
- **Reinforcement learning:** While not as popular as the previous two methods, reinforcement learning is an important part of the field. As opposed to supervised and unsupervised learning, this algorithm learns through trial and error, ultimately learning how to choose the option that will result in the greatest reward. This method is common in robotics, navigation, gaming etc.

Machine learning is growing in popularity and importance in large part because companies and government agencies have large quantities of data that need to be sorted, analysed and leveraged to ensure a boosted return on investment. The data that is used in these algorithms can include everything from customer spreadsheets, past buyer information, loaner information, census information, survey information, website visiting rates and much more. Machine learning can not only reveal trends about this information, but can also give insight toward predicting things about future behaviour.

While machine learning is related to the broader field of artificial intelligence, these terms are not synonyms. AI is a branch of computer science that is primarily focused on creating machines that are capable of intelligent thought. However, this is hard to accomplish without the contributions of machine learning.

AI is basically the intelligence – how we make machines intelligent, while machine learning is the implementation of the compute methods that support it. AI is the science and machine learning is the algorithms that make the machines smarter, "So the enabler for AI is machine learning."

Though the idea of a machine making decisions on its own and thinking independently may sound almost like a work of fiction, machine learning is actually more common than many people may expect. The general public can find elements of it in many areas of daily life. For instance services provided by websites, such as the way that Amazon.com recommends items that consumer might be interested in based on his browsing history and previous purchases. While these are very useful applications of machine learning for the average person, the field is much more than shopping and entertainment.

Artificial Neural Networks (ANN)

The application of neuroscience to IT system architecture has led to the development of Artificial Neural Networks (ANN). Although this field was evolving quite some time it is only recently that computers with adequate power have been made available to make the task a reality. Neural networks take a different approach to problem solving than that of conventional computers.

Conventional computers use an algorithmic approach i.e. the computer follows a set of instructions in order to solve a problem. Unless the specific steps that the computer needs to follow are known the computer cannot solve the problem. That restricts the problem solving capability of conventional computers to problems that we already understand and know how to solve.

But computers would be so much more useful if they could do things that we don't exactly know how to do. Neural networks process information in a similar way the human brain does. The network is composed of a large number of highly interconnected processing elements (neurons) working in parallel to solve a specific problem. Neural networks learn by example. They cannot be programmed to perform a specific task. The examples must be selected carefully otherwise useful time is wasted or even worse the network might be functioning incorrectly. The disadvantage is that because the network finds out how to solve the problem by itself, its operation can be unpredictable.

On the other hand, conventional computers use a cognitive approach to problem solving; the way the problem is to be solved must be known and stated in small unambiguous instructions. These instructions are then converted to a high level language program and then into machine code that the computer can understand. These machines are totally predictable; if anything goes wrong is due to a software or hardware fault.

Neural networks and conventional algorithmic computers are not in competition but complement each other. There are tasks that are more suited to an algorithmic approach like arithmetic operations and tasks that are more suited to neural networks. Even more, a large number of tasks, require systems that use a combination of the two approaches (normally a conventional computer is used to supervise the neural network) in order to perform at maximum efficiency.

An Artificial Neural Network (ANN) is an information processing paradigm that is inspired by the way biological nervous systems, such as the brain, process information. The key element of this paradigm is the novel structure of the information processing system. It is composed of a large number of highly interconnected processing elements (neurons) working in unison to solve specific problems. ANNs, like people, learn by example. An ANN is configured for a specific application, such as pattern recognition or data classification, through a learning process. Learning in biological systems involves adjustments to the synaptic connections that exist between the neurons. This is true of ANNs as well.

An artificial neuron is a device with many inputs and one output (**Figure 1**). The neuron has two modes of operation; the training mode and the using mode. In the training mode, the neuron can be trained to fire (or not), for particular input patterns. In the using mode, when a taught input pattern is detected at the input, its associated output becomes the current output. If the input pattern does not belong in the taught list of input patterns, the firing rule is used to determine whether to fire or not.

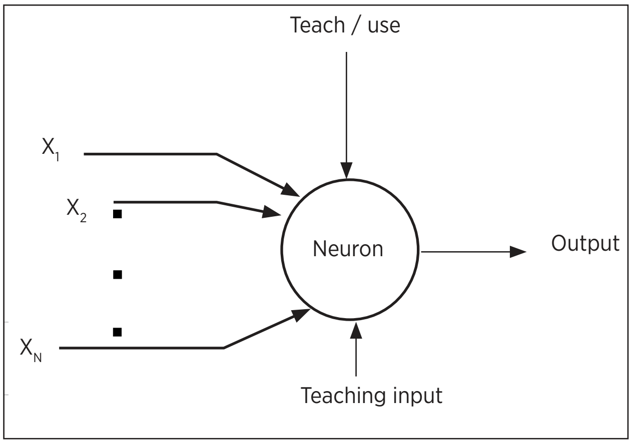


Figure 1

An important application of neural networks is pattern recognition. Pattern recognition can be implemented by using a feed-forward (**Figure 2**) neural network that has been trained accordingly. During training, the network is trained to associate outputs with input patterns. When the network is used, it identifies the input pattern and tries to output the associated output pattern. The power of neural networks comes to life when a pattern that has no output associated with it, is given as an input. In this case, the network gives the output that corresponds to a taught input pattern that is least different from the given pattern.

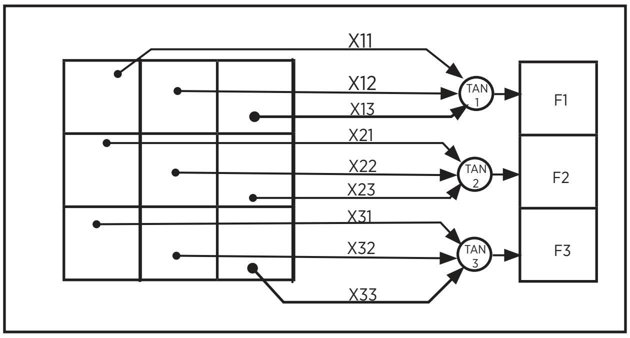


Figure 2

For example, the network of (**Figure 3**) is trained to recognise the patterns T and H. The associated patterns are all black and all white respectively as shown below.

Figure 3

A more sophisticated neuron (**Figure 4**) is that the inputs are 'weighted'; the effect that each input has at decision making is dependent on the weight of the particular input. The weight of an input is a number which when multiplied with the input gives the weighted input. These weighted inputs are then added together and if they exceed a pre-set threshold value, the neuron fires. In any other case the neuron does not fire.

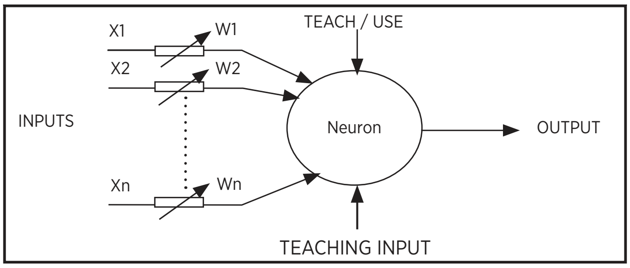


Figure 4

In mathematical terms, the neuron fires if and only if;

$X1W1 + X2W2 + X3W3 + ... > T$

The addition of input weights and of the threshold makes this neuron a very flexible and powerful one. Various algorithms exist that cause the neuron to 'adapt'; the most used ones are the Delta rule and the back error propagation. The former is used in feed-forward networks and the latter in feedback networks.

The commonest type of artificial neural network consists of three groups, or layers, of units: a layer of "input" units is connected to a layer of "hidden" units, which is connected to a layer of "output" units. (See **Figure 5**)

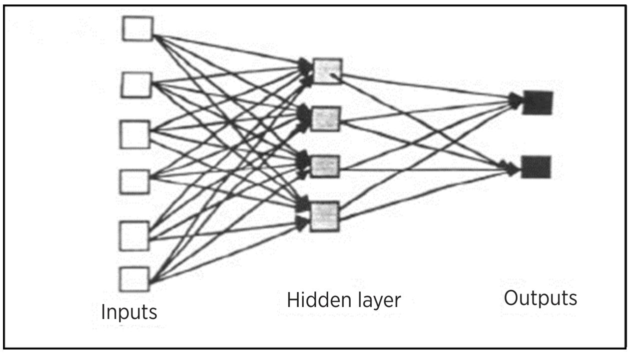


Figure 5

The activity of the input units represents the raw information that is fed into the network. The activity of each hidden unit is determined by the activities of the input units and the weights on the connections between the input and the hidden units. The behaviour of the output units depends on the activity of the hidden units and the weights between the hidden and output units. Feedback networks are very powerful and can get extremely complicated. Feedback networks are dynamic; their 'state' is changing continuously until they reach an equilibrium point.

Artificial Neural Networks (ANN) is currently a 'hot' research area and the explosion of data availability from things shared on social media and machinery data from industry connected through IOTs (Internet of Things) to help them learn more efficiently and make better decisions.

Predictive Maintenance

Predictive maintenance of equipment and plants promises increased reliability at lower cost, along with the possibility of determining which components and assets need maintenance, and when. Replacements when needed can be called up in advance and stored at the dock for timely installation. Where maintenance isn't needed, despite what an OEM's maintenance schedule says, money simply doesn't need to be spent. The drive for cost savings and efficiency improvements is an important goal to operators in a marine industry that is still reeling from a downturn in the market.

Since the advent of the digital era many have expounded that ship-owners need to invest in digital systems, data analytics and machine learning if they are serious about being key players in the marine industry in the future. There is a range of software solutions coming onto the market that enables more collaboration between departments and moves the industry toward autonomous ships. But digitisation and the use of machine learning and artificial intelligence (AI) is not something that will happen overnight. Instead it is a step-by-step process as the industry learns and adapts to working with the new technology.

Machine learning can perform predictive analytics far faster and more accurately than any human can. The potential for marine maintenance is to move completely away from time-based scheduled maintenance, to maintenance that is based on equipment use and true plant condition. The enabling of predictive maintenance through data-driven systems is expected to add further value to the maintenance process. "It's safe to assume that AI could help early failure detection in all types of equipment and machinery on board a vessel."

Through machine learning and better data-driven optimisation, AI will not just save costs in maintenance, but also the time spent maintaining vessels. Machine learning is a set of algorithms, tools and techniques that mimic human learning behaviour to solve problems. Machine learning algorithms are used to analyse data from currently operational marine equipment and train software models that can recognise unknown patterns in the data and make a prognosis about how that equipment is performing. "If the data we analyse is 'big', then the model can recognise more complex patterns and make more accurate predictions about the state of the marine equipment than any human could." Potentially this means maintenance in the future could be carried out in a more timely and cost-effective way and could further improve the reliability of equipment.

"Since 60-80% of defects have been ascribed to incorrect maintenance, there are good reasons from every angle to perform maintenance only when it is needed."

Digital Twins

Another advantage that AI will bring is through the digital twin –a complete digital representation of a physical asset. Having a digital twin provides all the information of that asset through its lifetime by using sensors enabled through the Internet of Things. Future digital twins will be central to all forms of shipping, especially for autonomous and remotely controlled vessels. “With a digital twin, the shore-based control centre and engineers will be able to explore the entire vessel from their desktop or phone and compare both real-time and historic data,”. “3D images and virtual reality will enable engineers to familiarise themselves with a task before they go on board. AI models running on a digital twin will identify and prioritise maintenance needs.” Further developments to the technology, such as more layers of redundancy and self-healing capabilities, will need to be added before AI systems will truly start to take effect and be trusted by the industry. Autonomous technology in the future may have to integrate with non-autonomous solutions. How they work around and with each other is another point that needs to be considered. “The big challenge is making peace between autonomous and non-autonomous in the future”.

Corrosion & Bio-fouling

Ship builders and vessel owners have a common interest in protecting marine vessels against corrosion and bio-fouling. For ship builders, protection involves the application of a paint system incorporating a primer, a binder and a final coat that releases chemicals to deter organisms from attaching themselves to the hull.

To combat corrosion, ship-owners apply coatings that will protect their assets over the long term, without the need for extended maintenance. Owners are also looking for consistent fouling control protection across a full dry dock cycle, accompanied by a minimum drop in vessel performance.

Most coatings are applied when a ship is under construction or during routine dry dockings. Heavy duty coatings are applied to areas of extensive wear and tear, such as near rudders, where surfaces need protection against the cavitations damage caused by the propellers as they churn the water, or complex structures that can be more costly and difficult to repair, such as water ballast tanks.

Visual inspection is an important component of marine and offshore asset management. However, applying artificial intelligence (AI) models to detect levels of corrosion and coating breakdown on ships and offshore structures can reduce required man hours and may increase the safety of inspection operations.

The ability to identify corrosion from surface images is a first step to achieving this goal. American Bureau of Shipping (ABS) plans to leverage remote inspection technologies (including drones) to perform remote inspections and detect in real-time corroded areas that require additional attention. Furthermore, by capturing the history of corrosion progression, ABS may predict required inspections more precisely by using historical data and prediction modeling.

The data analytics component of a comprehensive inspection system for marine and offshore structures that consists of data collection tools (UAVs, ROVs), a digital model of the asset where collected data is mapped (stored), and tools to analyse the data and make decisions.

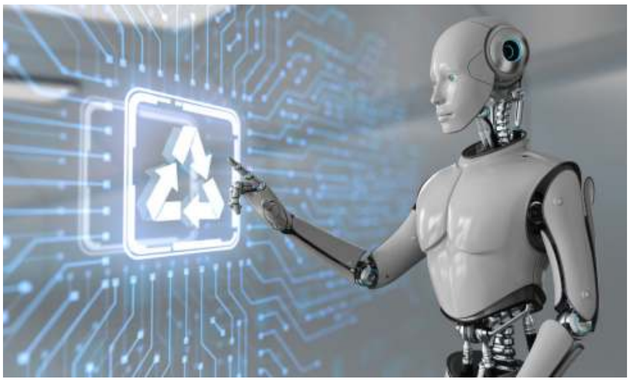
Robotics

There are a growing number of remotely operated and autonomous drones available to carry out marine maintenance tasks. An increasing number of companies, from ship operators to offshore developers, are waking up to the potential benefits of using drones to do the marine inspection and maintenance tasks that are dull and dangerous for humans in situ.

Floating drones: The remotely operated robotic inspection devices are small multi-use surface vessels with the ability to collect data autonomously by deploying a range of sensors and cameras. This is achieved through the combination of an autonomous operating system with object detection and avoidance, as well as automated path planning algorithms capable of calculating the optimum time to start missions based on weather forecasts and waterway traffic. The drones analyse the data they collect on board, using interpretation and predictive maintenance models for post-processing. This runs alongside algorithms which calculate the degradation of assets. This information can be used by managers to make strategic decisions about maintenance.

Underwater drones: The device takes the form of self-propelled robotic arms, capable of traveling long distances to carry out inspection, maintenance and repair (IMR) tasks in confined spaces not generally accessible by other underwater vehicles. The robot consists of a chain of joints, thruster modules and payloads, such as tools to provide torque and for cleaning. It is designed to stay permanently underwater on the seabed for up to six months at a time. This enables the robot to be used around the clock, irrespective of the weather.

Aerial drones: The use of Unattended Aerial Vehicle (UAVs) is becoming increasingly accepted by the marine industry, especially for inspections of difficult to reach areas and infrastructure for example, internal inspections of tanks. As part of the external specialist certification procedure, the surveyor can complete all safety and inspection processes required to accept the examination of tanks. Using UAVs for tank inspection reduces the need to use a technique called rafting. This involves filling the tank being inspected with water, allowing the surveyor to use a raft or dinghy to view critical inspection areas of the tank that would otherwise be inaccessible from the tank floor. Rafting creates a large volume of oil-contaminated water that has to be decanted from the vessel at a port. Using a UAV eliminates this and the safety risks associated with rafting. “UAVs are enabling the next generation of marine and offshore surveys and inspections, providing



less intrusive, safer and more efficient ways of assessing critical areas,

Crawler drones: Another emerging application of robotic technology for marine maintenance is the use of remotely operated drones for inspecting and cleaning hulls. A prominent example of this type of approach is the underwater drone designed to carry out cleaning and hull inspection activities. The device works by generating vacuum and aspiration force via a central turbine driven by an electric motor, which performs the dual function of keeping the robot attached to the hull and removing any algae that has formed on it.

Conclusion

Dependency on a new technology to understand the behaviour of machines is a paradigm shift away from thinking about ships. Lloyd's Register, in its "Global Marine Technology Trends 2030," estimated a 4,300% increase in the annual data generated by ships by 2020, and says that "by 2030, that figure will have increased even further as this is an accelerating trend." Data itself can now be considered a new class of "asset." And if ship-owners look after the asset that is their data, their data will help look after everything else.

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Email: massa.mohan287@gmail.com

LUBE MATTERS # 18
INTRODUCTION TO TRIBOLOGY

Sanjiv Wazir

Introduction

Tribology is “the science and technology concerned with interacting surfaces in relative motion, including friction, lubrication, wear, and erosion.” (ASTM G 40).

From predicting earthquakes by studying plate tectonics, to making hard disc drives work, tribology plays a big part in our world and in our lives - and barely anyone seems to know about it.

Tribology: timeline
Pre-History

While the term ’Tribology’ (from the Greek *tribos* – to rub) was coined only in 1966 (1), humans have been using tribological concepts since times immemorial.

Control of fire gave humans light, safety, warmth, cooked food, and a weapon to drive off large predators

Control of Fire

While archaeological evidence for the use of fire by Homo Erectus dates back about one million years, the oldest evidence, indicating control of fire by Homo Sapiens and Neanderthals (Qesems Cave-Israel), dates back 300,000 to 400,000 years (2). Humanoids had realised that rotating a dry wooden stick in a hollow of another dry piece of wood (friction), would generate sufficient heat to kindle a fire (**Figure. 1**)

Control of fire gave humans light, safety, warmth, cooked food, and a weapon to drive off large predators (3).

As humans turned from ‘hunter-gatherers’ to farming, fashioning agricultural tools by grinding (wear) rocks (stone-age) and metals (bronze age) became widespread.

The Wheel

The practice of placing logs underneath large objects to move

Figure 1. Gaining control over fire

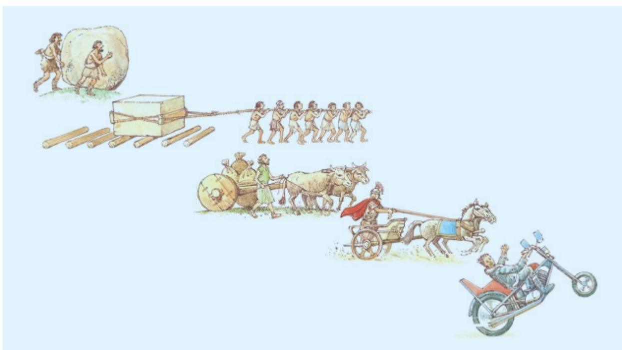

Figure 2. Evolution of the wheel (4)

them easily is so old that evidence for its origin remains unclear.

The wheel is a wholly human invention, it does not appear anywhere in nature, (**Figure. 2**). The potter's wheel had been invented in Mesopotamia by 4000 B.C. It was followed by early wheeled vehicles in Asia & Europe by 3300 B.C. The oldest excavated wheel (Mesopotamia) dates to 3500 B.C. (4) .

The potter's wheel had been invented in Mesopotamia by 4000 B.C. It was followed by early wheeled vehicles in Asia & Europe by 3300 B.C. The oldest excavated wheel (Mesopotamia) dates to 3500 B.C.

Figure. 3 depicts Egyptian slaves dragging a large statue along sand or ground (2040 B.C.). One man (ancient tribologist), standing on the sledge supporting the statue, is shown pouring a lubricant (water or olive oil) as a to reduce friction between sledge and the desert sand. It is surmised that the liquid was used to bind the sand particles to present a harder surface, making dragging easier, rather than dragging through soft sand.

By the time, the great pyramids and monuments were being built in Egypt (2500 B.C.), many techniques such as use of lubricants (clays, soaps, vegetable oils, animal fats) and use of different surface materials (hydrated earths) to reduce wear, were well established.

Specimens from Egyptian chariots dating to around 1400 B.C. (**Figure. 4)** indicate the use of tallow (animal fat) to lubricate the wheels.

One can only marvel at the ingenuity of our ancestors, in inventing pivots for the gates of ancient cities, and the axles of chariots and wagons. This was the work of everyday craftsmen, not scientists and engineers! These may seem commonplace today but were vital for survival at that time.

Unquestionably, mankind's earliest, and most impactful inventions – controlled fire, and the wheel - were tribological ideas in action. Control of fire required increased friction, while the wheel was a way to reduce friction.

Middle Ages

Though mankind had been using tribological concepts for millennia, it wasn't until the Renaissance (14^{th}-18^{th} centuries), that the scientific study of friction and lubrication began.

Leonardo da Vinci (1442-1519) first deduced the laws governing the motion of a brick over a flat surface, that the scientific study of friction and lubrication began. His sketches show test apparatus remarkably like current ASTM standard sled friction tests.

He understood the key role played by friction, and how it was a limiting factor in the efficiency of his revolutionary machines. He distinguished between sliding and rolling friction. He noted that frictional resistance was proportional to the applied load but independent on contact area. His writings include the idea that friction was the result of roughness of the material, and that smoother materials resulted in less friction. He even conceptualised rolling element bearings (**Figure 5**). His studies and postulates related to wear, lubrication, and contact mechanics, laid the scientific foundations of tribology (5).

The following centuries brought about many more advances in the areas of bearings, gears, lubricant application, and theories regarding friction and wear. Robert Hooke invented the universal joint. Newton laid down the foundations of viscosity and the concept of Newtonian and Non-Newtonian fluids. Euler advanced theories of friction and viscosity. Desaguliers proposed the adhesion concept of friction.

Amontons, postulated three laws applicable to dry friction viz. 1. The force of friction is directly proportional to the applied load (Amontons' 1st Law); 2. The force of friction is independent of the apparent area of contact (Amontons' 2nd Law); 3.

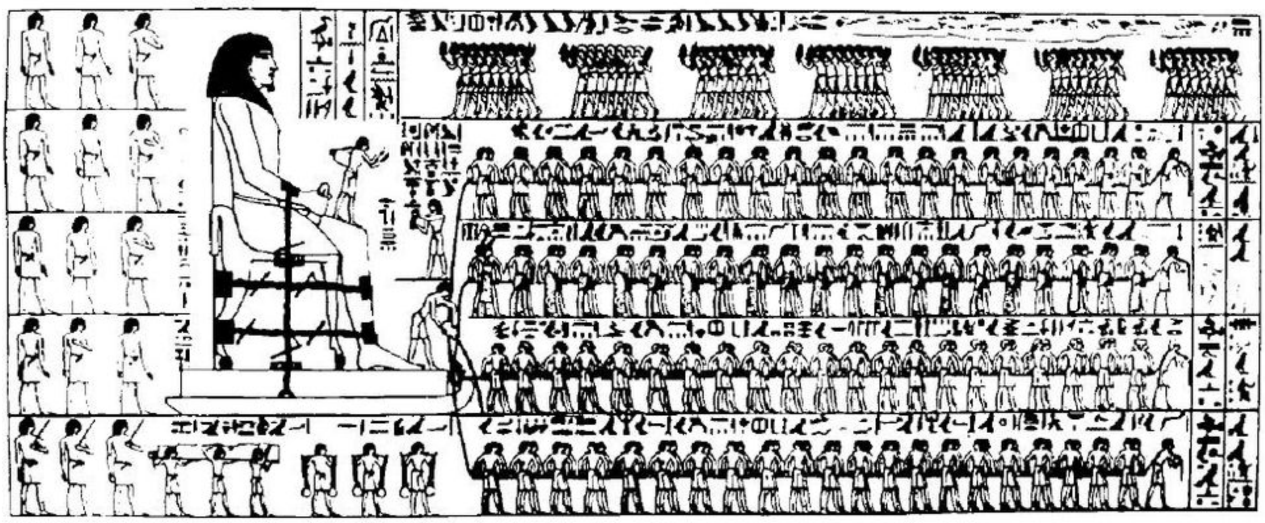

Figure 3. Egyptian hieroglyphic showing modulation of frictional resistance of surface materials (5)

Figure 4. Chariot with lubricated wheels (5)

Kinetic friction is independent of the sliding velocity (Coulomb's Law).

Long before the industrial revolution, friction was a major concern because motive power was supplied by humans or animals, and to some extent water wheels (3000 B.C. -Greece/China) and sails (3200 B.C., Egypt). The main fuels were wood, charcoal, coal, whale oil, and vegetable oils. The machines used simple plain bearings such as a shaft rotating in a hole in a block of wood. Natural rock materials and later iron were the wear resistant materials.

The use of lubricants derived from nature, such as animal fats (tallow) and vegetable oils (olive, castor, and linseed) and naturally occurring graphite continued until the 18th Century when whale oil was being used to lubricating rudders and pulleys on ships. Tallow was being used in steam machinery until the 1950s!

Industrial Revolution Period 1750 – 1850):

The industrial revolution marked the beginning of change from rural to industrialised urban societies.

Handmade goods began to be produced in mass quantities by machines in factories. Transportation became mechanised. Trains and ships were the earliest large machines that had to undergo tough conditions, while far from their breakdown/maintenance support. Service life of components gained importance.

The machines used simple plain bearings such as a shaft rotating in a hole in a block of wood. Natural rock materials and later iron were the wear resistant materials.

It was realised that steel on steel is a poor combination under sliding contact but good for rolling contact. Lead based alloys (from Isaac Babbitt) came into use. Tallow was resistant to water wash off and continued to be used on steam ships and locomotives. John Harrison, a carpenter, and clockmaker invented caged roller bearings. **Roller element bearings dramatically reduced friction and increased load bearing capacity.** Once electrical power became available, attention shifted to performance of bearings in generators and steam turbines.

Many patents for lubricants were granted during this time. In 1845 a cotton spinning mill in Pittsburgh, USA, first used crude oil mixed with sperm whale oil to lubricate spindles on a weaving loom. Other lubricants included mixtures of graphite and tallow, as well as mixtures of olive oil and lime in water.

He noted that frictional resistance was proportional to the applied load but independent on contact area

Scientists Rennie, Hatchett, and Stokes promoted theories regarding friction, wear, and hydrodynamic lubrication.

Period 1850 – 1925:

The idea of journal or shaft floating in an oil film in the bearing became understood during this period. Studies were undertaken to minimise

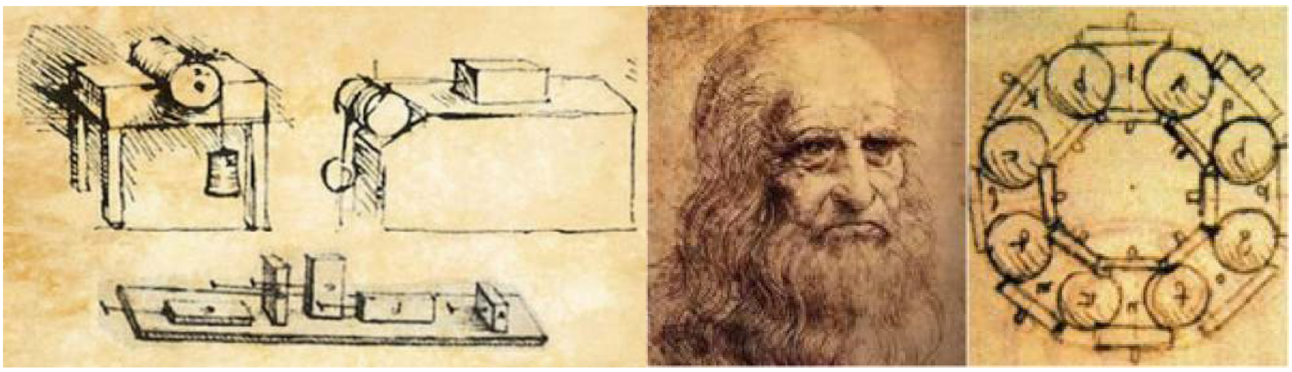

Figure 5. Leonardo da Vinci's experiments with friction underpinned the modern science of Tribology (5)

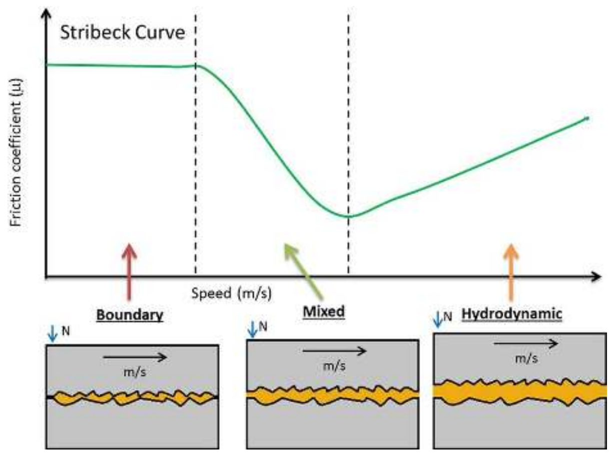

Figure 6. Stribeck Curve

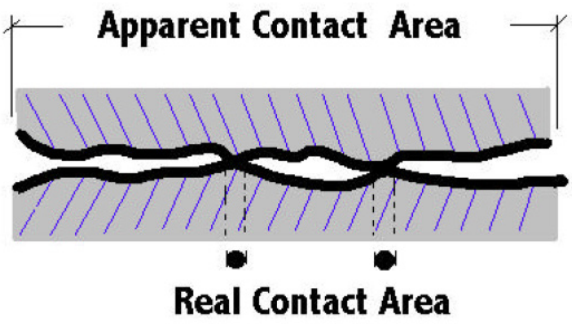

Figure 7. Apparent contact area and Real Contact area

the friction and wear during start-stop operations and minimising energy loss in the bearings.

Many engineers and scientists turned their attention to bearing studies. Rolling element bearings that had been used in small appliance (clocks) for some decades and began to be developed for heavier applications.

In 1886 Professor Osborne Reynolds published his "On the Theory of Lubrication and Its Application to Mr. Beauchamp Tower's Experiments, Including an Experimental Determination of the Viscosity of Olive Oil". In this manuscript, a famous equation of thin fluid film flow in the narrow gap between two solids was formulated. This equation became the basis of classical lubrication theory.

In 1902 Richard Stribeck developed the Stribeck curve, a plot that related friction with viscosity, speed, and load.

Growing demands from the emerging automobile industry saw lubricant manufacturers begin to process petroleum-based oils to improve lubricant performance.

"It was realised that steel on steel is a poor combination under sliding contact but good for rolling contact"

In 1902 Richard Stribeck developed the Stribeck curve, a plot that related friction with viscosity, speed, and load

Modern Tribology

Bowden and Tabor (1939) determined that the true area of contact is an exceedingly small percentage of the apparent contact area. The true contact area is formed by the asperities. **In 1950 they introduced the idea of asperity junctions as a mechanism for friction between rough surfaces.** Their model of friction provides a good

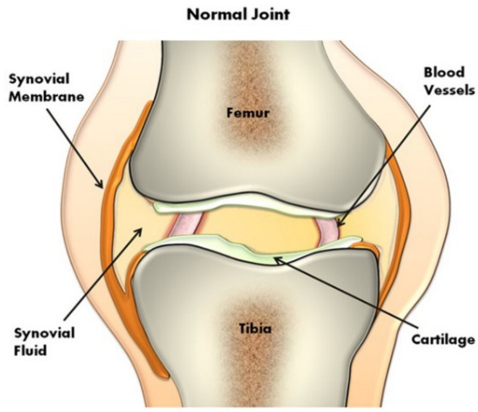

Figure 8. Synovial fluid & membranes enable joint movement

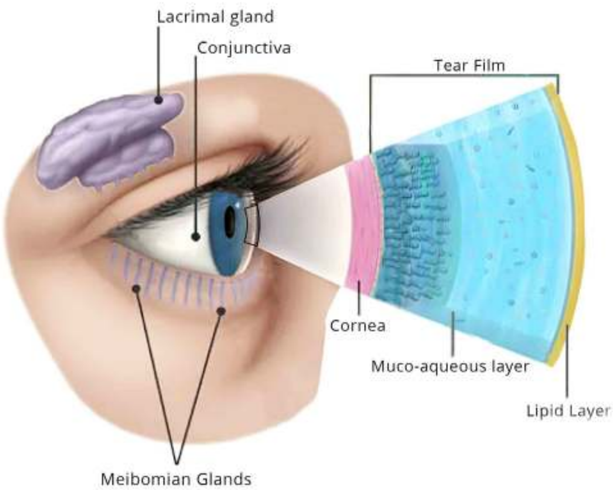

Figure 9. Complex structure of tear-film

They postulated that friction coefficient depends on the normal load, the real contact area, and the shear strength of the interfacial tribofilm. This laid the foundation for later developments the tribology theories

starting point for understanding how a thin interface film (or a so-called third body or tribofilm) can drastically reduce the friction coefficient [6]. They postulated that friction coefficient depends on the normal load, the real contact area, and the shear strength of the interfacial tribofilm. This laid the foundation for later developments the tribology theories.

Automobile engine oils without additives would typically last only up to one hundred hours of service life. Additives to inhibit corrosion, oxidation and improve viscosity characteristics were developed in the 1930s and 1940s, improving oil performance and extending service life. Multigrade engine oils (initially 10W-30) were introduced in the late 1950s, eliminating the need to change engine oils from season to season.

WW2 accelerated developments in machines used on land, in the air, and at sea. Tribological advances moved in-step to enable these developments. The wartime years and following decades saw rapid growth in tribological research and better understanding of underlying principles, including Elasto-Hydrodynamic Lubrication (1949). Continuous developments in additives, lubricants and lubricating systems, bearings and bearing materials, surface materials, spectrometry, tribometers, atomic force microscopy, etc. Oil analysis was introduced in 1949.

Synthetic lubricants were developed in the 1950s, driven by demands of the aviation and aerospace industries.

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Tribology Today

Every step we take requires grip; saliva lubricates the food that we swallow; we use shampoos to smoothen hair, other shampoos give hair volume; our kitchen knives dull with use; car tires wear out; laptop touchscreens are carefully calibrated for our touch; some face creams are formulated to give a smooth feel, while other give a matt finish; the metal fillings in our teeth grind down; wooden chopsticks work much better than porcelain ones. We would not be able to move without synovial fluid lubrication of our joints; nor blink without a tear-film lubricating our eyes.

Today, tribology's applications range far beyond machinery lubrication. Tribology of today is a well evolved highly interdisciplinary field, encompassing elements of mechanical engineering, materials science, biology, medicine, geology, quantum mechanics, etc.

Geotribology covers tribological phenomena in the earths sub-surface, such as

- Stick-slip friction of tectonic plates (earthquake prediction),
- Induced seismicity because of extraction (or storage) of natural gas/crude oil, (soon maybe CO2 storage), etc

Nanotribology covers tribological phenomena from the perspective of atoms and molecules.

- Nano Electro-mechanical System [NEMS] components used in electronic devices, computers, etc.
- Development of PFPE lubricants for disk drives,
- Diamond like carbon (DLC) coatings,
- Molecular sieves etc.

Space Tribology (8) covers tribology applications in the harsh conditions experienced by launch vehicles, space shuttles, satellites, international space station where conditions can vary from cryogenic to hundreds of °C.

Solid lubricants of several types, such as lamellar solids, polymers and soft metals applied as thin films have been utilised in space.

In 2009, the tribology community, keenly followed what many consider the most extreme lube job in history: Space-walking astronauts Heidemarie Stefanyshyn-Piper, Steve Bowen and Shane Kimbrough, grease guns in hand, added liquid lubricants to bearing surfaces of the International Space Station's Solar Alpha Rotary Joint (which supports its massive solar panels).

The bearings were originally designed to operate solely under solid lubrication but were malfunctioning due to seizing of spherical-rod end bearings. These thumbnail-sized bearings experience little or no load when operating and were thought to require only minimal lubrication for long life. A simple burnished film of solid lubricant applied during initial assembly was found sufficient in life tests.

Unfortunately, in orbit, the cable ends began to seize prematurely. Ground trials showed that a dab of grease applied to the parts, accompanied by wiggling of the cables to spread

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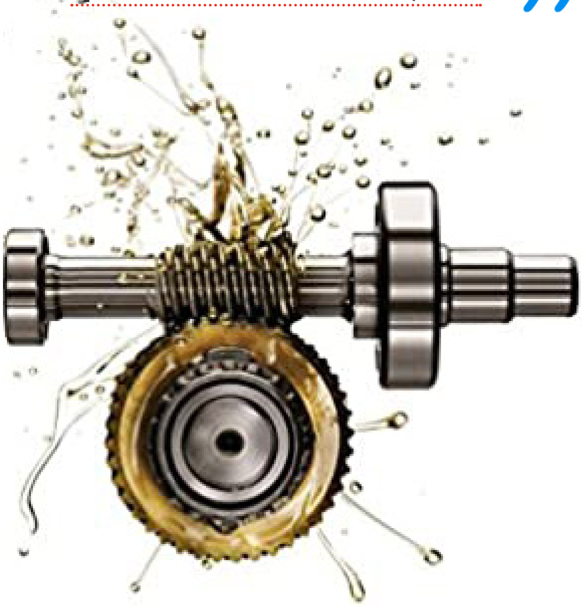
Biotribology (9) (human/animal related tribology) specialisations cover

- Joints & body interfaces: Synovial joints, Artificial joint transplants, Implant corrosion and wear, Artificial cartilage, Prosthetic-human coupling, catheters, heart pumps, stents, bio-probes, needles
- Biomimetics: Bio-inspired tribology (e.g., Shark-skin inspired swimsuits)
- Ocular tribology: Contact lenses, tear lubrication and Dry Eye Syndrome
- Skin tribology: Damage, blistering, bedsores, sweat lubrication
- Personal care: Skin creams, cosmetics, hair care products, shaving products, exfoliants, toothpaste
- Food processing: Foodstuffs and beverages, mouth feel and taste perception, food texture
- Dental tribology: Tooth and implant wear, tribo-corrosion of dental surfaces

> **Solid lubricants of several types, such as lamellar solids, polymers and soft metals applied as thin films have been utilised in space**

> **Tribology of today is a well evolved highly interdisciplinary field, encompassing elements of mechanical engineering, materials science, biology, medicine, geology, quantum mechanics, etc**



- Sports Tribology: Equipment design and development, preparation, deterioration and testing of sport surfaces, grip, gait analysis
- Haptics: Tactile perception (e.g., handphone screens) and surface texture (e.g., Yoga mats),

Green Tribology is a new development. Its objectives are the environmental-friendly saving of energy and materials, and the enhancement of the environment and quality of life. The aims of green tribology are lower energy consumption, lower discharge (CO2), lower environmental cost (e.g., Environmentally Friendly Lubricants), and high quality of life. (10)

Currently, tribological phenomena being researched include atomic level understanding of friction and wear to bridge the knowledge gap between macro-micro- and nano levels of contact and motion, super-lubricity, wear less sliding, etc.

Conclusion

Tribology influences all fields of human endeavour and permeates our daily life. Its applications range from Nano to Space. Its impact on global energy consumption, emissions, healthcare, and sustainability is only going to increase.

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About the Author

Sanjiv Wazir is a Technical Adviser with LUKOIL Marine Lubricants. He is a mechanical engineer from IIT-Bombay. He is a marine engineer and a member of the Institute of Marine Engineers. He is a Certified Lubrication Specialist from the Society of Tribologists & Lubrication Engineers (STLE), USA and is a member of the Tribological Society of India. He has contributed to MER on marine lubrication developments in the past, and on oil contamination issues under "Lube Matters," earlier.

Email: sanjiv@lukoil.com

GOING ASTERN INTO MER ARCHIVES

MER... Four decades back...
The December 1982 Issue

This issue starts with interesting discussions. The scrap iron cost ranges, the merit of recycling and why the industry needs to be established are good points to ponder and reflect upon. Incidentally on the recycling front, while the global market is between US$ 10-12 billion, India's share is around US$100 million only (UNCTAD Report, 2021). So there is sense in the argument even in the present times.

Another piece to note in the Editorial is the appeal for the Life Membership, extra funds for Institute office space etc. Guess we have come a long way from this but look back we must, lest we forget the hard work of the earlier Marine Engineers.

Following the article on Rankine cycle for waste heat recovery, the 'Drives for Marine Pumps & Compressors', by L. Sterling is a very interesting read. There are few takeaways under the Condition Monitoring of Electrical Machinery. There is one short write-up on shipyards employing CAD techniques which had apparently improved the productivity by 16% (over a two year period) and another 5.5%, expectedly.

The 'Postbag' has a couple of interesting letters, one on FO viscosity issues and another on Korea moving ahead in maritime field. An observation worth a thought is that Singapore intending to double the training Faculty for marine engineering and related subjects. Then there are news items on oil injection aided propeller mounting and WMU starting operations.

Few extracts are inserted.

EDITORIAL

While the shipping industry all the world over is going through the throes of worst recession ever, there is one sector of the industry which is thriving on account of this recession. This sector is shipbreaking. According to the latest available figures, 1982 has set a record as far as breaking of ships goes. By the end of September, 1982, over 20 million DWT had been broken up, as much as was scrapped in 1978, the previous record year for *shipbreakers. The phenomena* of increased shipbreaking in times of recession in shipping industry is only natural and needs to be encouraged in order to restore balance between supply and demand.

Shipbreaking as a regular activity first started in U.K. and U.S.A. during and around second world war but later shifted to Europe and then South East Asia. Today, Taiwan leads the field in shipbreaking followed by Spain, South Korea and Pakistan. These countries have comparative advantage of low labour cost and their present stage of industrial activity can generate enough demand to recycle the waste material.

Unfortunately, inspite of all comparative advantages being available in India together with unlimited waterfront on three sides of the peninsula with ideal natural facilities at numerous locations, we have hardly made any headway in this direction, having between 1 and 2 percent share of this activity world-wise. If properly developed, this activity being highly labour intensive, can not only generate tremendous employment all along the coast line but also can become a major supplier of raw material to re-rolling mills, iron foundries and mini steel plants. The distribution of various materials recovered from a scrap ship are, steel re-rollable scrap 70 percent, steel melting scrap 10 percent, cast iron scrap 5 percent, machineries, motors, chains, anchors etc. 11 percent, non-ferrous material 2 percent, wood 2 percent. The percentage of course varies with the type of ship, its age and level of maintenance.

Despite the duties payable on import of scrap ships, the selling price of re-rollable scrap from a dismantling vessel is around Rs. 3100/- per tonne against Rs. 3600/- for billets from integrated steel plants and Rs. 3450/- per tonne for ingots from mini steel plants. Further the energy needed to convert re-rollable scrap into finished products is said to be much lower than the cost of converting melting scrap into ingots in an electric arc furnace. Thus the industry can be counted on to becoming major supplier to re-rolling mills.

Why then is this activity lagging behind and what should be done to give it a boost in the national interest? At present 80% of the shipbreaking activity is concentrated in an area of two and half sq. kilometers at Darukhana in Bombay. Facilities need to be provided all along our coastline and here the Governments of Coastal States can play an important role. It is heartening to note that Govt. of Gujarat has taken a lead in this matter by not only developing facilities for shipbreaking in Sachana and Papivave but also promising to provide financial assistance to prospective entrepreneurs.

Working capital for buying an old ship of 5000 LDT ranges from Rs. one crore to two crores. Such large funds cannot normally be raised by small-scale units. It has therefore been suggested that Reserve Bank of India should form a consortium of nationalised banks with one bank nominated as the lead bank for providing financial aid to the industry.

Climate and opportunity has never been more favourable as at present for fast development of this industry. The capacity utilisation of re-rolling mills is said to be less than 20 percent on account of shortage of re-rolling scrap. A buyer's market exists for scrap ships on account of world-wide recession. Other countries like Taiwan and Pakistan are taking full advantage of the situation and buying scrap ships on a large scale. Should we not wake up?

A word to our members. The Institute since its inception has been wanting to purchase a space for its office but always finds itself short of funds. It will greatly benefit the Institute and the members if members could consider taking up life membership. The extra funds so received will enable the Institute to buy an office. The members, once having taken the life membership would need have no worry about annual remittances and fear of increased subscription due to ever-increasing inflation. Think it over carefully! Good-bye for now till our next issue.

H. K. TANEJA

The case for ship scrapping and developing it as an industry.

The modern day VFDs, which are now widely used, could be the answer for this.

AN IMPORTANT but perhaps neglected, contribution to energy saving onboard is the seawater cooling pump.

Whereas the conventional seawater cooling pump must be designed for its full rated output at a seawater temperature of about 30°C, in areas where the seawater temperature is well below this figure, the flowrate, and thus pumping power, could be reduced quite considerably. In theory, a cut in flowrate of 50% would reduce power input to the pump shaft by more than 85%. This is when a two-speed, or frequency-controlled variable-speed pump might prove much more beneficial.

A recent analysis at the University of Newcastle upon Tyne, concludes that by, reducing the flowrate by 50% for about half the total running time, using a two-speed unit, the energy savings are about 25%.

But variable speed units (described briefly on page 12) are substantially more expensive and there could be problems emanating from using reduced flowrates. Engine designers may advise against it; small diameter cooling pipes require substantially higher flowrates than larger pipes; smaller flowrates may mean air entrainment and increased build-up of fouling in the pipes.

In view of the attraction of variable speed pumps it would be folley not to appraise thoroughly the problems involved. Even where these problems can be overcome, Hamworthy Engineering, a major pump manufacturer, view the variable frequency-controllers with scepticism. The advice is to opt for the lower cost two-speed motor. Where the whole sailing pattern changes it is more economical to modify the pump elements and re-optimise flowrates to suit.

Practical problems

Sir,
When I see the troubles some chief engineers have onboard their vessels, I often wonder if the manufacturers really know about the weakness of their products. I believe what manufacturers, designers, owners, surveyors all need is 'feedback'.

MER should request chief engineers to provide information on their difficulties encountered. Such stories would give significant 'down to earth' information for the whole shipping family!

Hans E Schreiber
Engineer Surveyor
South America

Mr Schreiber's comments echo our own. The MER 'Problems' pages are intended to disseminate information on practical problems with machinery that undoubtedly occur on board. Apparently, such problems seem to occur all too rarely, judging by the response to our repeated requests for such information.—Editor

Fuel viscosity

Sir,
In the October "Postbag", Mr Ashis Basu reaffirmed the experiences and conclusions contained in our paper "Energy conservation by seastaff",* an abridged version of which was published in the May MER. He also made a useful addition to the discussion and I would like to amplify some of his comments.

Regarding determination of viscosity and the need to regularly check viscotherms; it is our practice to independently check the viscosity of bunkered fuel with a simple onboard viscometer, not only to check the bunker receipt but also to check the viscotherm and to select correct storage and separation conditions.

Regarding "Double bottom tank heating" some clarification may be in order. The viscosity and pour point of a residual fuel pose two potential problems in the pumping and transfer of oil from storage tanks.

Due to design constraints within the fuel oil transfer system the limiting viscosity for practical pumping of residual fuel is about 1000 cSt. The viscosity of a fuel oil above its pour point is a logarithmic function of temperature. By way of an example, consider a fuel of 380 cSt at 50°C. It has a viscosity of 1000 cSt at a temperature of about 35°C. At only 5°C less, ie 30°C, this viscosity has increased to 1500 cSt and difficulty may be found in pumping, although the pour point of the fuel may be in the region of 25°C. The fuel at this lower temperature is still liquid and behaves as a Newtonian fluid, the only problem being that its resistance to flow at viscosities lower than 1000 cSt may mean that conventional pumps are unable to handle it.

As the fuel behaves as a Newtonian fluid, the introduction of heat will generate convection currents within the oil which will lower the viscosity and make it pumpable.

At the other extreme an intermediate fuel of 60 cSt at 50°C would only become unpumpable at 3°C, assuming pour point problems were not encountered.

I agree that pour point is not directly related to viscosity and is simply a measure of the temperature at which wax crystallisation prevents the fuel from flowing, ie, the fuel can be regarded for all intents and purposes as a non-Newtonian liquid-solid mixture. Once the oil has become solid by being cooled below its pour point, it is extremely difficult to reliquify by conventional steam coil tank heating arrangements. This is because the coefficient of heat transfer of the wax is such that only the oil in the immediate vicinity of the coil becomes liquid and because of its liquid-solid form convection currents do not exist; therefore, the remainder of the oil remains solid. This re-enforces Mr Basu's comment that the pour point of the oil must also be known to ensure trouble free storage and handling.

To summarise, double bottom heating of residual fuels must:

- Maintain the tank temperature about 5°C above the pour point of the fuel to ensure that it is "liquid" at all times.
- Be applied before fuel transfer to ensure a "pumpable" viscosity. In practice, this means heating for about two days before the contents of the tank are required.

To be able to achieve the above, knowledge of both viscosity and pour point are required, which are two of the standard tests in our Fuelab onboard test kit. Understanding of the implication of the tests is also required, which we achieve by onboard training videos and by our fuel courses.

S Sprague
Ocean Fleets Consultancy Services

*Trans IMarE (C) 82. Vol 94. Conference No 12. Paper C102.

This could be a topic for discussion in current scenarios too with additional factors of low sulphur FOs, closer pump clearances etc.

WANTED:

Technical Papers

The Institute's Papers' Committee invites suggestions for papers to be presented at meetings and conferences in the 1983/84 session and later. Practical papers are preferred which ... EC3 7JN. Tel: (01) 481 8493. Tlx: 886841.

The Korean miracle

Sir,
Having recently toured the Far East shipyards and educational institutions, concerned primarily with the applications of marine engineering, I found your articles on the Far East in the September issue of considerable interest.

It is abundantly clear that the Korean "miracle" has been achieved mainly by the implementation of a master plan established by the government but involving private industry; a situation which apparently, and tragically, does not exist in the UK. Objectives were set, together with associated required activities, thereby leading to progress analysis in developmental efficiency covering ship ownership, shipbuilding and, most importantly, educational growth.

All success has a price and it should be mentioned that modesty presumably prevented the author, Mr Suh, from indicating that in the major shipbuilding yards, all employees work a minimum 11-hour day, six days a week, and enjoy four to six days' annual vacation! Furthermore, one private company contributes about 11% of the GNP of Korea.

The disturbing aspect from the Western point of view must be that the plan is moving into phase 2. Ten Korean research institutes are in the process of being set up or are already operational. Although controlled by the government, commercial activities are encouraged by the setting up of science parks funded by industry on the same or a nearby campus. It would seem abundantly clear that, in terms of manufacturing capability (ie steel produced per annum per unit cost) we in the Western world are unlikely to compete. Consequently, we must emphasise technological developments with specific importance on propulsion plant efficiency and reliability and with considerable attention being paid to fuel tolerance (cf Opinion, October MER).

We have a lead in automation and control technology and this should be expanded immediately. However, such developments can only be achieved provided that the UK specifically has both a "Plan" and the resources in terms of money and manpower to apply it, together with the will to achieve. If such an approach is not implemented immediately during the current period of energy self-sufficiency, we, as a nation, have little or no future in the industrial market.

As a footnote, it was interesting to note in Singapore that the intention is to double the number of staff teaching marine engineering and related subjects in the majority of their institutions over the next two to five years, while we in this country are attempting to reduce our educational opportunities!

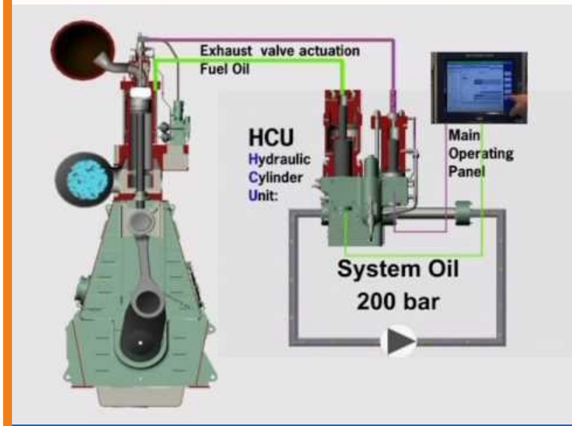
R V Thompson
School of Marine Technology
University of Newcastle upon Tyne

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

MASSA Maritime Academy, Chennai

The Institute of Marine Engineers (India)

Electronic Engine Familiarisation Course (ME-Type Engine) Delivered online with Cloud access to ME Engine Simulator



This 3 days course is designed for all Ship's Engineer Officers and Electro Technical Officers responsible for the operation of ME Engine. This course consists of technical lessons and practical instructions on the design, principles, operating procedures and maintenance activities for the safe, efficient and optimal performance of the engine system.

Course Aims and Objectives:

The course aims to provide practical understanding of the principles, design, operation and maintenance of the ME Engine System, enabling participants to safely and efficiently operate the engine and perform fault-finding in the control system.

Coverage / Program Focus:

This course deals with the following training areas:

- **Introduction to ME Engine**
- **Hydraulic Power Supply (HPS)**
- **Hydraulic Cylinder Unit (HCU)**
- **Engine Control System (ECS)**
- **Main Operating Panel (MOP)**
- **Standard Operation**

Entry Requirement / Target Group:

Entry is open to all Ship's Engineers and Electro Technical Officers with basic knowledge of diesel engines.

DATE & TIMING	:	**20th 21st, 22nd December 2022** **8:00 am - 4:00 pm IST**
VENUE	:	Web Platform / Zoom**. APPLICATION LINK:** https://forms.gle/e4As7kCucR5xoJBm9
REGISTRATION & PAYMENT	:	Rs. 15,000/- /- per participant – inclusive of taxes. For IME(I) Members 13,500/- per participant - inclusive of taxes. Payment to be made to: https://imare.in/buy-online.aspx (Under Category - Value added Courses) *10% discount available for IME(I) members*
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