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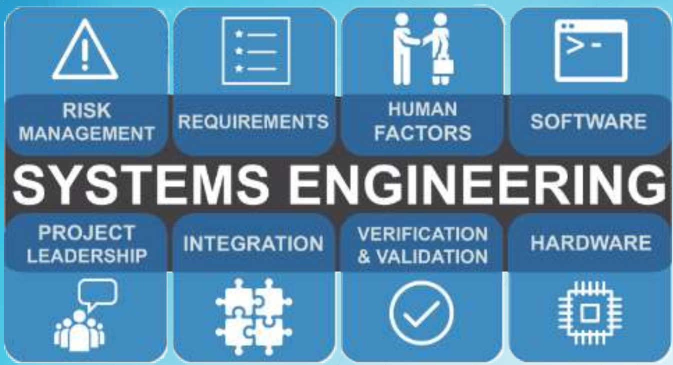

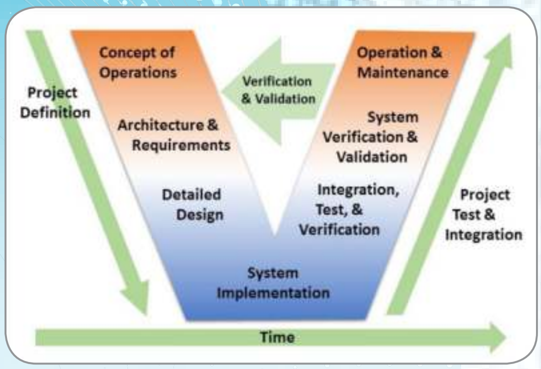

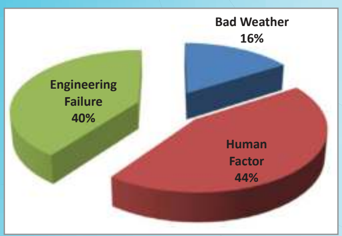

Marine Machinery Maintenance Management

EDITORIAL

Since human wisdom cannot secure us from accidents, it is the greatest effort of reason to bear them well.

- John Paul Jones (US Naval Hero)

We learn from all accidents. The recent railroad tragedy will be another one.

If the faulting finger arcs towards the electronics and the machine intelligence, it compels a serious look, since we are talking of autonomous ships and bullet trains in this age of speeds. Ironically, it is the electronics and automation which have helped technological applications breach their own limitations. In context, the wait could be fugacious before human factors are pointed at.

Meanwhile, the numbers indicate that the rail related deaths have become comparatively less in India. The annual numbers hover around 25000, while most of them occur due to falls and at crossings rather than being consumed by the recent Balasore like allision-collision causes. In comparison, lives lost on Indian roads count 5-10 times more than the railway fatalities. Moving to the marine side, the global listing of the marine casualties shows much lower counts in comparison. The decade reporting (2010-1019) of MCIs in the IMO's GISIS shows a total of 2290 VSMC (Very Serious Marine Casualties).

The comparison might do well for a bar room rhetoric exchanges, whereas there are some serious pointers for introspection. The EMSA's Annual Review of Marine Causalities and Incidents (2022) places Shipboard operations as the major contributing factor with human action as the major contributor therein, for the main accident-event type. While closing the loop with recommendations and actions to follow up, Ship related procedures and Human factors were the top two major focal areas. The maximum corrective actions were taken for 'training, skills & experience' under Human Factors. It brings us back to the training.

In a recent lecture on Cyber Security, it was observed that training in traditional chart work saved a situation (in one case), whereas only ENC/ECDIS training left no alternative when the security breach rendered the electronic charts non-functional. This twists the moot point on its head with the argument for 'retain pre-training skills'. The inflection or the cusp period for any technology transition faces this dilemma. The solution may be seen in the intensity and quantum of changes.

The increase in electronics and digitised ambience impresses on the need for upskilling (the user must at least know which module to replace in the myriad maze of controls and logic systems) leave alone the reskilling and retention of skills, which are tenets of competency training.

The simulator platforms will be good to adopt radical changes for reskilling/upskilling models. The training menu must increase the complexity of scenarios for problems injected for trouble shooting, improve the fidelity, physical/behavioural realism etc. Full mission systems with comprehensive solutions for any specialised vessel/engine/operation (e.g., port equipment etc.) with VR HMDs etc., must be introduced. AR supported training must be taken up in workplaces (ships/ports).

The STCW functions should give due space for the new knowledge pushing the borders of possibilities in all equipment ashore and on board. The way is not for changing the game for the sake of it but for exposure to the levels of failures so as to respond well in unsafe situations and emergencies. Else, with all our wisdom, we have to endure, as always, with the greatest effort of reason to bear more accidents. And the Titan implosion tragedy adding up.

*MCI: Marine Casualty and Incident; GISIS: Global Integrated Shipping Information System; EMSA: European Maritime Safety Agency; VR HMD: Virtual Reality Head Mounted Displays; AR: Augmented Reality; ENC: Electronic Nautical Charts; ECDIS: Electronic Chart Display and Information Systems.

In this issue...

The reliability on electronics keeps increasing as the capabilities and scope of systems expand. We look at an approach to maintenance from the perspective of systems engineering. Prabu Duplex educates us with examples from the ships' systems. There will be more on these lines.

We continue the conversation on maintenance management in relation to Human Reliability Analysis (HRA). This scientific approach is essential to see how improvements could be effected to avert accidents. Dr. Vedachalam takes us through this process and the mention of Lac-Mégantic disaster adds strength to the accidents discussed *ibid*.

Following this, we have the Part C of the Fuel Analyses discussions from Daga et al. The short section projects the comparative energy costs, emissions and production.

Under Lube Matters, Sanjiv starts an engaging discussion on tribology of engine components.

Competency Corner has Elstan Fernandez continuing with his electrical maintenance notes.

MER July 83 archives carries an interesting discussion on waste heat utilisation.

Contemplating on the tragedies to make technology work better, here is the July 2023 issue for your reading pleasure.

Dr Rajoo Balaji
Honorary Editor
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Systems Engineering for Maintenance Management

Prabu Duplex

1. Introduction

This work intends to provide a starter kit for the systems engineering in multidisciplinary development projects. As a case study introducing new maintenance concepts in the maritime sector is analysed in a systems engineering perspective.

1.1 Development of Modern Systems

Ships, cars and commercial aircraft are products that contain many parts and have to perform many functions. All parts and functions have to work together and work in an environment with users. Furthermore, some of these products have a long life in which the environment may change dramatically. Looking inside the products, we see that there are mechanical and electronic parts, software components, styled parts, and there is behaviour that is designed for good interaction with the users. Also, the products have to perform well from a financial point of view, whether that is because they are bought from hard-saved money of a consumer or paid for by tax money. At the same time the development, production and maintenance of the systems have to be financially profitable.

All these aspects are dealt with mostly by specialists: electronic, mechanic, software engineers, user interface designers, product styling designers, financial experts etc. Nowadays the effect is that these products, *systems* as we can call them in this work, are developed by a large team –often even several teams– of people with diverse backgrounds. Communicating and working towards a common goal is not easy in such a setting. *Systems engineering* is a discipline that aims at coping with this by focusing on the whole. Systems engineering provides a firm basis so that the design process can take place as smoothly and efficiently as possible. It rests on three pillars:

Systems Engineering Process: How is the process of bringing systems into being organised? The process is generally called *systems engineering and section 2 deals with this.*

Systems Thinking Tracks: Several ways of thinking about the system that is being designed, its context, its user, its past and its future are considered. These thinking tracks stimulate the creativity of the systems engineer, and force to think within and outside any limits set by the system requirements, defined in The Systems Engineering Process. Section 3 deals with few thinking tracks.

System Design Tools: These practical tools help in both The Systems Engineering Process and Systems Thinking Tracks (used in thinking tracks and not explicitly mentioned).

1.2 Maintenance Management

To sustain optimal performance, systems and structures must be maintained and maintenance activities need to be performed. For this purpose, many companies adopt in general a **Preventive Maintenance** strategy. However, the challenges of this strategy are organisationally baffling in terms of scheduling. An appropriate length of the maintenance interval should be determined; if the maintenance interval is too short then the components are replaced before the end of their service life leading to high costs and waste of resources. On the contrary, replacing too late implies failures and therefore severe consequences might be expected.

For those reasons, the actual condition of an asset needs to be monitored in order to regulate the appropriate time for performing maintenance, hence, the implementation of the Condition-based Maintenance (CBM) strategy. Performing CBM by selecting appropriate Condition Monitoring techniques (e.g. vibration, tribology, thermography analysis) or other Non-Destructive Testing (e.g. radiographic testing, magnetic particle testing) is a complex practice. These are technologically and economically challenging with respect to their industrial environment.

A condition monitoring technique is able to improve the quality of inspection and if correctly carried out, it can identify failures at an early stage along with their potential root causes. Many sensors and condition monitoring techniques are nowadays available, however selecting the most appropriate ones and applying them in a complex system remains challenging. Therefore, the goal of this work is to approach an effective and economic CBM strategy in a systems engineering perspective.

2. Requirements Engineering and Management

System engineering is, as **Figure. 1** shows, all about finding a solution to an identified issue, while considering the context, the stakeholders and the rest of the world. In fact, this is what happens at different levels of detail, see **Figure. 1:** defining the issue, then finding an appropriate solution and accepting it before proceeding. In line with this approach, "needs and requirements" of a typical ship management or an ownership company is assessed in the beginning as follows.

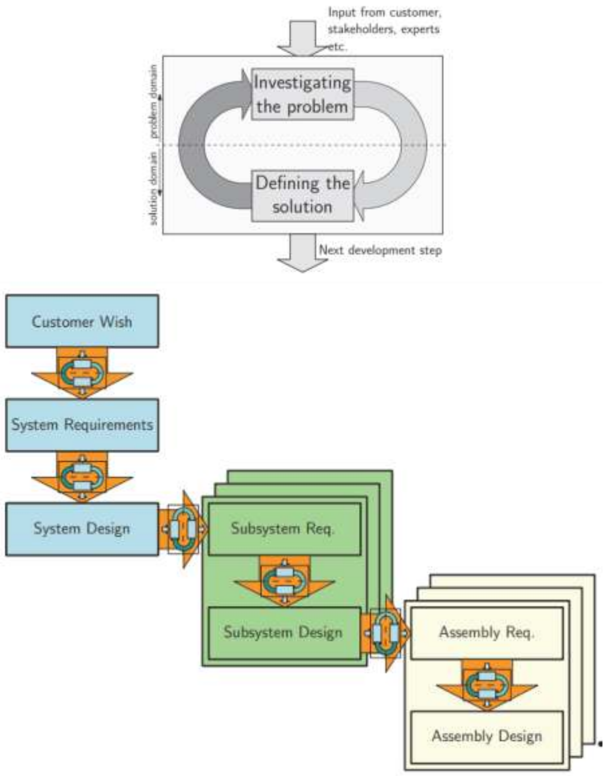

Figure. 1: System engineering process loop[13]

Performing CBM by selecting appropriate Condition Monitoring techniques (e.g. vibration, tribology, thermography analysis) or other Non-Destructive Testing (e.g. radiographic testing, magnetic particle testing) is a complex practice

2.1 Needs

Enterprise

The company needs to sustain its core values of safety, continuity and orientation towards the future.

Business Management

The ultimate need of the management is to develop innovative maintenance strategies. Offering just in time maintenance, in compliance with existing safety and operational regulations is the main objective.

Business Operations (stakeholder needs for the system of interest at the system level)

Business operation's needs, can be transformed into stake holder needs. Key stakeholders include, managers from companies, experts in the field of maintenance, potential users of the system such as operators, technicians and maintenance engineers in shipping company. The maintenance concepts applied in the maritime sector are often constant in time, independent of the specific usage of the systems and operating conditions. As a result, many systems and components are repaired or replaced before actually needed, while other components unexpectedly fail before the end of the interval. The companies require prognostics based maintenance methods, capable of identifying system health and expected life time, for given operation conditions. Such a **decision support system** needs to be efficient, user-friendly and able to be operated by its technicians. Furthermore, such techniques need to be validated by business case studies, in order to justify the investment.

System

The complex assets in the maritime sector are built from a large variety of individual systems that each contain significant numbers of parts or components. The physical failures will occur in a specific part, but modelling all parts of an asset is infeasible. Therefore, a decision support system, shall be capable of monitoring a component representative of the complete ship system. The decision support system shall be capable of handled by managers of moderate educational background. It shall be capable of predicting system health of various engine types present in the company.

System Elements

The system elements such as sensors or monitors needs to be reliable and maintainable, considering the external influence such as heat, humidity, vibration etc.

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The asset shall be capable of being monitored by system elements, and it should not to obstruct the asset's ability in performing its function.

2.2 Requirements

The needs can be subsequently used to formulate requirements as follows:

Business Management Level

R1: The decision support system shall be approved by industrial regulations (e.g.: DNV-GL).

R2: The decision support system shall be capable of maintaining the asset's present technical availability.

R3: The decision support system shall be capable of achieving the asset's operational availability target.

Business Operation Level

R4: The investment on the new technology shall be recovered in 5 years.

R5: The decision support tool shall be capable of lowering the life cycle costs by about 5%.

> *"On the business operational level, cost-effectiveness is the decisive factor"*

System Level

R6: The system shall be representative of the whole asset.

R7: The decision support system shall be utilised by decision-makers, managers and maintainers.

R8: The decision support system shall be operated by technicians of moderate educational background.

R9: The decision support system shall be capable of provided outputs with variables not more than 15.

R10: The decision support system shall be susceptible for any occasional up-date.

R11: The decision support system shall have prognostic capability.

R12: The decision support system shall be capable of assessing diesel and gas fuelled engines.

R13: The decision support system shall be capable of supporting various operational profiles of ships such as stand by, slow speed, moderate speed, full speed operations.

R14: The decision support system shall be capable of predicting the degradation to an accuracy of 10%.

System Element Level

R15: The sensors and its associated circuits shall be capable of operable in vibration, heat, humidity and safety levels as mentioned in industrial guide lines (DNV-GL code).

R16: The condition monitoring techniques shall not further hinder the asset's ability in performing its function.

R17: The system element shall have technical and operational availability levels not less than 96%.

R18: The system element shall be capable of measuring the expected range of operational conditions with an accuracy of 5%.

2.3 Verification & Validation

While formal transformation, the requirements can be established as per the guidelines of INCOSE 2015 [12]. The rules regarding clarity, wording structure and language to be respected as per the guidelines. Thus, the requirements can be verified. The requirements should also be validated whether they communicate the needs of the stakeholders, so that the design can be done according to well defined obligations. Therefore, requirements have to be formulated in an iterative approach after several brain storming sessions and case studies. Industrial and knowledge partners can be consulted in the end to ascertain the compliance of requirement against their wishes. Once requirements are well established it needs to be verified continuously in various stages of the project. There can be design reviews in various design phases such as conceptual design, detail design etc. At the end of each stage a design review will be done in order to validate the system operational requirements and specified technical performance measures (TPM). It can be first established in the beginning with case studies and verified continuously throughout the project length as follows:

Makers provide working environment and safety factors of the sensors in their technical specification manual (R15, R17). By referring this document, the sensors can be chosen according to the environment in which the ships are operating. The same holds true for reliability levels. Once the physical features of the sensors are known, further discussion can be held with company managers regarding its maintainability and interference with the asset (R16).

The systems need to be a representative of whole asset (R6). That means it should be the critical and maintenance driving component of the asset. This can be verified with FMECA studies by interviewing maintenance managers. The end user of the tool, and the skill set (R7, R8) can be verified in consultation with stake holders. Requirements R11 to R14 deals with accuracy of the model. It can be established in the beginning by comparing similar methods in the literature, and it can be verified by observation case studies along the length of the project.

Requirements R2, R3 (ability of maintenance analytics to improve maintainability) can be verified by comparing the results of prototype version of the decision support system against existing MTBM values. Once the prediction accuracy is proved, this can be utilised to assess MTBM values. R1 (approval) can be verified in consultation with classification society. Based on the scientific value of the prognosis system their approval is warranted.

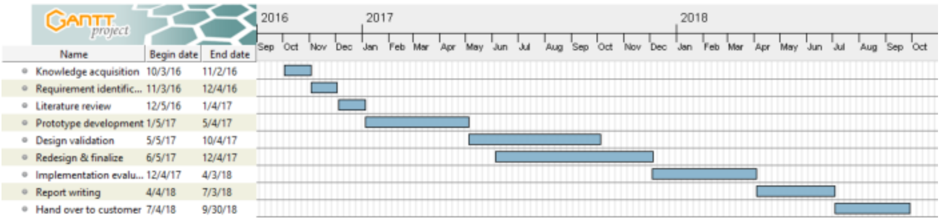

Figure. 2: Gantt chart

On the business operational level, cost-effectiveness is the decisive factor. In the beginning similar approaches in the industry can be reviewed, in order to assess the benefits of condition monitoring system. Once prototype is validated successfully, the viability of a condition monitoring system can be verified by business case studies (R4, R5) to evaluate its cost effectiveness. Upon successful validation this can be implemented across the marine fleet.

2.4 Risk Mitigation Plans

As technology is evolving day by day, there are possibilities such that existing design can be outdated any time. To reduce such effects, artefacts involved in a project need to be designed as modules, such that it can be upgraded separately as per technological growth (R10). In the beginning of the project, a work plan is formulated based on the requirements, and approved by the project manager, which consists of various timelines associated with the project.

During the development process, the results are continuously tested to meet the initial requirements and the corresponding time lines. These assessments include monthly meeting with project manager, bi yearly meeting with consortium partners. Adjustments will be made according to the uncertainties; in such a way the project still complies the requirements. The project is moving in close collaboration with the companies. As companies work on a busy schedule, alternate back up plans are established in the beginning for such uncertainties. Valid simplifications as mentioned in the literature will be kept as substitute, in case the company deviates from its commitment.

2.5 Requirements as Performance Indicators

By satisfying all technical performance measures (TPM), the performance of the system can be ascertained. In the beginning of the project a work plan can be formulated based on the requirements. It is approved by the project manager, which consists of various timelines associated with the project. By establishing a Gantt chart **(Figure. 2)**, the project progress and corresponding time lines are being monitored in closed intervals.

3. Systems Thinking Tracks

To achieve the optimal fit between the system under design (SUD), the identified issue, the context, stakeholders and the rest of the world, a system designer has to think along several lines. In this section a number of these lines based on scientific research, literature and experience from the authors are elaborated [13].

A system is a set of objects with relationships between the objects and between their attributes. System as a set of interrelated components works together with the common objective of fulfilling some designated need. At the start of the design process, the outcome is unknown, while the freedom to make decisions is infinite. In that situation the architecture of the system has to be defined, shapes the overall system, thus making good decisions, based on limited information. The thinking tracks are meant for dealing with this uncertainty, uncover information and knowledge.

A systems thinking is mandatory for performing good systems engineering. The nine-window diagram **(Figure. 3)**, puts the system to be developed in its temporal and hierarchical context. It gives the opportunity to describe the previous, present and the future situation at the level of the system to be developed, that is decision support system.

Dynamic Thinking

Ships have lifetime of three decades. Over such a period, many changes in goals and context may occur. Such changes should be dealt with to prevent a premature end

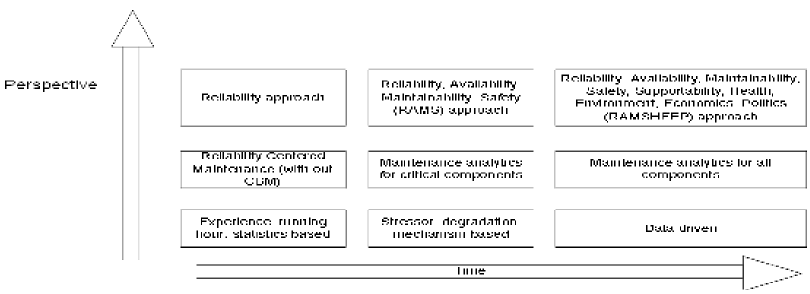

Figure. 3: 9-Window diagram of decision support system [4]

to the asset's useful life. However, current maintenance methodologies focus mainly on the short term and on operation in a stable context. New maintenance concepts or decision making systems should consider Technical, Economic, Compliance and Commercial (TECCO) perspectives to identify long-term challenges and opportunities for the asset [5]. The time scales indicate the necessity of the decision support system as follows:

> *"Ships have lifetime of three decades. Over such a period, many changes in goals and context may occur"*

Hours: How does the weather change, and what is the effect on ship operation? How will it react to high seas?

Weeks: Time spent in logistics support (maintenance and spare parts).

Months: Maintenance activities take months in case of adverse main engine failure. It affects heavily on vessel operational availability. Presently the achieved values are below the target levels.

Scales Thinking

The number of failures in this sector of industry is nowadays typically controlled by performing a lot of preventive maintenance. The preventive maintenance intervals must be set to very conservative values to assure that severely loaded subsystems do not fail. Increasing or decreasing maintenance intervals didn't yield fruitful results. Therefore, strategy has to shift from preventive maintenance to new domains such as maintenance analytics.

Feedforward Thinking

Ships are typically operated in a harsh and largely variable environment. Failures in any of the subsystems or components may have large consequences or environmental impacts. The preventive maintenance intervals must be set to very conservative values to assure that subsystems do not fail. The unexpected failures still occur, leading to long down time of the system. To improve the situation, a better prediction of failures for systems operated under expected conditions is required. Only when such a proactive, prognostic method is available to provide such a prediction, maintenance can be performed in a just-in-time manner. This is symbolically shown in **Figure. 4**.

Specific Generic Thinking

Static experience-based predictions or following OEM instructions, results in average estimations under historical average conditions [6]. It will not offer correct forecasts when systems are loaded dynamically (naval ship performing different types of missions in different regions). Therefore, life time estimation of specific system in specified conditions is expected by means of maintenance analytics.

Hierarchical Thinking

Ships and other maritime systems are typically complex systems containing large numbers of subsystems and components (**Figure. 5**), which are each again subdivided into subsystems. For the diesel engine, these are bearings, liners, pistons, etc. Asset owners and operators are interested in the functioning and maintenance optimisation on the highest (system/ship) level. But prognostic methods, are typically developed at this lowest (component) level. This immediately demonstrates one of the largest challenges in predictive maintenance: how can the system level maintenance optimisation be connected to the component level prognostic methods? Even though prognostic models for all individual components are available, full coverage of all components is not feasible in the practice. The consequence is, a suitable selection method is required to select those components representative of the whole system.

Safety Thinking

Safety is the primary concern of the maintenance policy. Premature failure happening in critical missions (heavy weather), jeopardise the safety of personnel and machinery on ships. Therefore, a prognostic capability is the requirement of the system to foresee critical failures. Based on these decisions, missions can be avoided or changed. More over such capability reduces workers mean exposure to occupational hazards.

Risk Thinking

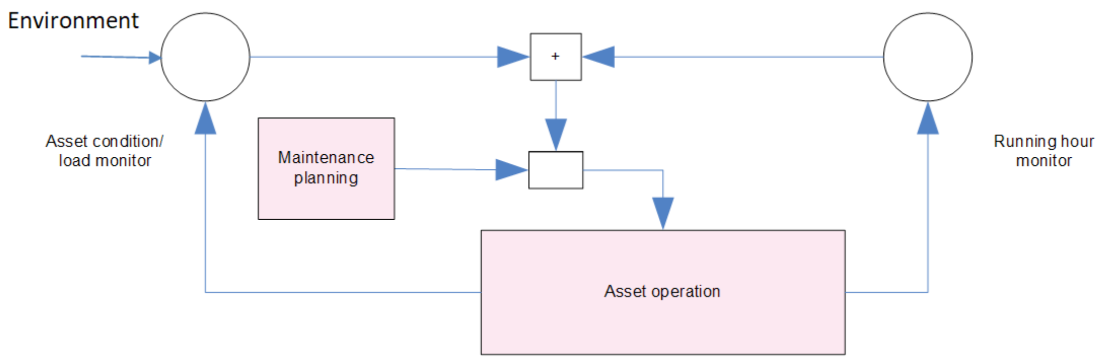

Figure. 4: Feed forward thinking (necessity of condition based maintenance)

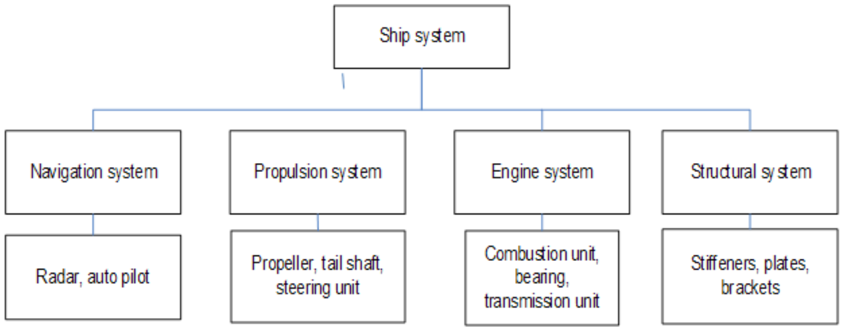

Figure. 5: Ship system decomposition

Table 1: FMECA Results

Part	Component	Failure Mode	Mechanism	Downtime	RPN
Diesel engine	Bearing (main, connecting-rod, crank shaft)	Worn, damaged	Wear, human error, misalignment	Company 1	384

New condition based maintenance policies shall be developed based on prioritising the equipment's risk level (safety, environmental, and maintenance cost). Risk can be defined as the mathematical product of failure frequency, probability of failure, and detectability, which must be established based on experience or maintenance data analysis. A typical risk evaluation tool is shown in **Table 1.**

Scientific Thinking

The main design question is, "How to identify a maintenance driving and critical component representative of engine system, and develop a mathematical model, capable of predicting the component's life based on usage profile?" In project initiation stage, critical component suitable for prognostic techniques, can be selected based on FMECA analysis. Based on observed failure mechanism, diagnosis systems can be developed. The selection of the type of maintenance analysis can be made from experience-based, reliability statistics, stressor-based, degradation-based, or mechanism based methods. Instead of starting with high accurate models, it will be preferable to develop artefacts with less accurate methods (empirical formulas), and based on preliminary prototype results, artefacts can be improved or redesigned to meet the design criteria [2]. This can be done in an iterative way **(Figure. 6).**

Operational Thinking

More restrictions are added to implement maintenance analytics in reality. The monitoring technique must be customised to operator's skill set and remote monitoring capability. By only specifying a limited number of parameters, the failure behaviour needs to be predicted accurately for all operational scenarios.

Life Cycle Thinking

Out of product life cycle, resource life cycle and project life cycle, product life cycle partially applies to this project.

The objective of this project is to develop a mathematical model for life prediction of engine components. This can be realised in conceptual design, detail design and implementation phases. In conceptual design phase, need, feasibility studies and requirement can be formulated. In detail design phase the design activities, as an outcome of conceptual design stage can be realised, tested and finalised. The cycle can be defined as (1) Problem investigation: What phenomena must be improved? Why? (2) Treatment design: Design one or more artefacts that could treat the problem. (3) Treatment validation (4) Implementation (5) Implementation evaluation stages.

Decomposition and Composition Thinking

The steps followed to implement maintenance analytics in the industry can also be decomposed in the form of Vee

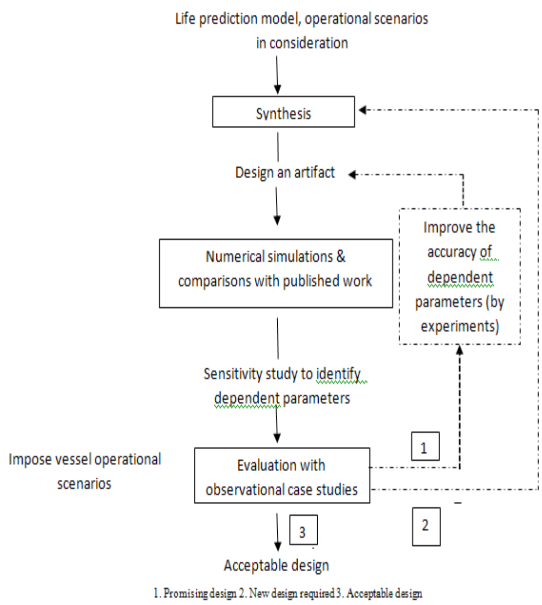

Figure. 6: Design process

model **(Figure. 7).** It starts with identifying the equipment and ends with a feasibility study. At intermediate levels, this will be progressively verified leading to final system level verification. The model starts with the user needs on the upper left and ends with the user's validation on the system at the right. Each step downwards from the left side, a testing should be performed on the opposite side.

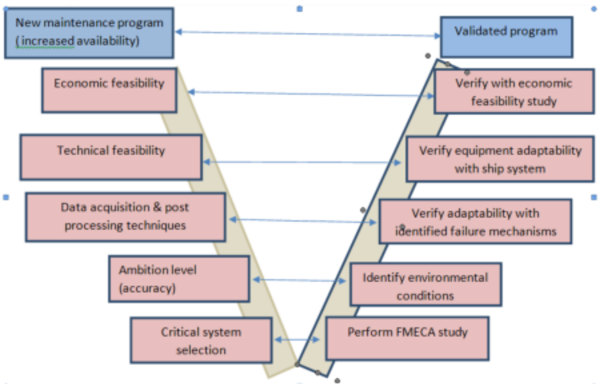

Figure. 7: Steps to implement new maintenance techniques

4. Value Engineering

As mentioned in the introduction sections and also in the system thinking tracks, time based preventive maintenance policy is conservative. It increases technical availability, however because of increased maintenance efforts, operational availability decreased. Companies strive to reduce preventive maintenance tasks without safety risks (unexpected downtime) [8]. Even though one can introduce predictive maintenance as a part of decision support system it has to be economically viable. The goal is to increase operational availability at a lower cost, which can be achieved through value engineering [10].

The aim of this part is to establish an overview of the whole system from a functional point of view. Basic functions and supportive functions are organised and analysed in detail, by means of FAST diagram (Figure. 8). The objective of improving maintenance policy can be supported by satisfying operational availability (primary), technical availability & enhanced work practices (secondary). Improving logistics network is bit ambitious, because the ships will be away from shore in certain missions. Therefore, logistics part is not included in discussions. In the meantime, it is well known that increased spare parts investment can't satisfy the requirement and buying additional ships is an expensive alternative. Therefore, these factors need not be considered for availability and reliability discussions. The main focus will be on maintenance analytics which is a proven technique in the industry to increase maintenance intervals and reliability of components in uncertain environments.

The FAST diagram starts from the highest technical performance measure, which is crucial for the output and of high interest to the partners. By moving on the in the X-axis to the right by asking the question "how", By answering this questions a cost effective condition monitoring technique can be designed that helps to achieve the value goal. The primary goal (Improve maintenance policy, improve availability) and Supporting decisions or secondary goals (Improve reliability, enhance work practices) are shown in **Figure. 8.**

Outcome

The most expensive function (80/20 rule) shall be identified in this phase. It is found that **(Figure. 8),** offering health monitoring system to few critical equipment, and offering scientific input for the chosen decision support system will be more expensive, and the same can be optimised using four quadrant analysis [15] (for critical

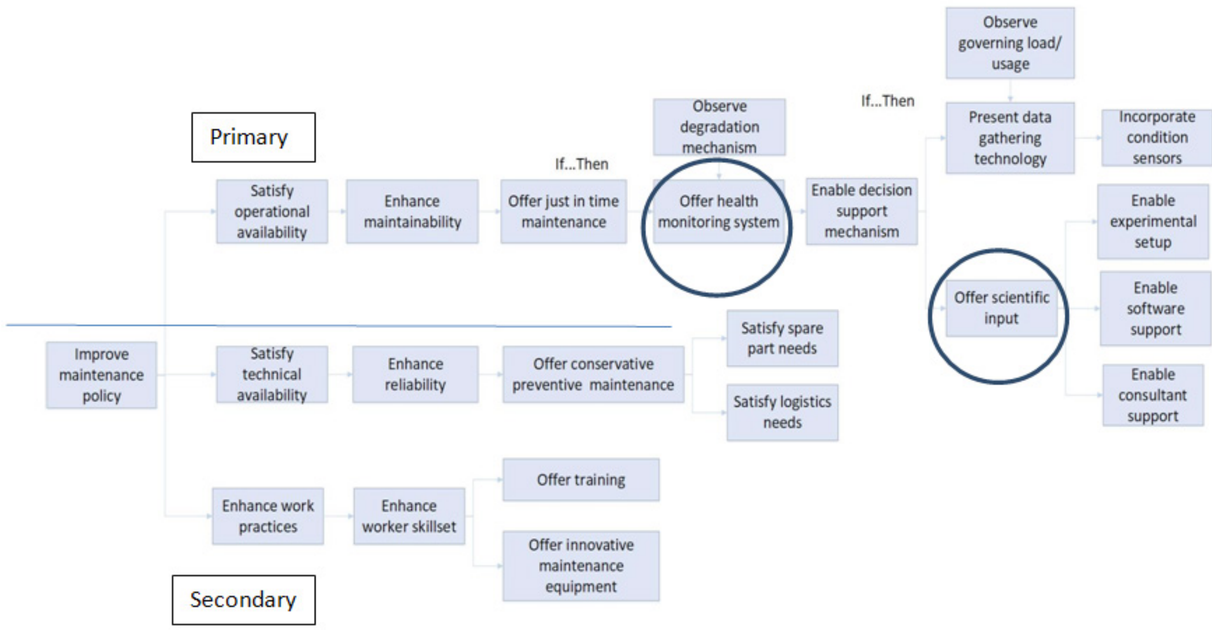

Figure. 8: Fast Diagram

component selection) and design science methodology [2] (for making iterations in design).

To elaborate more on the previous paragraph, developing decision support system is feasible, by considering the failure phenomena in a component. If a mathematical model is required as a part of it, it requires evaluating engineering relations. This can be derived by means of experiments, numerical simulations or values can be taken from literature. Relying of literature values could be a choice because of time and budgetary constraints. So they can be preferred, and in case of simulations required, open source software can be preferred, which come under free licensing agreement. Similarly, certain experiments will require purchasing new equipment. If discussion can be held with subject experts in the initial model development stages empirical values can be used. After a first validation campaign adjustments can be made accordingly.

5. Model Based Systems Engineering (MBSE)

Figure. 9 depicts the project in wider view. Various stages of the project such as problem identification, treatment design, design validation and integration steps are shown in it. This outlines the various steps involved in a typical product development life cycle [14]. The structural view of the ship and its sub system decomposition is shown. The associated major aspect concerned with the ship system is the reduced operational availability, which initiated the design activity. This is depicted in the beginning. The required characteristics of the system to be developed, such as less CPU power, versatile engine application and user friendliness are highlighted. As shown in **Figure. 9**, structural, design views and its association and interrelation is shown in one single model, the so-called project model, which depicts the project setup.

6. Conclusion

Systems engineering, is introduced briefly in this work in the context of improving maintenance management. From this work, one can realise systems engineering potential to solve real world problems or design new systems/components. A firm basis is provided in this work, so that the design process can take place as smoothly and efficiently as possible, there by new technologies, process can be introduced in the industry.

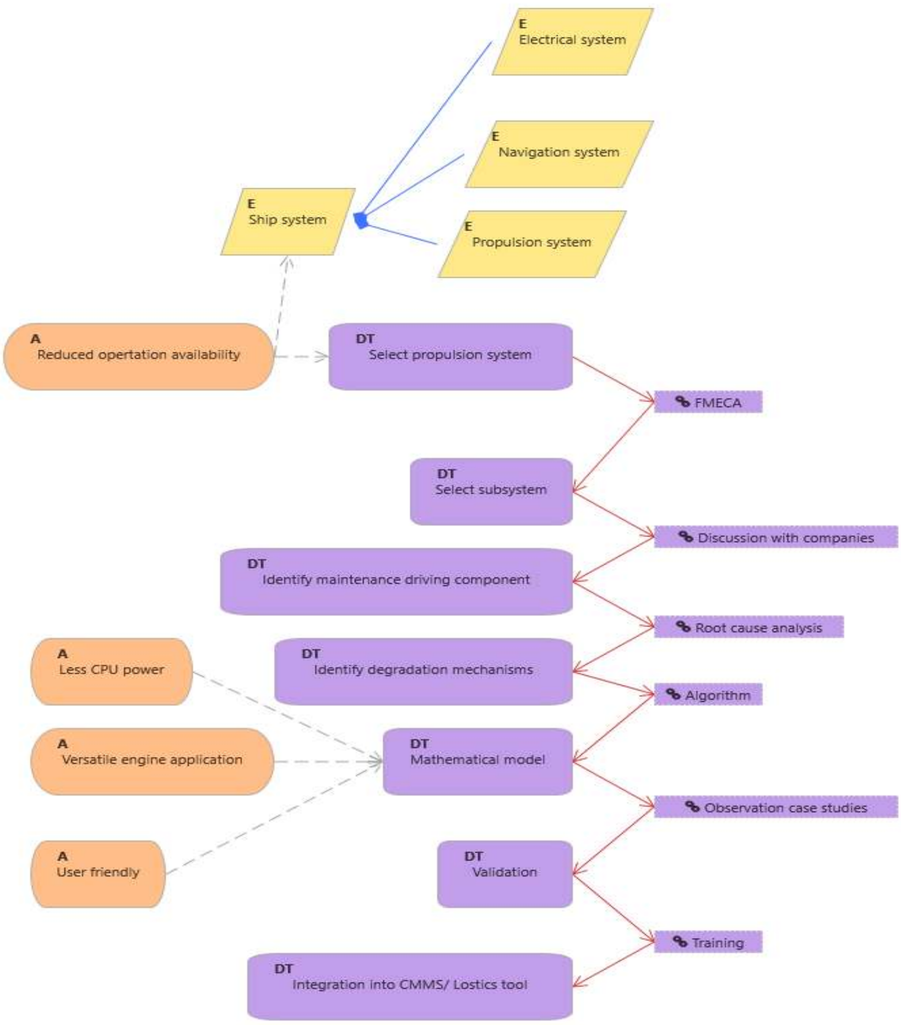

Figure. 9: Project model

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About the author

Prabu Duplex had sailed as a marine engineer between 2005- 2013. He graduated from a Professional Doctorate in Engineering (PDEng) program 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 in developing physics based mathematical models to predict the life time of diesel engines components in maritime propulsion systems. He has also a Master's degree in Naval Architecture. He is open for careers in design or research activities in naval, wind, offshore or predictive maintenance domains.

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Prediction of Human Factor in Offshore System Reliability

N. Vedachalam

Abstract: Human Reliability Analysis (HRA) is a proactive approach that involves systematically identifying the causes of failures that could arise due to human errors, quantifying its probability of occurrence and implement safety improvement measures in offshore systems. There are a number of HRA methods, differing in scope, types and levels of decomposition of the tasks, and the performance shaping factors that contribute to human error probability. The article describes the importance of human reliability in offshore system engineering, approach to HRA, proven methods to compute human reliability and the importance of cognizance-centered approach in executing time-bound actions during emergency. By effective use of modern HRA tools, operational errors could be reduced by training the operating personnel using simulators, improved ergonomics, hardware and providing software interlocks.

Introduction

Based on the experiences from World War 1 and 2, the need to consider reliability engineering as an integral sub-discipline of systems engineering was well understood. In 1920, the product improvement through the use of statistical process control was undertaken by Bell Labs, around the time Waloodi Weibull was working on statistic fatigue models.

The modern use of the word reliability was defined by the U.S military in the 1940s, characterising a product that would operate when expected and for a specified period of time. Understanding the importance of reliability, the IEEE reliability society was formed in 1948. During 1950, the US Department of Defense formed the advisory group on the reliability of Electronic Equipment to investigate reliability methods for military equipment, that later recommended ways to improve component reliability, establish quality and reliability requirement for manufacturers, collect field data and identify the root cause of the failures. Over the past six decades, based on the lessons learnt from the catastrophic failures in space, marine, offshore oil and gas, power generation, chemical and transportations sectors **(Table.1),** the importance of **Reliability, Availability, Maintainability & Safety (RAMS)-centered system engineering** gained importance.

Table.1. Safety-rated catastrophic accidents

Period	Safety-related accidents/breakdowns
Till 1970	Apollo 13, Torrey Canyon oil spill, RMS Titanic sinkage
1970-1980	Tenerife airport disaster, Three miles island nuclear reactor meltdown, Flixborough chemical plant explosion, Seveso chemical industry accident, Exon Valdez oil spill, French power grid collapse
1980-1990	Bhopal gas tragedy, Chernobyl nuclear disaster, Piper Alpha oil platform accident, Challenger space shuttle accident
1990-2000	MS Estonia ferry sinkage, Eschede train accident, Ariane rocket launch failure, Concorde flight accident, Paddington rail accident
2000-2010	Prestige oil spill, European power grid collapse

Period	Safety-related accidents/breakdowns
2010-2020	Macondo oil spill, Fukushima nuclear disaster, Costa Concordia ship grounding, Lac-Mégantic rail disaster, Santiago de Compostela derailment, Boeing 739 Max8 crash, Grande America sink and oil spill , Indian power grid collapse

The evolution of RAMS standards, tools and databases since 1970 is mapped in **Table. 2.**

Table.2. Evolution of RAMS tools, standards and database

Period	Tools, Standards and databases
Till 1970	Markov analysis[1906], FMECA[1940], HAZOP[1960], Probabilistic Safety Studies[1960], MIL-217[1965], THERP[1963], MIL STD-882[1969], PHA[1969]
1970-1990	OREDA[1982] , ISO 6527[1982], SDRF database for nuclear[1984], HRA HEART[1985],BDD[1986], Markov model[1986]
1990-2010	MIL HDBK 217[1995], IEC 60300 Collection of data [2004], Markov standardization IEC 61165[2006], ISO Guide 73[2009], IEC 61508 functional safety[1998] , IEC 61511[2003] , SysML[2005]
2011-2015	ILS[2011],RBT[2011], Petrinet[2012], IEC62551[2012], ISO/TR 12489[2013],IEC Guide 51[2014], Quantenium 217 plus[2015]
2016-2018	HAZOP standardization IEC 61882[2016], ISO 14224 Collection of data[2016], IEC 60300 life cycle costs[2017], RCM IEC 60300-3-11[2017], ISO 20815[2018]
2019-Till date	Alta Rica[2019], FMECA standardization IEC 60812 [2019], IEC 31010[2019], UML[2020],ALARP [2020], PERD CCPS 202[2020], IEC 63142[2020]

RAMS-centered system engineering utilises information about the system to identify sources of risk and risk drivers, and provide important inputs for system design and operations. During early phases of a project, RAMS analysis helps designers understand the inter-relationships of requirements, constraints, resources, and uncover key relationships and drivers so that they can be properly considered. As the design matures, reliability analysis is carried out using established techniques. The design and the Concept of Operations (ConOps) are thoroughly examined for accident initiators and hazards that could lead to mishaps **(Figure.1).**

From more than 4100 world-wide marine accident events, including oil and gas installations, ~ 66% were due to human errors

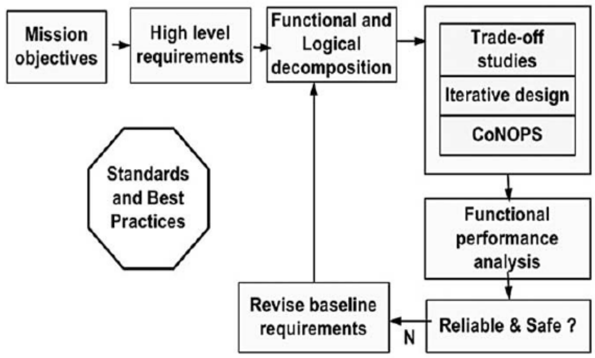


Figure.1. RAMS-centered system engineering

Importance of Human Reliability in Offshore Sector

It is well known that humans play a substantial role in the social-technical systems, involved in the design, construction, installation, maintenance and operation of offshore installations. With the advances in materials, technology, and engineering, the complex systems have become more and more reliable, whereas human factors (such as erroneous behavior, poor judgment or failure to comply with standard procedures) has been long regarded as a dominant contributor leading to accidents.

Statistically, human-error accounts for > 90% of failures in the nuclear plants, > 80% of accidents in chemical and petro-chemical industries, 75% in automotive, 75% in aviation and 90% in air traffic control. From more than 4100 world-wide marine accident events, including oil and gas installations, ~ 66% were due to human errors. In 2019, ~80% of the ship accidents in Japan were due to human errors. According to the International Maritime Contractors Association (IMCA) database with 71 dynamic positioning (DP) related incidents reported from 54 vessels, ~50% of the failures were due to human errors, **procedural and environment-related**.

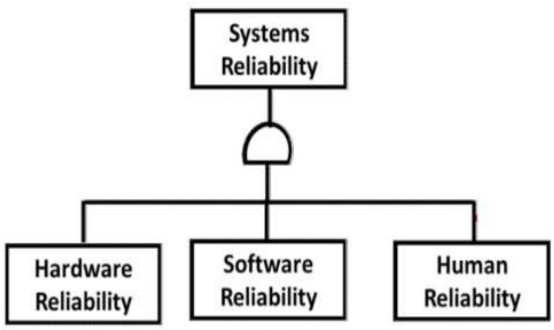
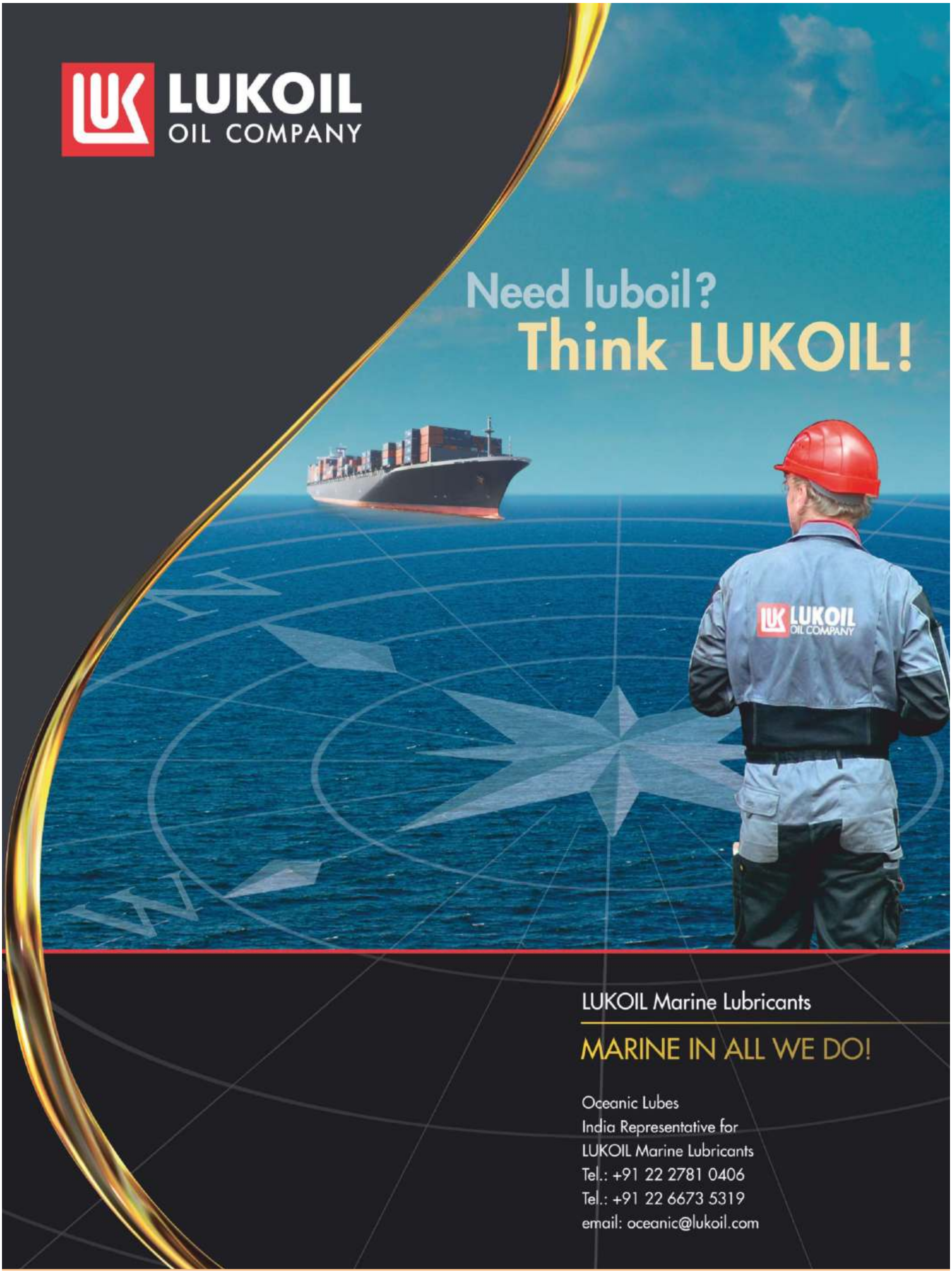


Figure.2. Human reliability as a part of systems engineering

In order to avoid equipment and operational failures, International Maritime Organization (IMO) and International Association of Classification Societies (IACS) recommend carrying out reliability and functional safety assessments during system engineering and operational phases of major offshore developments/ systems such as ships, submarines, floating and subsea oil and gas installations, renewable energy systems and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subsea intervention systems. Hence system engineering should include human reliability component, in addition to hardware and software reliability **(Figure.2),** and assessment of the factors determining human reliability using scientific methodologies are important.

> *Human Reliability Analysis (HRA) is the discipline that provides methods and tools for qualitatively and quantitatively predicting human errors in systems in which people have monitoring and control functions, through human-machine interfaces*

Progress in Human Reliability Analysis

Human Reliability Analysis (HRA) is the discipline that provides methods and tools for qualitatively and quantitatively predicting human errors in systems in which people have monitoring and control functions, through human-machine interfaces. The first systematic assessment of human reliability was initiated in the military domain for predicting and quantifying the probability of human errors in nuclear weapon assemblies. The second main driver came from the developments in Probabilistic Risk Assessment (PRA) for nuclear power industry, a technique for quantifying the risks posed to the public by a serious core-melt accident at a nuclear power plant. These assessments resulted in the development of the early versions of Techniques for Human Error Rate Prediction (THERP) to identify potential operator errors and to systematically estimate their failure probability.

In case of repetitive and predictable tasks, operators could be readily modelled as components that either acted as required by the system or deviated from the requirements. Early applications in the nuclear industry maintained the assumption of the **operator as a component** performing a set of assigned functions. This allowed for a single reliability engineering framework to be applied to the entire human-machine system for which failure probabilities were required. However, it was later recognised that, instead of modelling humans as technical components, a more detailed human reliability modelling was needed. Unlike equipment that have very specific functions in response to limited inputs and outputs, man-in-the-safety-loop should interpret the inputs according to the safety goals they are pursuing and autonomously decide among a vast array of strategies or subtasks to achieve safe results. In addition, human performance is strongly influenced by variations in the task and workplace conditions, as well as individual and cognitive aspects.

Subsequent to the first-generation HRA models such as THERP and SPAR-H, the second generation HRA models including SLIM ATHEANA, Integrated Reactor Operator/System (INTEROPS), CREAM, Cognitive Simulation Model (COSIMO), Dynamical Logical Analytical Methodology (DYLAM/HERMES), Méthode d'Evaluation de la Réalisation des Missions Opérateurs pour la Sûreté (MERMOS), Simulation-based Evaluation and Analysis support system for Man-machine Interface Design (SEAMAID), Cognitive and Action Modeling of an Erring Operator (CAMEO), and Simulation System for Behavior of an Operating Group (SYBORG) represent complex modeling, both for HRA and Human-Machine Interface (HMI) design.

The HRA tools including HEART, THERP and TESCO use data-driven techniques, SLIM is based on structured expert opinion and the present generation Human Cognitive Reliability (HCR) method is based on accident data. Most of the present generation dynamic HRA simulations have cognizance capabilities, coupled event/accident simulations and incorporate cognitive psychology models.

Models such as Adaptive Control of Thought – Rational (ACT-R), Systematic Omics Analysis Review (SOAR), Connectionist Learning with Adaptive Rule Induction On-line (CLARION) evaluate human performance without the intention of serving as an HRA tool, but have a detailed understanding of micro-cognition and cognitive mechanisms of human error, which is the key for an HRA model that is comprehensive enough in terms of the various cognitive function failures. The evolution of various important HRA tools and methodologies for quantifying the risks arising out of human error is summarised in **Table.3.**

Table 3. Evolution of HRA tools

Tool	Objective
Technique for Human Error Rate Prediction (THERP)	Assess failure in task or action sequence. It is applied in maintenance, operational or incident analysis with complex graphic representation (1975)
Operator Action Trees (OAT)	Assess failure in task or action sequence. It is applied in maintenance, operational, or incident analysis with simple graphic representation (1982)
Success Likelihood Index Methodology (SLIM)	Assess failure in task or action sequence. It is applied in maintenance, operational or incident analysis and regards human factors performance based on specialist opinion (1984)
Systematic Human Action Reliability Procedure (SHARP)	Assess cognitive human process of failure (detection, understanding, decision, and action), being applied in maintenance, operational, or incident analysis (1983)

Tool	Objective
Sociotechnical Assessment of Human Reliability (STAHR)	Assess failure in task or action sequence and is applied in maintenance, operational, or incident analysis and regards human factors performance based on specialist opinion (1984)
Accident Sequence Evaluation program (ASEP)	Simplified form of THERP. Comprises of HRA for pre-Accident screening, post-accident screening, pre-accident nominal and post-accident nominal (1990).
Standardized Plant Analysis Risk - Human Reliability Analysis (SPAR-H)	Process to identify nominal human error probabilities HEP and then modify those HEPs on the basis of summary-level performance-shaping factors (PSFs) and dependence (1990)
Cognitive simulation model (COSIMO)	It simulates the behavior of an operator reproduced through the Fallible Machine model by Reason, coupled with a model for the system specific for the system to be considered. Study the operator actions in abnormal plant conditions (1992)
A Technique for Human Error Analysis (ATHEANA)	Assess cognitive human process of failure (detection, understanding, decision, and action), being applied in maintenance, operational, or incident analysis (1996)
Cognitive Reliability and Error Analysis Method (CREAM)	Assess cognitive human process of failure (detection, understanding, decision, and action), being applied in maintenance, operational, or incident analysis (1998)
Bayesian network	Assess failure in task or action sequence and is applied in maintenance, operational, or incident analysis and regards human factors performance based on specialist opinion; in addition, such methods regard human factors performance dependency (2005)
Simulation System for Behavior of an Operating group (SYBORG)	It simulates a group of nuclear power plant operators. It needs input coming from a specific plant simulator. It highlights some possible combinations of operator errors and plant condition that can lead to accident sequences; it proposes different strategies to improve the collaboration within the group

Tool	Objective
Man, Machine Integration Design and Analysis system (MIDAS)	It is an integrated suite of software components developed to aid designers and analysts to apply human factor principles and human performance models to the design of complex human–machine systems in aviation. It can simulate the behavior of a pilot for civil aviation or an air traffic controller. The model of the operator is based on Rasmussen's model.

Approach to Human Reliability Assessment

In marine applications, HRA aims at designing operator interfaces that can minimise operator errors provide means for error correction and recovery capability. The process of HRA ensures that potential effects of system safety and reliability are analysed and human actions that are important to plant/system risk are identified so that they can be addressed in the plant design. Hence, when designing systems involving human intervention during critical operations, Human Factors Engineering (HFE) is considered as a critical part of the design process. HFE studies human-machine interfaces and provides requirements, standards and guidelines to ensure the human component is well-integrated. HFE includes consideration of anthropometry & biomechanics, sensation and perception, environment, temperature, lighting, and physiological factors **(Figure.3).**

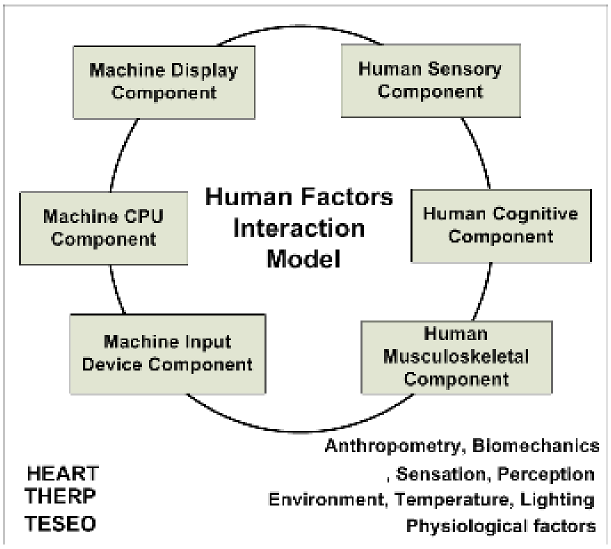

Figure.3. Human factors intercation in HFE

The major stages involved in HRA **(Figure.4)** include:

- Identifying critical human involvements in a system and how they can fail.
- Quantifying the probability of failure of human involved actions (HEP).

> *PSF are environmental, personal or task-oriented factors that influence the probability of human error*

- Determining how to improve human reliability, if performance needs improvement.
- If calculated risk levels are higher than expected and if human performance error is contributing significantly to those risk levels, incorporate appropriate risk reduction measures.

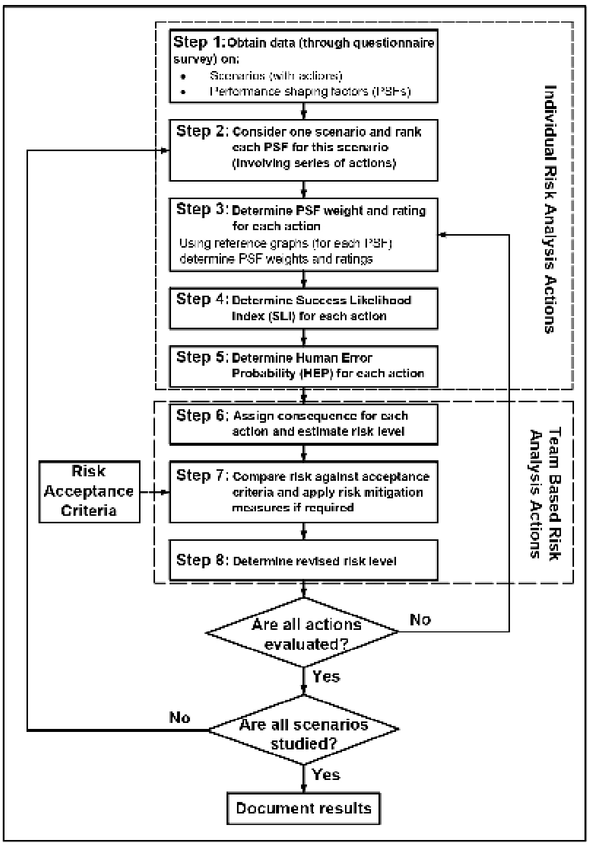

Figure.4. Human reliability assesment process

As described in Step-2 of the HRA process, human performance is determined by various factors that influence how humans act. These factors are called Performance Shaping Factors (PSF) are categorised into external, internal and stressor **(Figure.5).**

PSF are environmental, personal or task-oriented factors that influence the probability of human error. PSF has to be considered as an integral part of error modeling that must be used during human error quantification to obtain the human error rate applicable to a particular set of circumstances. Specifically, the basic HEP obtained from generic circumstances are modified (adjusted) as per the situation. Methods for estimating the HEP parameters are described in the UK Atomic Energy Authority (UKAEA) document SRDA-R11.

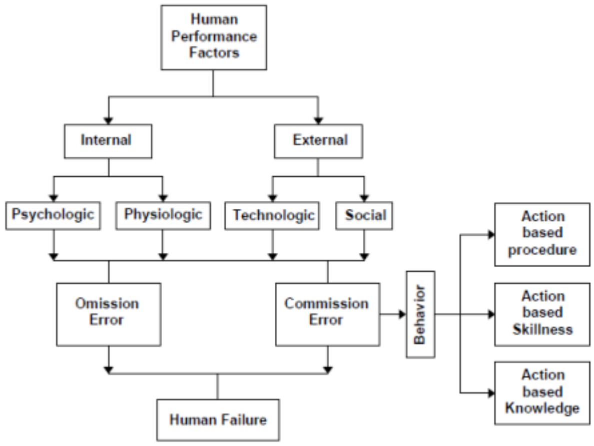

Figure 5. Determinants of human performance

External PSFs include factors like work environment, nature of Human Machine Interface (HMI), quality of procedures, situational characteristics, task and equipment characteristics. The situational characteristics include vessel/submarine/hydrocarbon rig/subsea process control room environment such as ambient temperature, humidity, air quality, noise, illumination, work and break hours, shift rotation and night work, availability and adequacy of equipment/system. The task and equipment characteristics include perceptual requirements, motor requirements, complexity, criticality, frequency, repetitiveness and HMI factors. The job and task instructions include ship/plant operations manual, procedures, oral/paper communication, alert and attention.

The internal PSFs include factors like motivation, emotional state, physical condition of the individual, operator training experience, working experience and skill and sex differences. When the ship/marine crew are well trained and qualified, the internal PSFs will not have conspicuous effect on HEP compared with the external PSFs. The stressor PSFs are generally overlooked as they are difficult to comprehend, but their influence is considerable, particularly in hazardous situations. The stressor is any external or internal force that causes bodily or mental tension. It appears to arise whenever there is a mismatch between the internal PSFs and the external PSFs.

Stressors can be psychological, physiological, or a combination of both. The psychological stressors are due to suddenness of onset of a disturbance, task overload, information overload, pressure of time, fear of failure, repetitive meaningless work, uneventful periods during continuous monitoring and distractions that affect attentiveness. The physiological stressors include duration of stress, fatigue, pain or discomfort, hunger or thirst, temperature extremes, radiation, oxygen insufficiency, vibration and disruption of circadian rhythm. Physical stressors include fatigue, discomfort, vibration and disruption of the circadian rhythm. Others considerations include level of knowledge, experience,

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- 2 to 3 years in ship operation, experience in teaching / auditing preferred.
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trainings undergone, cognitive performance, cognitive bias and malevolence. The sources of human error are summarised in **Table.4.**

Table 4. Description on the sources of human error

Nature of error	Description
Omission	When one action is not performed because of lapse or misperception.
Commission	Happens when an action is performed incorrectly because of an incorrect quantity or quality of action or a mistake in selecting or proceeding with a sequence.
Psychological	Related to emotional issues such as stress, overworked psyche, depression, demotivation, and lack of concentration.
Technological	Related to work conditions, tools, and technology, such as ergonomics, procedures, and equipment.
Social	Related to social issues in and out of the workplace, such as poor social conditions and lack of acceptance in the group.

The first and second generation HRA tools (such as THERP and ASEP) contains many PSFs embedded in failure rates which are represented as HMI (alarm response, tagging, color coding, similarity, chart type, functional grouping, population stereotypes, rotary controls), procedures (short, long, written notes etc) and stress (skill, novice, dynamics), situation outside control room, stress, time and procedures. Present generation HRA tools, in addition to PSF, factors-in human cognizance capabilities to the extent required for the operator and the emergency situation. CREAM incorporates organisational factors such as working conditions, MMI, procedures, plans, goals, time available, time of the day, training, crew, collaboration factors, stress etc. HRA studies done by an Indian nuclear power establishment indicate 6% failure probability in starting the emergency systems involving trained personnel.

Computation of Human Error Probability

In HRA studies, human reliability is quantified in terms of Human Error Probabilities (HEP). HEP is the ratio of the number of observed errors to the total number of chances for error to occur. The HEP defined according to Weibull distribution is,

$$\text{HEP nom} = 1 - e^{-\lambda t \beta}$$

where λ and β represent the scale and shape of the curves. As an example, when an operator is engaged for a duty period of 8h, based on the above formula, HEP is minimum during beginning (1st hour) of the work. Consecutively, the probability distribution of error is,

$$\text{HEP nom}(t) = 1 - k * e - \lambda(1-t)\beta \text{ for } t(0,1)$$
$$= 1 - k * e - \lambda(t-1)\beta \text{ for } t(1,\alpha)$$

The parameters defining the HEP based on the nature of job and response warranted from the human are summarised in **Table.5.**

Table 5. Parameters defining HEP

Nature	Limits of unreliability %	K		α	β
		t=0	t=8		
1	35-97	0.65	0.03	0.17	1.5
2	12-28	0.88	0.72	0.01	1.5
3	1-5	0.99	0.95	0.002	1.5

1- Totally unfamiliar;
2- Complex task requiring high skill and comprehension;
3- Routine task

Once the HEP nom is calculated, PSF allows taking into account all the environmental and behavioral factors that influence operator's cognitive behavior. In particular, PSFs helps to incorporate factors for simulating different emergency scenarios that influence HEP. The HEP multiplication factors for a few PSFs related standardised instructions, experience, safety culture, stress, complexity and population demography are represented in **Table.6.**

Table 6. HEP multipliers for various PSF

PSF	PSF level	HEP multipliers
Available time	Inadequate	1
	5 x required time	0.1
	50 x required time	0.01
Stressors	Extreme	5
	High	2
	Nominal	1
Complexity	High	5
	Moderate	2
	Nominal	1
	Good	0.5
Standardized instructions	Not available	50
	Incomplete	20
	Poor	5
	Nominal	1
	Good	0.5
Experience	Low	10
	Nominal	1
	High	0.5
Safety culture	Poor	2
	Nominal	1
	Good	0.8

PSF	PSF level	HEP multipliers
Population demography	Unfit	20
	Degraded	5
	Nominal	1
Ergonomics	Poor	10
	Nominal	1
	Good	0.5
Fitness to duty	Unfit	10
	Degraded fitness	5
	Nominal	1

Based on the specific situation, other factors could be nominalised and incorporated as multipliers for HEP. E.g., Influence of sleep **(Table.7).**

Table 7. Sleep related factor in HEP computation

Degree of sleepiness	Scale (SLI)
Active & Alert	1
Able to concentrate	2
Responsive, but not fully alert	3
Figurehting sleep prefer lying down	5
Onset of sleep	7

HEP final = HEP nom - calibrated HEP (SLI).

After defining the PSF and its multipliers, the overall PSF index (PSF comp) is computed. In the equation PSF comp index summarises the weight of each influencing factor with respect to the actions/decisions operator.

PSF comp = Σ PSF i

Based on the above inputs the following equation HEP cont provides the level of probability of error of the decision maker, in function of the influencing factors. The HEP cont value increases with the increase in time.

$$HEP_{\text{cont}} = \frac{HEP_{\text{nom}} * PSF_{\text{comp}}}{HEP_{\text{nom}} * (PSF_{\text{comp}} - 1) + 1}$$

The value of HEP cont provides the level of probability of error of the decision maker, in function of influencing factors. The value increases with time and with the nature of the emergency situation.

As an example, **Figure.6** shows the operator response tree to a given situation, incorporating behavioral science knowledge by providing the decompositions of human failures/failure mechanisms/failure factors built from bottom-up approach. The structure provides a roadmap for incorporating the phenomena with which operators would be dealing, the bridge/ plant characteristics (e.g., design, indications, procedures, training), and human performance capabilities (awareness, decision, action). In terms of quantification, the approach uses the typical PRA conditional probability expression, which is delineated to a level adequate for associating the probability of a human failure event with conditional probabilities of the associated contexts, failure mechanisms, and corresponding PSF. Such mathematical formulation can be used to directly estimate HEPs using various data sources (e.g., expert estimations, anchor values, simulator or historical data), or can be modified to interface with existing quantification approaches.

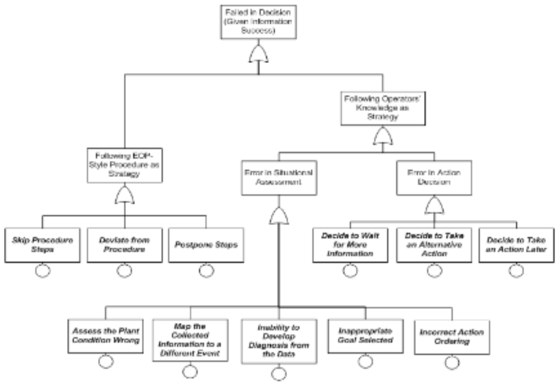

Figure.6. Operators' response tree to a given situation

Importance of Cognizance Factor in HRA

Recent third generation HRA tools incorporate cognitive capabilities in addition to the stimulus-organism-response (SOR) and information processing (like in human brain) features, the basis on which second generation HRA tools are built. The information processing model can be viewed from diverse disciplines ranging from psychology science to sport sciences. There are mainly three models proposed by Wicken **(Figure.7),** Welford and Whiting. The information-processing model describes the human cognitive process from the information transmission perspective, that is, the cognitive process is regarded as a cognitive information transmission process in the human brain.

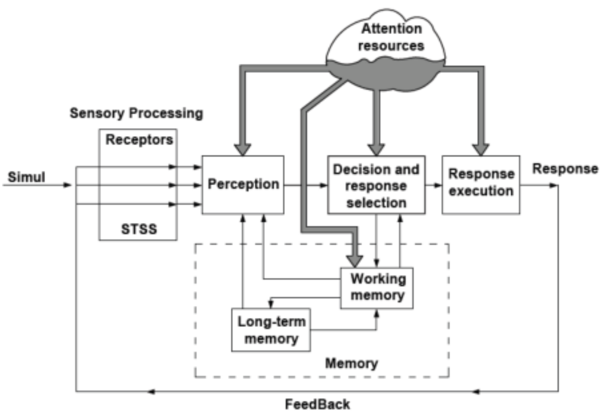

Figure.7. Stimulus-organism-response (SOR) and information processing in human brain

The input is the available cognitive information formed by receiving external event or stimulus information through human sensors (eyes or ears) and then perceiving it (perception). The process handles the input cognitive information, makes decisions and choices, and then gives the decision outcomes (response/ behavior). The output is the result of information processing (response/behavior), which exchanges feedback with cognitive perception so that cognitive outcomes can be amended and adjusted in the cognitive process. Human mental and memory-related factors are also considered in this model. The attention resource and memory interact with each other to affect and assist the process. The described Wicken model is used as a basis of cognitive science that applies to HFE in aviation industry.

In Welford's model, all information gathered from various sensory inputs is stored for a split second in the short-term memory before processing. The short-term memory can only hold up to seven pieces of information and is retained only for less than a minute, while long-term memory holds past information.

This model is used for sport application as the athlete has to learn and perform a wide range of perpetual motor skills and the select the appropriate skill action based on the situation. Over time, the knowledge growth mechanism is achieved through cognitive process. **Figure. 8** depicts the macro-cognitive capabilities of the human brain, in which all processes interact with one another in parallel, and knowledge is thought to reside in the connections and patterns of activation among neural units. For example, the function of detecting problems involves the functions of understanding the perceived information, making a decision about whether it is important or relevant, and adapting plans to the new information.

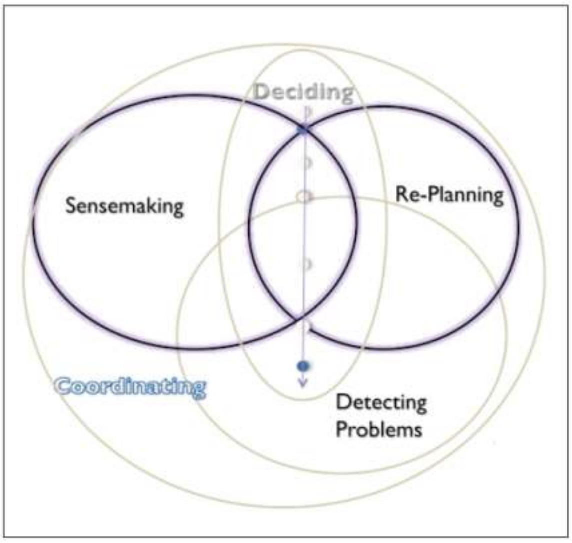

Figure.8. Overlapping function model of macro-cognition

Macro-cognition is one of the key requirements for ensuring human reliability while handling emergency situations in the field where complex decisions are to be made quickly. Cognition includes the mental processes of perception, attention, memory, reasoning, decision-making, judgment, emotion, planning, and action, learning and problem-solving. Macro-cognition features in HRA tools integrates the more narrowly focused micro-cognition laboratory research findings together into a larger picture that describes what people actually do with their brains in applied and complex settings.

The first model which brought out human cognitive factors to the study of human behavior and classifying the human errors (based on skills) is the Rasmussen's SRK (skill-based, rule-based and knowledge-based behavior) framework. Skill-based action primarily represents sensory-motor performance, which typically takes place without conscious effort and follows the intent of the operators in a simple and familiar task context. Rule-based action is a series of actions made by operators within a familiar task context and subject to pre-set rules and procedures.

Knowledge-based action is made by operators after self-set goals, decision making, and judgment based on their own knowledge and experience without guidelines even in an unfamiliar task context. As an example, Cognitive Event Tree System (COGENT) combines skill-based, rule-based, and knowledge-based behavior with the slip, lapse, and mistake definitions into various types of human error. The tools use a classification scheme consisting of a number of groups that describe the phenotypes (error modes) and genotypes (causes) of erroneous actions. **The classifications can be used by the analyst to predict and describe how errors could**

potentially occur. The error mode, in addition to the ones indicated in **Table. 8,** include subgroups like Action at wrong time, Action of wrong type, Action at wrong object and Action in wrong place.

Table 8. Error modes

Modes	Influencing Factors
Timing	Too early, Too late, Omission
Duration	Too long, Too short
Sequence	Reversal, repetition, commission, intrusion
Object	Wrong action, wrong object
Force	Too much, too little
Direction	Wrong direction
Distance	Too short, Too far
Speed	Too fast, Too slow

The classification scheme also allows the analyst to define the links between the causes and consequences of the error under analysis. The classification scheme falls under three genotypes based on individual, technological and organisational causes. These genotype categories are further classified **(Table. 9).**

Table.9. Classification of genotypes

Category	Sub-classification
Individual person-related	Specific cognitive functions- Temporary and permanent
Technology-related	Equipment, procedures, interface (temporary) and interface (permanent).
Organization-related	Communication, organization, training, ambient conditions, working conditions

Human Cognitive Reliability (HCR) models include both the expected human variability (randomness) and uncertainty. The probability of failure of the human operations /Human Error Probability (HEP) based on operator's skill, pre-defined rules and knowledge is represented in HCR **(Figure.9).** The HCR model is mathematically represented by three normalised three-parameter Weibull distributions (one for each behavior category). The HCR correlation does not include uncertainty distributions for either the Weibull parameters or the median response time. However, it allows for sensitivity analyses by changing the time windows, median response times and PSFs.

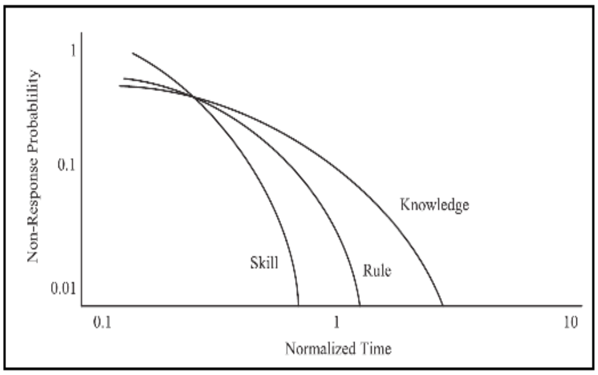

Figure.9. Human cognitive reliability method correlation

Conclusion

Human reliability analysis involves systematically identifying the causes of failures in a system that could arise due to human errors, quantifying its probability of occurrence and determine safety improvement measures. The article described the importance of human reliability in offshore system engineering, approach to human reliability analysis, proven methods to compute human reliability and the importance of cognizance-centered approach in executing emergency time-bound complex decisions. Modern HRA tools with cognition features enable us to-

- Identify those parts of the work, tasks or actions that require or depend upon human cognition, and which therefore may be affected by variations in cognitive reliability.
- Determine the conditions under which the reliability of cognition may be reduced, and where therefore the actions may constitute a source of risk.
- Provide an appraisal of consequences of human performance on system safety, which can be used in probabilistic reliability analysis.
- Develop and specify modifications that improve these conditions, hence serve to increase the reliability of cognition and reduce the risk.

Studies on cognitive models that attempt to model human error and human performance are under continuous development through the advancing research results from related disciplines, such as behavioral science, psychology, and computer science. Future HRA tools developments are focusing on the establishment of the models that takes includes adaptation, performance shaping factors, cognitive simulation, human error behavior that are captured through human experiments.

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Alternative Fuels and Technologies for Decarbonization in Maritime Field – A Preliminary Analysis (Part C)

S. Daga, K.M. Doshi,
S. Gupta, D.R. Sonawane

Battery Technology

Battery powered ships have been gaining prominence especially in the Nordic countries. EMSA (2020) reported a comprehensive review on electrical energy storage on ships. The contents of this section are sourced from their review.

Batteries may be used to completely or partly supply power to propulsion of the ship and/or to improve performance and energy efficiency of the vessel (as often could be the key purpose). A battery consists of cathode, anode, electrolyte and means to complete the circuit during charging and discharging.

Life of battery is influenced by the selection of cathode, anode, electrolyte, manufacturing process controls, usage of battery, operation temperatures, humidity, storage etc.

The following types of technology (select) are available for use:

1. Lithium ion
2. Lead Oxide
3. Rechargeable Nickel
4. High Temperature Sodium

Upcoming technology which could be used in batteries include the Solid State and Rechargeable metal air batteries which were demonstrated to be promising if the technology could be commercialised. Solid State batteries are similar to lithium-ion batteries except that the electrolyte used is a solid electrolyte. These have energy yields similar to conventional Lithium-ion batteries

The main issue at present is with the practical use of batteries for propulsion power generation, that is the space and weight requirements of such batteries when used for oceangoing vessels. Even using lithium-ion batteries over short distances can be overwhelming for ship design. Other issues involve rapid charging facilities at berths.

The main issue at present is with the practical use of batteries for propulsion power generation, that is the space and weight requirements of such batteries when used for oceangoing vessels

At the present stage of time, battery powered propulsion would be limited to small passenger ships or ferries engaged on very short voyages. It is envisaged in the report that with the current pace of research, Solid State batteries should be commercialised by 2050. Rechargeable metal-air batteries may also be viable at that time. The aforementioned discussion should be noted keeping in mind that the electricity used to power these batteries needs to be generated from renewable sources or fossil fuel sources with carbon capture for these systems to be having low lifecycle GHG emissions.

Fuel Cell Technology

A fuel cell (FC) consists of a fuel and gas processing system and a stack of fuel cells which convert chemical energy of the fuel to electric power through electrochemical reactions (Tronstad et al, 2017). Like batteries, fuel cells consist of anode, cathode and an electrolyte plus a fuel supply system at the cathode and the anode. The fuel commonly used is hydrogen and oxygen (via materials rich in hydrogen and oxygen carriage).

Different types of fuel cells can be used in practice. Detailed description of these is provided by Tronstad et al., (2017). The present paper lists the top 3 types of fuel cells with the greatest potential for maritime applications as below. Further details can be obtained from the reference as quoted above.

1. Proton Exchange Membrane Cell (PEM FC)
2. High Temperature PEM (HT-PEM)
3. Solid Oxide Fuel Cell (SO FC)

This technology is still in its early days and it may take time for it to mature so as to be used for maritime transport of international seagoing cargo. It may also be noted that recently IMO (IMO, 2022) has developed interim guidelines for safety of ships with fuel cell technology.

Onboard Carbon Capture and Storage

Onboard carbon capture post combustion from ships is also being explored as a potential option to prevent CO_2 release either completely or partially (Van deAkker, 2017; Luo & Wang, 2017; Ros et al, 2020; Al Baroudi et al, 2021; Zhou & Wang, 2014; Haggquist, 2020; Malmgren et al, 2021). This is envisaged preliminarily for LNG Carriers. The process to extract CO_2 from the waste gases as well as the subsequent liquefaction and storage of CO_2 onboard may involve additional costs (also due to sacrifice of possible cargo space, installation of CO_2 handling systems and sailing with the additional CO_2 as a burden).

However, the CO_2 obtained from such storage could have purity of as much as 90% and be disposed off at onshore facilities (provided reception facilities are available). There it may be recycled for production of syngas or other applications. The main advantage of this system is that it would avoid change of the conventional marine engines or fuels onboard. The main limitations for existing ships to use this system would be the following:

1. Installation of technology to capture the CO_2 from the exhaust – Whether this can be accommodated within the engine rooms of ships in service.
2. Availability of power to operate the additional technology to capture CO_2 from the flue gases
3. Availability of space to store the CO_2 until it can be safely discharged to a reception facility at a port or offshore.

Nuclear Powered Ships

Nuclear Powered Marine Vehicles have been in operation in the world in form of Naval Ships or Submarines. Some Icebreakers operating in the Polar regions also use nuclear power. Hence the marine industry is not new to the use of power generated from nuclear fuel. The use of nuclear power onboard merchant ships may offer wide possibilities in the form of very less frequency of bunkering, lower fuel storage capacity (hence increased deadweight). The implications of reactor failure, consequences due to accidents (fire, collision, grounding, structural failure etc.) however would need more detailed study. The crew would also need advanced training for

The process to extract CO2 from the waste gases as well as the subsequent liquefaction and storage of CO2 onboard may involve additional costs (also due to sacrifice of possible cargo space, installation of CO2 handling systems and sailing with the additional CO2 as a burden)

safety related aspects. Security related aspects would also need consideration. Having said the above, nuclear powered ships are however being considered as potential options (e.g. please refer Ovcina, 2022) and the present paper hence attempts to bring this to light of the readers.

Comparison of Fuel Candidates – Onboard Storage Capacity

The Alternative fuel candidates have different energy contents and different densities. Hence they would require storage capacities which exceed the present capacities (if the frequency of bunkering was to be kept unchanged). **Figure 1** provides an estimate of the increase in storage capacities relative to HFO for various alternative fuels.

It can be observed that use of all alternative fuels would necessitate comparatively higher storage capacity when compared to HFO. The increase in capacity required is significantly high when hydrogen fuel is considered. Even for Ammonia and Methanol, the storage capacity would have to be more than doubled for existing ships. For biodiesels in form of FAME and HVO the increase in capacity required is nearly 20-30%.

Comparison of Fuel Candidates – Cost of Energy

The cost of Alternative Fuels would be another important consideration for the maritime industry. **Figure. 2** presents the costs per tonne of each alternative fuel (as if it were to be used 'neat'). The prices were as of 1 April 2022 and obtained from various commodities and marine fuel websites. **Figure 2** also juxtaposes the fuel cost in terms of energy capacity per unit volume (considering that Alternative fuels have different densities and energy contents).

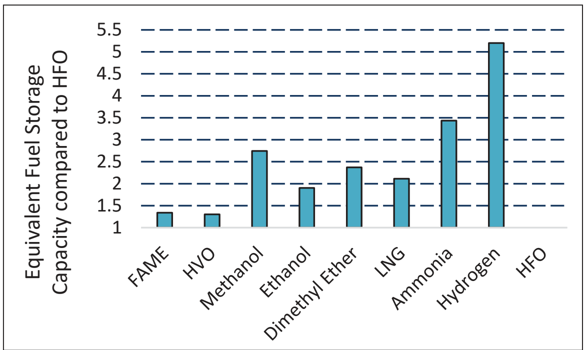

Figure 1: Equivalent Capacities of Storage required for Alternative Fuels when compared with HFO

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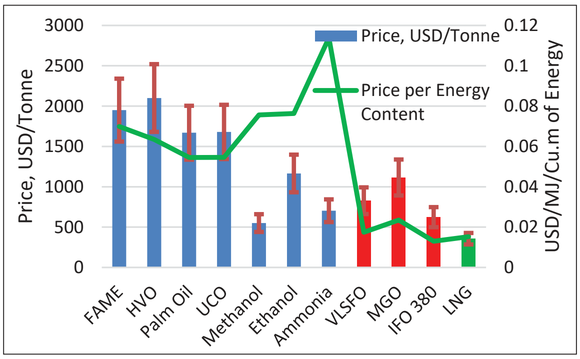

Figure 2: Comparison of the Costs of Alternative Fuel Candidates as compared with conventional marine fuels

It can be observed from **Figure 2** that the conventional marine fuels are priced economically in terms of the cost as well as the energy content of the fuels. Methanol and LNG fuels appear to be competitive as compared to the conventional fuels. Biodiesels are expensive to be used onboard as the prices are very high as compared to the conventional marine fuels.

Comparison of Fuel Candidates – CO_2 Equivalent Emissions

The equivalent CO_2 emissions resulting from use of Alternative Fuels are presented in **Figure 3**. The Well-Wake approach has been used for evaluating the emissions (which are obtained from various references, hence a range of values is provided).

It can be observed that there is a wide range of CO_2 emissions when considered for any given fuel. Thus, the effect of the production pathway is clearly visible. **Figure 3** also depicts that the Ammonia and Hydrogen Fuels may also lead to more emissions than conventional marine fuels if the pathway for their production is not appropriate. Hence **Figure 3** brings out the importance of considering the Well-Wake approach and the life cycle of these fuels. Interestingly, **Figure 3** also brings out that not all fuels of biological origin may be suitable to reduce the CO_2 equivalent emissions. For example, fuels obtained from Forestry Products processing and Bio-Ethanol may lead to more emissions.

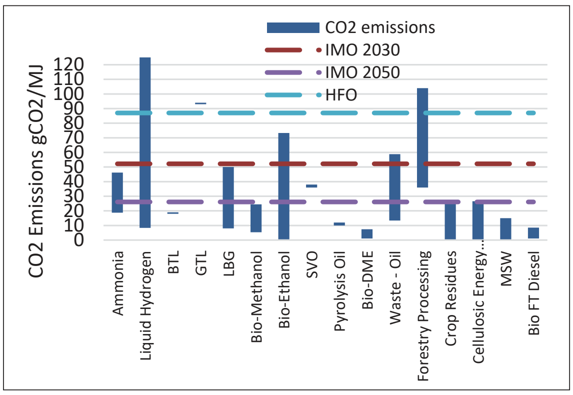

Figure 3: CO_2 equivalent emissions using different fuels (including biofuels and biodiesels)

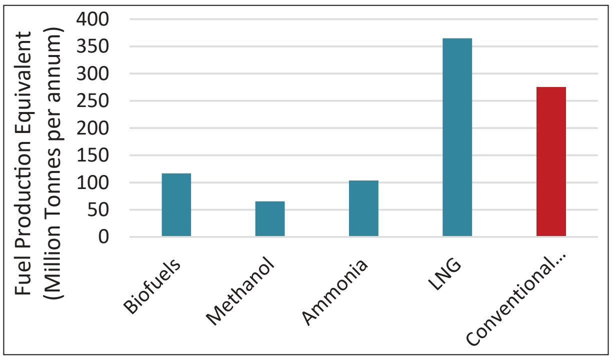

Figure 4: Global Production Capacities of Alternative Fuels as compared to Conventional Marine Fuels

Comparison of Fuel Candidates – Global Production

It is also important to understand the global availability of the various fuels so as to conclude whether there can be a preferred fuel candidate for the Marine Industry to consider. **Figure 4** presents the total annual production capacities globally of the various alternative fuel candidates as of April 2022. Conventional Marine Fuels are also presented in the plot for easy comparison. The comparison provides the ordinate in terms of equivalent HFO (tonnes) recognising that the energy contents and densities of each fuel are different and that it may not be logical to directly compare the masses of the fuel versus one another.

It can be observed that neither of the alternative fuel candidates have the production capacities to as to support replacement of the conventional marine fuels individually. LNG production even though greater than the conventional marine fuel production; it should be remembered that this would be shared by the land based industries also. Likewise, biofuels and methanol would be in demand from the land-based industries as well. Hence, it is not so trivial to replace the conventional marine fuels; this would require time.

All References shall be provided in the last part of the series. [This paper was presented at INMARCO (November, 2022)

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IME (I) GOVERNING COUNCIL, BRANCH AND CHAPTER COMMITTEE ELECTIONS 2023-25

- Election process of The Institute of Marine Engineers (India) for the term 2023-25 is now underway and receipt of nominations for the positions of Office Bearers for the Governing Council, Branch & Chapter Committees was closed on 15th June 2023.
- Thereafter, the Election Officer along with the Members of the Election Committee scrutinised the validity of the nominations received. On scrutiny of nominations, and further considering the nominations withdrawn by 30th June 2023, it has emerged that there will be an election only for the position of Vice-President and all other positions for GC, Branches and Chapters will be elected uncontested.
- The Ballot paper on the election of the Vice-President will be sent to all eligible Corporate Members and the election will be through only e-Voting from 15 July 2023 until 1700 hrs on 31 August 2023.
- Eligible Corporate Members will receive an email, with Member's ID and Password, to enable them to vote online. An eligible Member may contact the undersigned, if he or she does not receive the email by 15 July 2023.
- Counting of e-votes on the said election will take place at 1000 hrs on 02 September 2023 at IME(I), House, Nerul, Navi Mumbai and the election result will be published in the MER. Members who wish to be present at the time of counting of the votes should inform the Election Officer before 23rd of August 2023.

Members needing any clarification(s), may kindly contact the Election Officer by email.

Election Officer
The Institute of Marine Engineers (India)
IME (I) House
Plot No. 94, Sector 19,
Nerul (East), Navi Mumbai – 400 706
(electionofficer@imare.in)

TECHNICAL NOTES

LUBE MATTERS # 24

TRIBOLOGY OF MARINE DIESEL ENGINE COMPONENTS I (BEARINGS)

Sanjiv Wazir

Introduction

Diesel engines propel and power over 90% of ocean-going and coastal vessels. In general, slow speed (< 150 rpm) two-stroke diesel engines are used to drive the propellers and medium speed (350 – 1200 rpm) four-stroke engines are used for electric power generation. Tribology plays an important role in the operation and reliability of major engine components such as bearings, pistons, liners, fuel pumps, etc.

Engine Bearings

Bearings support the moving parts of the engine in its housing. Due to the high loads generated during combustion strokes and the heavy reciprocating and rotating masses of pistons, connecting rods, counterweights, etc, sliding element bearings are used.

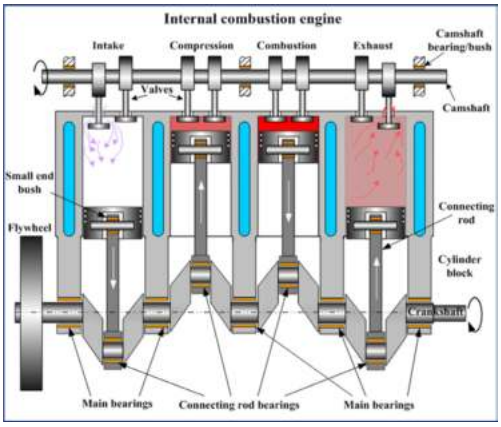

Figure. 1: Schematic of Internal combustion engine (1)

The main sliding bearings used in engines are main bearing, connecting rod bearing, small end bush, and camshaft bearing. Based on the operating conditions, these bearings work under different lubrication regimes. At start-up, boundary lubrication prevails. When speeds increase, the lubrication regime transitions to mixed film lubrication, and eventually to hydrodynamic lubrication. At shutdown, this sequence is reversed.

Bearing materials need to have a wide range of properties including compressive strength, fatigue strength, wear resistance, compatibility, corrosion resistance, conformability, embeddability. Bearings may be mono-metal, bi-metal, or tri-metal.

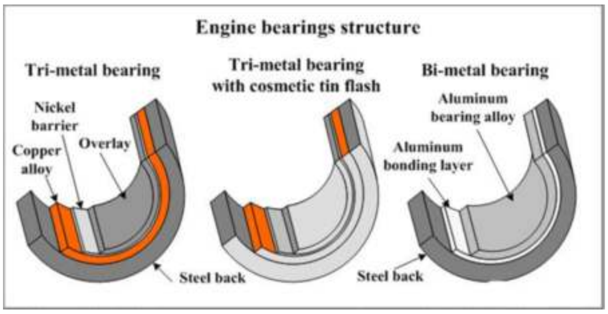

Figure. 2: Typical multi-layer engine bearing structure (1)

These bearings are susceptible to wear in conditions of low oil film thickness (adhesive wear), dirty oil (abrasive wear) and high oil pressure (fatigue wear). Insufficient lubrication is the most common cause of loss of bearing life. In a journal-bearing system loss of lubrication will lead to bearing seizure, destruction of the components and much collateral damage. Lubrication can be influenced by poor/incorrect machining in the manufacture of the pin and the bearing leading to metal-metal contact between them.

Crosshead Bearing

Long-stroke, low speed, two-stroke crosshead diesel engines are the predominant prime movers for ships. They

> *Bearing materials need to have a wide range of properties including compressive strength, fatigue strength, wear resistance, compatibility, corrosion resistance, conformability, embeddability.*

offer high power, good combustion efficiency (low SFOC), long service life, capability to burn poor quality residual fuels, and high propeller efficiency. These engines are also fitted with Crosshead bearings.

The main function of the crosshead bearing is to transmit the load from the piston to the connecting rod. Apart from this, it enables the large horizontal forces to be transmitted to the guide shoes from which it is subsequently transmitted through the rails to the housing. In a trunk piston engine such horizontal forces are usually borne by the piston skirt and transmitted through the liner. The separation of piston from connecting rod also enables fitment of a diaphragm between the combustion space and the crankcase. Thus, special cylinder oils can be used to lubricate the combustion space components and system oils can be used to lubricate the crankcase bearings.

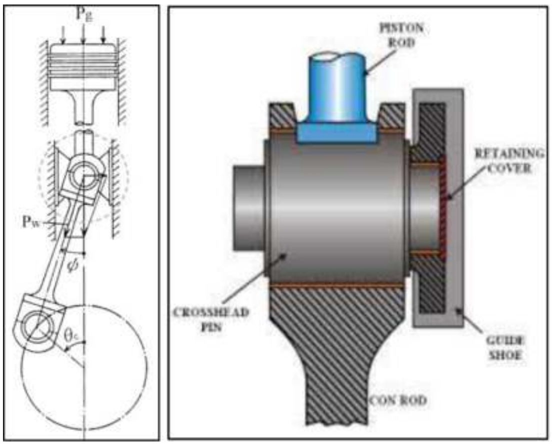

Figure. 3: Crosshead Schematic and Assembly (2)

The crosshead-pin oscillates in the bearing, within a small angle, at low speeds, and is always subject to a very high downward-load. There are several axial grooves on the loaded surface of the bearing to facilitate oil exchange during the oscillation. These grooves may further reduce load carrying area and impact film formation. The bearing is therefore likely to experience high friction and wear due to the difficulty in generating a good hydrodynamic lubrication film. Some crosshead bearing designs therefore promote the formation of hydrostatic squeeze lubricating film by supplying high pressure lubricating oil during a part of the load cycle. Other design measures are also incorporated to maximise hydrodynamic film and squeeze film formation.

Bearing Design

Since the size of most bearings in marine applications are large, it is difficult to carry out experimental studies. In recent years most research to investigate the lubrication characteristics of marine bearings has been carried out by analytical simulation studies based on hydrodynamic, elasto-hydrodynamic lubrication (EHL) and nonlinear multi-body dynamics (MBD) theories. This has led to better understanding of the prevailing tribo-system and led to improved designs, as described below.

Main Bearing Geometry Change (2)

It had been noted that in certain positions during the operating cycle, main bearing journal inclination was becoming excessive causing damage to the shell, starting primarily from the edges.

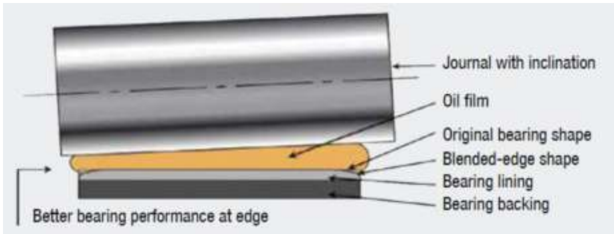

Figure. 4: Principle of BE main bearing (2)

Elasto-hydrodynamic bearing calculations showed possibility of increasing the oil film thickness on the bearing edge by changing its geometry. This resulted in development of the blended edge (BE) bearing design from MAN.

Some journals were also exhibiting wear down to an "hourglass" shape. Often, this would result in fatigue failure of the bearing starting from the edges.

Figure. 5: Main bearing failure due to concavity of pin (2)

Replacement of straight edge bearing with BE bearing helped resolve this issue too.

Crosshead Bearing Design Change (2)

Analysis of the crosshead system using elasto-hydrodynamic lubrication principles and validating experimental results have shown:

> *Some crosshead bearing designs therefore promote the formation of hydrostatic squeeze lubricating film by supplying high pressure lubricating oil during a part of the load cycle*

Influence of Clearance Ratio:

A decrease in radial clearance ratio improves the squeeze action on the entire bearing pad, thereby decreasing the maximum oil pressure and increasing the load carrying capacity.

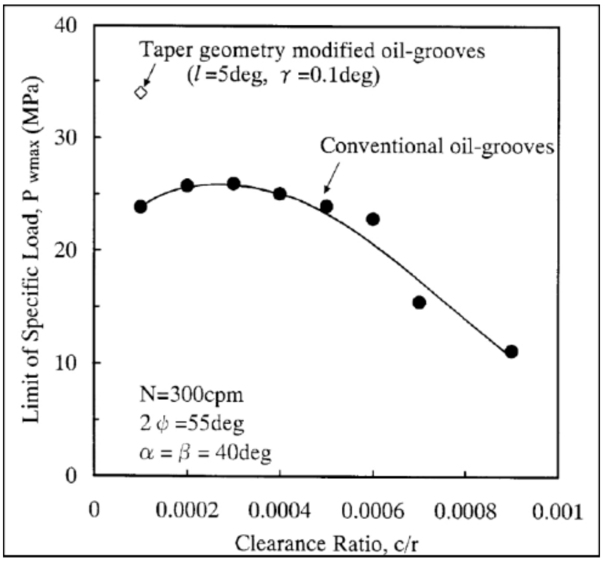

Figure. 6 Influence of clearance ratio on wear resistance for a conventional bearing

However, when the clearance ratio becomes too low, the capacity to form sufficiently thick oil film is lost, resulting in decrease in load carrying capacity (**fig 6**).

Influence of Oil-Groove Taper Geometry:

Even with low clearance ratio, a larger taper angle of the oil groove improves hydrodynamic wedge action, thereby increasing oil film formation, and load carrying ability. However, if the taper angle becomes too large, wedge action is reduced thereby reducing oil film thickness, and load carrying ability.

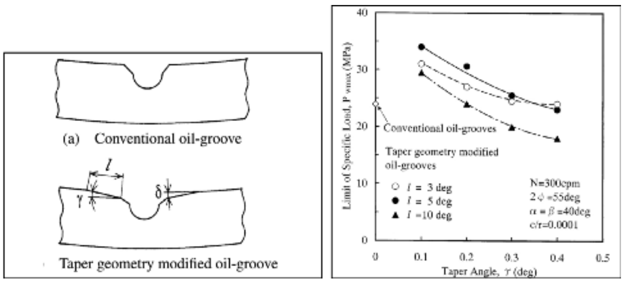

Figure. 7: Influence of taper geometry on load carrying (2)

Optimising taper geometry of oil grooves promotes formation of thick oil film without significant increase in oil film pressure, resulting in higher load carrying capacity compared with conventional geometry.

Influence of centre-pad length:

In the case on conventional bearing, since the oil exchange is dependent upon the oscillation motion, the centre pad length cannot exceed the oscillation angle. In the case of taper geometry modified bearings, formation of thicker oil film enhances oil exchange, hence centre-pad can be made larger than the oscillation angle, increasing the load carrying capacity.

Many of these understandings have been incorporated in the MAN wide-pad crosshead bearing design.

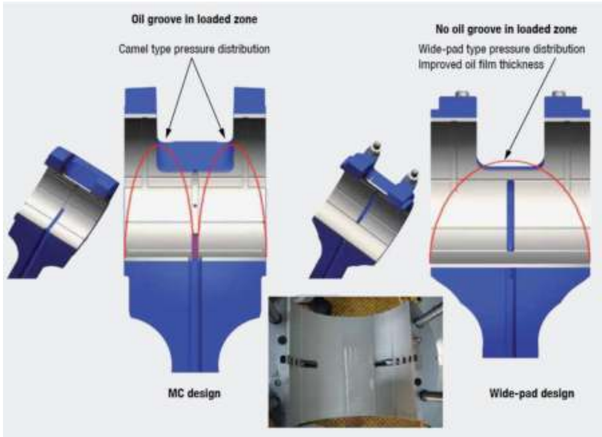

Figure. 8: MAN Crosshead bearing designs MC & Wide-pad (3).

The wide-pad design has an uninterrupted centre-pad in the lower bearing shell. The oil grooves in the centre pad have been omitted. The distance between axial grooves has also been widened.

Adhesive Wear Incident Investigation

An analytical investigation of an adhesive failure of a marine two stroke engine, was carried out assuming hydrodynamic lubrication with three lubricant temperatures of 40°C, 50°C, 60°C and three bearing clearances of 240µm, 200µm, 160µm.

It concluded that:

- the maximum film pressure decreased with decreasing clearance and lubricant temperature,
- the film thickness increased with decreasing clearance and lubricant temperature,
- the lubricant temperature had a higher effect on the film thickness than the clearance

Other wear mechanisms in engine bearings

Fretting/Corrosion in Main Bearing

"Fretting-corrosion has been observed between main bearing shells and main bearing caps in MAN 4-Stroke engines without main bearing temperature sensors"

Fretting-corrosion has been observed between main bearing shells and main bearing caps in MAN 4-Stroke engines without main bearing temperature sensors. Fretting is caused by relative motion between shell and cap during engine operation. Oil and water can enter the space between the shell and cap though the sensor hole and cause corrosion on the bearing surface.

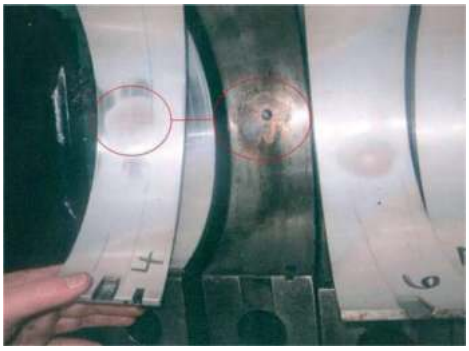

Figure. 9: Fretting/corrosion and related imprint on shell

The extent of damage is related to the water content in the oil and hence this should be kept as low as possible.

Abrasion Causing Formation of Ridge on 4-S Crankpin

Abrasive contaminants in the oil have been known to cause wear down of crank pin on both sides of the centre of the pin.

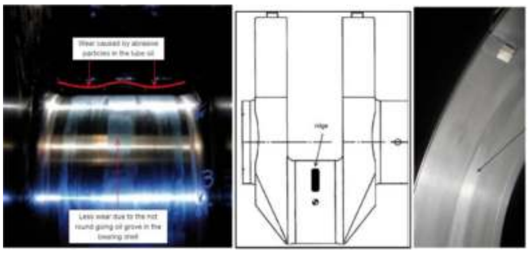

Figure. 10: Ridge formation caused by abrasion by particulate contaminants in oil

Since oil groove does not go all the way around, some area of the pin of does not experience wear.

Eventually a ridge is formed in the central area, in the highest loaded zone 15^0 to 60^0 after BDC, which causes wear of the shell.

Fatigue

In sliding contact bearings, during hydrodynamic or electrohydrodynamic lubrication, metal-to-metal contact is absent and hence adhesive wear eliminated. However, fatigue may be initiated by the peak oil pressure, the rate of increase/decrease of the pressure with time, and the number of cycles of such loading. Repeated high stress due to the peak oil pressure may initiate cracks on the surface. Oil entering the crack and getting trapped within may induce high pressure during opening and closing of the crack, and enabling crack to propagate further inside, reaching the interface between the bearing lining and steel backing in bimetal bearings or between the overlay and lining in trimetal bearings.

Figure. 11: Flaking of bearing metal following fatigue induced cracks.

Under continued usage, the cracks run parallel to the lining surface or steel surface, eventually cracks link up and lining in the affected area starts flaking off, exposing the bearing backing.

Many other types of failures may also be encountered in bearings, such as,

- Abrasion by foreign matter or dirt
- Babbitt bond failure
- Brinelling and fretting wear in bearing pads and shells
- Corrosion by acidified/oxidised lubricant
- Damage by electrical shaft currents
- Distorted connecting rod
- Imperfect Journal geometry
- Incorrect assembly
- Overload leading to Babbitt wiping
- Porosity and blisters in babbitt material
- Shaft misalignment
- Spinning of bearing shell in housing
- Thermal creep of babbitt material

Conclusion

Theoretically hydrodynamic bearings have an infinite life. The practical world begs to differ. Engine bearings are an important component for combustion engines. Due to the complex requirements and high loads, despite advances in materials, design, and manufacturing, tribology continues to play a critical role in engine bearing performance and life.

About the author

Sanjiv Wazir is a Certified Lubrication Specialist (CLS) from the Society of Tribologists & Lubrication Engineers (STLE), USA. He is a mechanical engineer from IIT-Bombay. He is a marine engineer and a consultant on marine lubrication. He has contributed to MER on marine lubrication developments in the past. He has written a series of articles on tribology & lubrication issues under "Lube Matters".

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COMPETENCY CORNER

Troubleshooting Marine Electrical Equipment: International Standards (Part 4)

Elstan A. Fernandez

51 – AC Inverse Time Overcurrent Relay

A relay that functions when the ac input current exceeds a predetermined value, and in which the input current and operating time are inversely related through a substantial portion of the performance range.

52 – AC Circuit Breaker or Moulded Case Circuit Breaker

A device that is used to close and interrupt an ac power circuit under normal conditions or to interrupt this circuit under fault or emergency conditions.

52a – AC Circuit Breaker Position (contact open when the breaker is open)

52b – AC Circuit Breaker Position (contact closed when the breaker is open)

53 – Exciter or Dc Generator Relay

A relay that forces the dc machine field excitation to build up during starting or that functions when the machine voltage has built up to a given value.

54 – Turning Gear Engaging Device

An electrically operated, controlled, or monitored device that functions to cause the turning gear to engage (or disengage) the machine shaft.

55 – Power Factor Relay

A relay that operates when the power factor in an ac circuit rises above or falls below a predetermined value.

56 – Field Application Relay

A relay that automatically controls the application of the field excitation to an ac motor at some predetermined point in the slip cycle.

57 – Short-Circuiting or Grounding Device

A primary circuit switching device that functions to short-circuit or ground a circuit in response to automatic or manual means.

58 – Rectification Failure Relay

A device that functions if a power rectifier fails to conduct or block properly.

59 – Overvoltage Relay

A relay that operates when its input voltage is more than a predetermined value.

60 – Voltage or Current Balance Relay

A relay that operates on a given difference in voltage, or current input or output, of two circuits.

61 – Density Switch or Sensor

A device that operates on a given value, or a given rate of change, of gas density.

62 – Time-Delay Stopping or Opening Relay

A time-delay relay that serves in conjunction with the device that initiates the shutdown, stopping, or opening operation in an automatic sequence or protective relay system.

63 – Pressure Switch

A switch that operates on given values, or on a given rate of change, of pressure.

64 – Ground Detector Relay

A relay that operates upon failure of a machine or other apparatus insulation with respect to the earth.

Note: *This function is not applied to a device connected in the secondary circuit of current transformers in a normally grounded power system, where other device numbers with the suffix G or N should be used; that is, 51N for an ac-time overcurrent relay connected in the secondary neutral of the current transformers.*

65 – Governor

The assembly of fluid, electrical, or mechanical control equipment used for regulating the flow of water, steam, or other media to the prime mover for such purposes as starting, holding speed or load, or stopping.

66 – Notching or Jogging Device

A device that functions to allow only a specified number of operations of a given device or equipment, or a specified number of successive operations within a given time of each other. It is also a device that functions to energize a circuit periodically or for fractions of specified time intervals, or that is used to permit intermittent acceleration or jogging of a machine at low speeds for mechanical positioning.

67 – AC Directional Overcurrent Relay

A relay that functions on a desired value of ac overcurrent flowing in a predetermined direction.

68 – Blocking Relay

A relay that initiates a pilot signal for blocking of tripping on external faults in a transmission line or in other apparatus under predetermined conditions, or that cooperates with other devices to block tripping or to block reclosing on an out-of-step condition or on power swings.

69 – Permissive Control Device

Generally, a two-position device that in one position permits the closing of a circuit breaker, or the placing of an equipment into operation, and in the other position prevents the circuit breaker or the equipment from being operated.

70 – Rheostat

A variable resistance device used in an electric circuit when the device is electrically operated or has other electrical accessories, such as auxiliary, position, or limit switches.

71 – Liquid Level Switch

A switch that operates on given values, or on a given rate of change, of level.

72 – DC Circuit Breaker

A circuit breaker that is used to close and interrupt a dc power circuit under normal conditions or to interrupt this circuit under fault or emergency conditions.

73 – Load-Resistor Contactor

A contactor that is used to shunt or insert a step of load limiting, shifting, or indicating resistance in a power circuit; to switch a space heater in circuit; or to switch a light or regenerative load resistor of a power rectifier or other machine in and out of circuit.

74 – Alarm Relay

A relay other than an annunciator, as covered under device function 30, that is used to operate, or that operates in connection with, a visual or audible alarm.

75 – Position Changing Mechanism

A mechanism that is used for moving a main device from one position to another in equipment; for example, shifting a removable circuit breaker unit to and from the connected, disconnected, and test positions.

76 – DC Overcurrent Relay

A relay that functions when the current in a dc circuit exceeds a given value.

77 – Telemetering Device

A transmitter used to generate and transmit to a remote location an electrical signal representing a measured quantity, or a receiver used to receive the electrical signal from a remote transmitter and convert the signal to represent the original measured quantity

78 – Phase-Angle Measuring or Out-of-Step Protective Relay

A relay that functions at a predetermined phase angle between two voltages, between two currents, or between voltage and current.

79 – AC Re-Closing Relay (Auto Reclosing)

A relay that controls the automatic reclosing and locking out of an ac circuit interrupter.

80 – Flow Switch

A switch that operates on given values, or on a given rate of change, of flow.

81 – Frequency Relay

A relay that responds to the frequency of an electrical quantity, operating when the frequency or rate of change of frequency exceeds or is less than a predetermined value.

82 – DC Load-Measuring Re-closing Relay

A relay that controls the automatic closing and reclosing of a dc circuit interrupter, generally in response to load circuit conditions.

83 – Automatic Selective Control or Transfer Relay

A relay that operates to select automatically between certain sources or conditions in equipment or that performs a transfer operation automatically.

84 – Operating Mechanism

The complete electrical mechanism or servo mechanism, including the operating motor, solenoids, position switches, etc., for a tap changer, induction regulator, or any similar piece of apparatus that otherwise has no device function number.

85 – Communications, Carrier, or Pilot-Wire Receiver Relay

A relay that is operated or restrained by a signal used in connection with carrier current or dc pilot-wire fault relaying.

86 – Lockout Relay / Master Trip

A hand or electrically reset auxiliary relay that is operated upon the occurrence of abnormal conditions to maintain associated equipment or devices inoperative until it is reset.

87 – Differential Protective Relay

A protective relay that functions on a percentage, phase angle, or other quantitative difference between two currents or some other electrical quantities.

88 – Auxiliary Motor or Motor Generator

A device used for operating auxiliary equipment, such as pumps, blowers, exciters, rotating magnetic amplifiers, etc.

89 – Line Switch

A switch used as a disconnecting, load-interrupter, or isolating switch in an ac or dc power circuit. (This device function number is normally not necessary unless the switch is electrically operated or has electrical accessories, such as an auxiliary switch, a magnetic lock, etc.)

89 - Also a Fuse Switch-Isolator

It is largely used as a reliable isolation switching and fuse circuit protection device in low voltage switchgears for distribution of power and isolation of loads during maintenance.

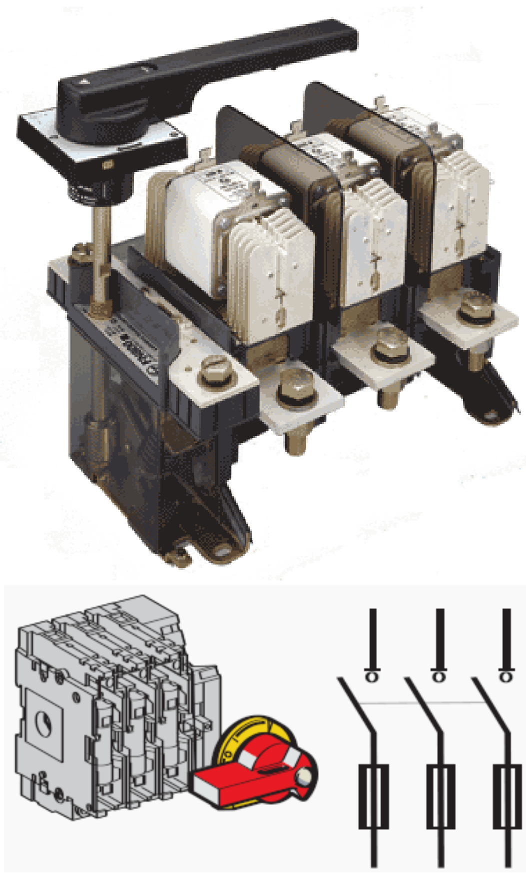

Figure 1 – Fuse Switch Isolator

90 – Regulating Device

A device that functions to regulate a quantity or quantities, such as voltage, current, power, speed, frequency, temperature, and load, at a certain value or between certain (generally close) limits for machines, tie lines, or other apparatus.

91 – Voltage Directional Relay

A relay that operates when the voltage across an open circuit breaker or contactor exceeds a given value in a given direction.

92 – Voltage and Power Directional Relay

A relay that permits or causes the connection of two circuits when the voltage difference between them exceeds a given value in a predetermined direction and causes these two circuits to be disconnected from each other when the power flowing between them exceeds a given value in the opposite direction.

93 – Field-Changing Contactor

A contactor that functions to increase or decrease, in one step, the value of field excitation on a machine.

94 – Tripping or Trip-Free Relay

A relay that functions to trip a circuit breaker, contactor, or equipment; to permit immediate tripping by other devices; or to prevent immediate reclosing of a circuit interrupter if it should open automatically, even though its closing circuit is maintained closed.

95 – For specific applications where other numbers are not suitable

96 – Busbar Trip Lockout Relay

97 – For specific applications where other numbers are not suitable

98 – For specific applications where other numbers are not suitable

99 – For specific applications where other numbers are not suitable

About the author

Elstan A. Fernandez has 43 years of experience in the Maritime and Energy Indutries; Author / Co-author of 80 Books; Chartered Eng., FIE, MIET (UK), MLE℠ Harvard Square (USA); Joint Inventor with a Patent for Supervised BNWAS; Promising Indian of the Year in 2017; LinkedIn Profile: https://www.linkedin.com/in/elstan/

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Do mention your name, email, membership grade and number (if Member of IMEI) with your mails.

Fuelling the Inland Waterways

Natural Gas either in compressed or in liquefied form is definitely an acceptable fuel for inland water navigation in India (MER Paper May 2023). Many marine diesel engines of ocean going vessels now are running on Gaseous Fuel.

However, unlike use of CNG in cars, trucks and buses in India, Marine fuel could pose the following technical challenges that the Government need to be address as appropriate before introducing the fuel.

1. **Storage of Methane on board** – Need to conclude if the fuel is to be stored in Liquefied form or in compressed gaseous form as it impacts the quantity that needs to be stored.

   If stored in Liquefied form, additional challenge for cryogenic storage, protected fuel piping (refer IGF code) and appropriate safety, dealing with boil off gases etc. would have to be addressed.

   Compressed gaseous form would require modification to include appropriate sized pressure vessel together with necessary piping and safety systems.

2. **Operating Personnel** – Especially the engineers would have to qualified to IGF code. This may pose a challenge as the inland transport is currently manned by NCV or Coastal certified personnel. Does the country have sufficient number of suitably qualified persons or would the Government agree for exemptions?

3. **Bunkering of vessels** – It is felt to be the biggest challenge for this option. Unlike land-based vehicles that can be driven to the filling stations, it is difficult to manoeuvre larger inland vessels to bunkering points. The paper does state that bunker facility is now available at PLL terminal in Kochi, which means that the inland vessel needs to be manoeuvred to that point and in my opinion, it could incur serious delays in vessel operation.

   Hence appropriate bunker vessels or conveniently placed bunker stations need to be made available on the channel at both ends – start and end of passage.

   If it is a bunker vessel additional challenges in construction, storage and safety during custody transfer need to be incorporated.

   If the proposal is to have bunkering stations, facility for berthing and mooring these vessels and safety during custody transfer need to be made available including provision for multiple stations on the intended passage.

   Presently for conventional diesel-powered vessels where appropriate/adequate bunkering facilities are not available, fuel is often received and stored on board in drums on deck and is transferred by a portable pump to service tanks. With methane as fuel this is not possible due to safety concerns.

4. **Conversion of existing vessels** to burn Methane or operate in dual fuel mode too needs to be addressed.

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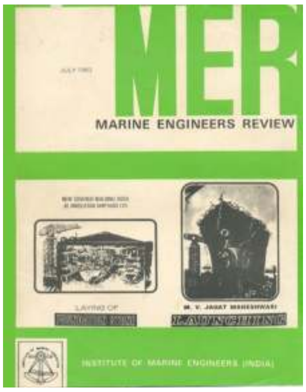
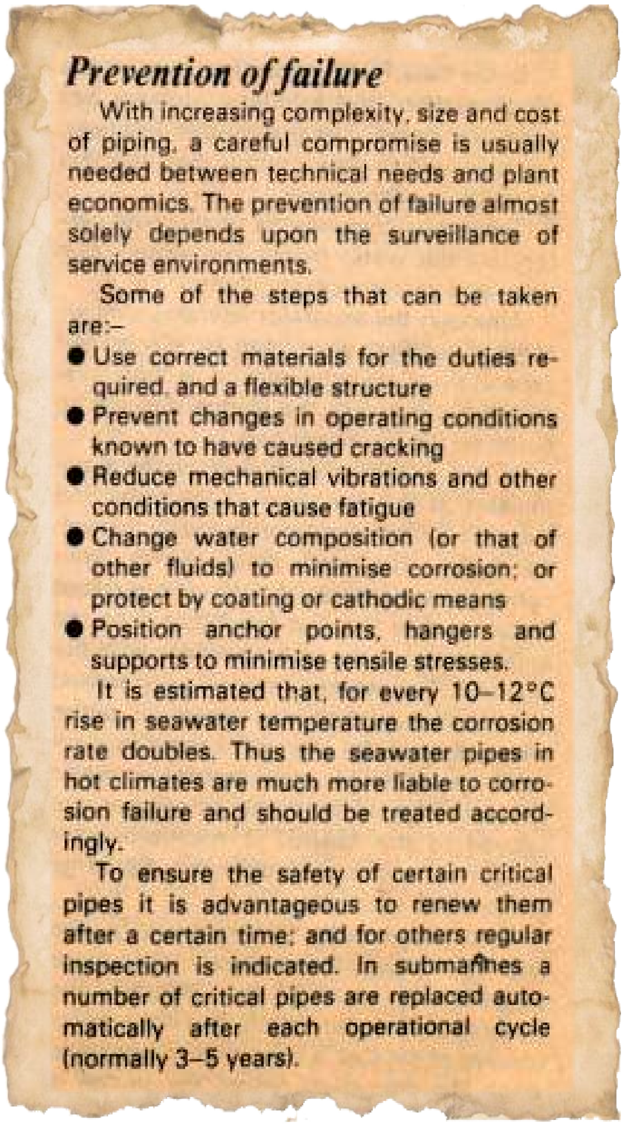


Four decades back… The July 1983 Issue

The issue starts with a concern on the prevailing recession.

It moves on to an interesting article on PVC coating of pipelines. There merits of galvanised steel, coated steel and use of non-ferrous alloys. The next article is on service failures of pumps. This will get the attention of the practicing marine engineers. An extract is inserted.



Prevention of failure

With increasing complexity, size and cost of piping, a careful compromise is usually needed between technical needs and plant economics. The prevention of failure almost solely depends upon the surveillance of service environments.

Some of the steps that can be taken are:–

- Use correct materials for the duties required, and a flexible structure
- Prevent changes in operating conditions known to have caused cracking
- Reduce mechanical vibrations and other conditions that cause fatigue
- Change water composition (or that of other fluids) to minimise corrosion; or protect by coating or cathodic means
- Position anchor points, hangers and supports to minimise tensile stresses.

It is estimated that, for every 10–12°C rise in seawater temperature the corrosion rate doubles. Thus the seawater pipes in hot climates are much more liable to corrosion failure and should be treated accordingly.

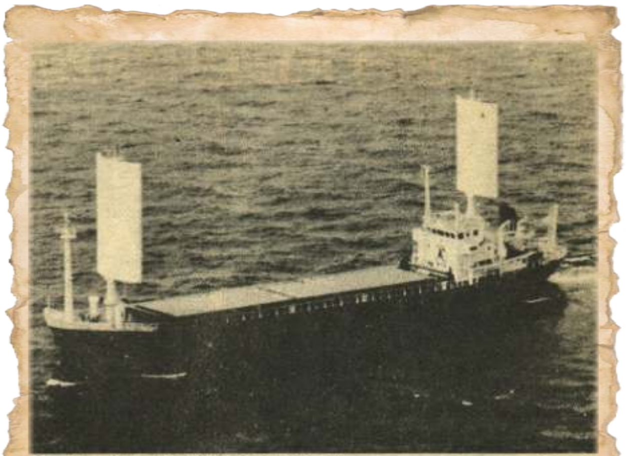
To ensure the safety of certain critical pipes it is advantageous to renew them after a certain time; and for others regular inspection is indicated. In submarines a number of critical pipes are replaced automatically after each operational cycle (normally 3–5 years).

And then there in one article on arrival of separators, which can purify oils of density 1010 kg/m^3 followed by a write-up on engaging merchant ships during wartime for various support purposes.

The Postbag has a very interesting letter on turbo-driven dynamo and electric lighting luxury for first class passengers.

On news-item describes commercial sail vessels being put into service by Japan. The sails are made up of steel frames and polycoated canvasses. A microcomputer controls the pitch of the propeller. In the present day, such ideas are being revisited. Had someone sailed on these, it would be *deja vu* moment.

(I tried to find out the status of this ship or any other which might have come out of the Japanese yards, but could find no trail. It would be a good discussion if someone can throw more light on such vessels, which were imagined then.)



Senyo Maru will be used mainly to carry steel products.

Going further, the Business news section carries the news of falling ship building orders reflecting the recessionary trends and another item advises on the importance of boiler water testing and how a new video by Videotel highlights its importance.

POSTBAG

Halon fire extinguishers

Sir,
I read with interest Dr Taylor's recent IMarE paper 'Problems of fire control onboard ships' and specifically his remarks concerning Halons. I am not a chemist but I understand there is a marked difference in toxicity between 1211 and 1301 in the latter's favour. A recent paper at a safety seminar in the USA indicated the possibility of using Halon 1301 in passenger aircraft for total flooding.

Halon 1301 portable units and a range of small automatics, activated by smoke sensors and covering spaces from 75 to 1000 ft^3, are available and I believe both must have a marine application. Halon 1301 is three times as effective as CO_2 and can be discharged without personnel evacuation (even if it is wise to get out as soon as possible). A 7% concentration is sufficient to extinguish fire.

Perhaps areas like paint lockers would benefit from such automatic units; so much less costly than total flooding. Similarly, portable units in the wireless room and maybe at the control panels would be useful as they can be played onto computers, telecommunications equipment and radar without any secondary damage. Emerging as a pure gas, 1301, unlike 1211, has great penetrating power, causes no corrosion and does not stain.

Although many fixed installations use Halon 1301, few portable extinguishers use this gas and I would welcome comments on why this should be.

K D P Shilleto

Internaft Ltd, London

Priority for retrofits?

Sir,
I read with interest your opening remarks in Opinion for April 1983. May I protest at your unfortunate phrasing. Neither my own company nor, I would believe, the other to which you refer, can be accused of foisting our designs upon shipowners.

During the period of increasing fuel prices my company has concentrated on providing shipowners with highly efficient engines, coupled with minimum maintenance and maximum reliability. To do this with adequate research and development has cost fantastic sums of money. Whose heart are we contenting? The Sulzer statement to which you refer merely confirmed that we felt we must react to market pressures, not just those of competition.

Upgrading packages are clearly worthwhile and we have made a number available. However, the majority of the great fuel savings that have been made with the new designs are associated with higher bmep and higher firing pressures, requiring much increased scantlings and therefore not suitable for retrofit. My own good wishes to Doxford in their efforts are unlikely to be exceeded by anyone but the improvements they may attain of some 5 g/bhp h SFC are not really in the same ball park as the foregoing.

To revert to my opening remarks, I would hope that it is unnecessary in a technical review to adopt abrasion to stimulate constructive debate.

David B Stables

Sulzer Bros (UK) Ltd

● *While 'foist' was perhaps an unhappy word to choose, we did want to imply that the shipowner, in order to operate competitively, has little option but to buy the latest, most fuel-efficient engine; which will make his own existing engines obsolescent. This is, of course, a perfectly legitimate way of selling engines*—Editor.

Incomplete manuals

Sir,
Mr T Carson's letter (March MER) has prompted me to describe some of my own work for PERA (the Production Engineering Research Association of Great Britain) which, among other services, prepares shipboard operating instruction manuals.

Mr Carson complains of the lack of reliable information about a main engine/cp propeller control system. In my experience, it is often the case that there are gaps and errors, no doubt unintentional, in the information supplied by the various subcontractors and the shipyard, not about the parts supplied, but at the interfaces between parts supplied or built by different companies and the shipyard.

This gap can be bridged by producing operating manuals which combine the available information into a manual drafted specifically for the ship in question. This is done usually by visiting the ship, checking systems and pipe layouts, then producing schematic diagrams which represent as accurately as possible the layout on board, together with descriptive text and operating procedures.

While a manual of this type might have solved some of Mr Carson's problems, it could in no way have overcome the problem caused by the hydraulic valve block being mounted the wrong way round. This should surely have come to light during acceptance trials.

T J Egginton

Royston, Herts.

Novel energy

Sir,
I note from Mr E F Kirton's letter (April MER) that Parsons had installed several hundred turbo-dynamo sets onboard ships by 1887. My father was a marine engineer in the Red Star Line, engaged on the N Atlantic trade in the 1890s, and frequently spoke about the turbine-driven dynamo on one of his passenger ships. This was a 10 hp machine with a bedplate about 10 ft long and, when running, was almost hidden by a cloud of steam.

In an age when many ships were still propelled by tall tandem compound reciprocators and lit by oil lamps, and when few marine engineers had even seen electric light or a turbine, this combination of two entirely new forms of energy in the one package must have jolted many a Victorian engineer out of his comfortable routine.

In passing, the electric lighting was reserved for first class passengers; the engine room staff still used their duck lamps down below.

J Guthrie

Eastbourne, Sussex

Exhaust engine

Sir,
With reference to Mr E F Kirton's letter (April MER), I wonder whether Professor Ingvar Jung's *History of the Marine Turbine* mentions the work of Messrs Corder and Locke, whose 'Breast Wheel Steam Engine' is detailed in Luke Herbert's *Encyclopaedia of Machinery* published in 1842.

The engine appears very like De Laval's single-stage turbine and there was a detailed note to the effect that 'if applied to the exhaust of a condensing engine, useful power might be gained before the steam arrived at the condenser'—exactly as practised by Messrs Harland and Wolff in the early years of this century.

The above reference to Messrs Harland and Wolff reminds me of the late C C Pounder's lecture to the Belfast Association of Engineers on 3 March 1948. He observed 'almost all the ideas which were developed in the second half of the century had been originated in the first half of the 19th'.

F S Dinnis

Cowes, Isle of Wight

ME driven pumps

Sir,
Mr Church (MER April p 25) puts the case for main engine driven pumps very well.

In his historical review, however, he does omit the well-known engine driven arrangement designed by Burmeister & Wain with the pumps, if I remember rightly, driven by gearing from the centre of the engine. These were uni-directional flow pumps suitable while manoeuvring ahead and astern.

Being of the positive displacement screw type, the pumps gave a satisfactory output at low speed (as opposed to the centrifugal pump). These pumps were built over a considerable period in the UK by Stothert & Pitt and fitted to the Kincaid-B&W engines which were designed *ab initio* to take the pump drive. The arrangement could be superior to the belt-driven method Mr Church has in mind, which seems rather cumbersome.

It was perhaps unfortunate that the cost of stainless steel and bronze (used in the water pumps) rose heavily before the oil price rise, otherwise these pumps might have been specified for a considerably longer period.

C M Hall

Newbridge, Penzance

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Under 'Engines', technical note on waste heat recovery from auxiliary engines is worth a read. The advantage projected is that the oil fired boiler need not be used at all if this system works to its efficiencies. Couple of extracts are inserted to catch your interest. The Books section carries a review of the book, *Collisions and their Causes*. A perfect 'T' collision photo (discussed in the book) is inserted for reflecting upon.

Table 1: Savings from utilising the heat of exhaust gases from two auxiliary diesel generators, compared to oil-fired-boilers.

Expressed in kg steam/h
$2 \times 6900\ (430 - 175)\ 0{\cdot}25 = (660{\cdot}8 - 60)\ \chi$
$\chi = 1464$ kg/h

Expressed in fuel/h
$2 \times 6900\ (430 - 175)\ 0{\cdot}25 = 10\,000 \times 0{\cdot}75\ \chi$
$\chi \doteq 117$ kg/h

Expressed in pounds sterling
$0{\cdot}117 \times 210 = 24{\cdot}57$/h = 590/day = 17 770/month

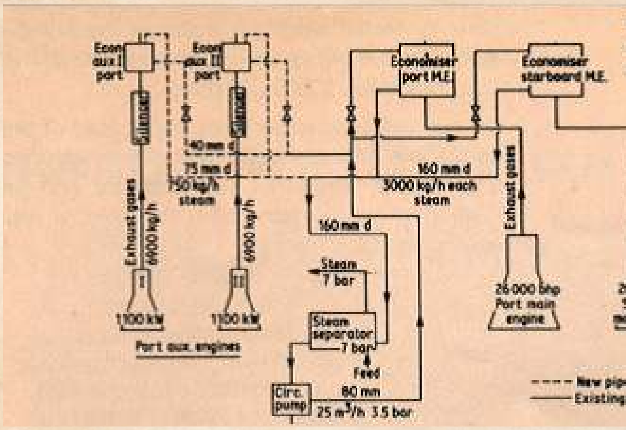


Fig 1: Waste heat recovery extended to the diesel generators.

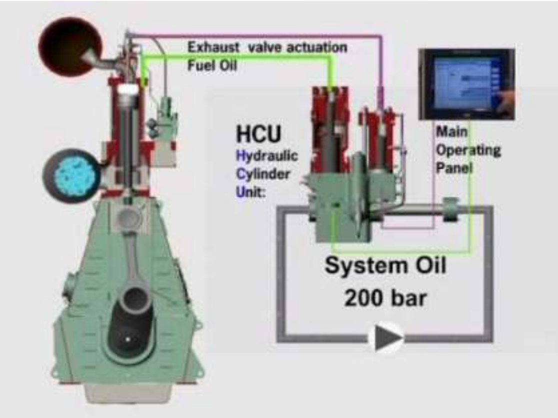
The *Transhawaii/Republica de Colombia* collision is discussed in a new book by Richard Cahill.

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.

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DATE & TIMING	:	**25th, 26th, 27th July 2023 / 29th, 30th, 31st August 2023 / 26th, 27th, 28th September / 25th, 26th, 27th October 2023 | 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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