THE POTENTIAL FOR ENERGY

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SUMMARY

However it is defined, sustainability with regard to the provision of shipboard energy, is arguably the marine industry's greatest challenge. Lloyd's Register is striving to ensure that its *Rules and Regulations*, intended to protect life and the environment, facilitate the introduction of the technologies and developments needed to help ensure that the industry can respond to this challenge. This paper outlines some of the potential options for future marine power generation, focusing on particular options for which such *Rules and Regulations* are already in place.

NOMENCLATURE

Nitrogen Oxides (NO_x) Sulphur Oxides (SO_x) Carbon dioxide (CO_2), Particulate Matter (PM), Heavy Fuel Oil (HFO), Marine Diesel Oil (MDO), International Maritime Organization (IMO), International Association of Classification Societies (IACS), Solid Oxide Fuel Cell (SOFC), Proton Exchange Membrane Fuel Cell (PEMFC).

1. INTRODUCTION

Sustainability means different things to different people. According to the Renewable Energy & Energy Efficiency Partnership [1], sustainable energy has two key components; renewable energy and energy efficiency. In the longer term, such a definition may well be appropriate. In the near term, however, with respect to the provision of shipboard energy, sustainability is really about achieving two objectives.

Harmful emissions, particularly airborne pollutants and greenhouse gases, need to be reduced. However unjustifiably [2], ships are increasingly portrayed as among the worst offenders in the struggle to combat climate change. Whether sustainable power generation will ultimately mean zero emissions remains to be seen, but in the near term, at least, the perception is that the emission of nitrogen oxides, sulphur oxides, carbon dioxide and particulate matter from the ship's power plant needs to be significantly reduced compared to current levels.

Inextricably linked to reducing emissions is the need to reduce oil fuel consumption. While the effect of pollutants and greenhouse gases on climate change remains the subject of intense debate, it is universally recognised that society's dependence on fossil fuels is unsustainable. It may be assumed that sustainable power generation will ultimately mean an end to the combustion of fossil fuels. In the near term, however, ships need to become significantly more efficient than they are at present.

This paper looks at a number of less controversial power generation technologies which have the potential to play a part in achieving the aforementioned aims. It focuses particularly on fuel cell technology, widely regarded as a panacea to the challenges of sustainable marine power generation, and, indeed, power generation generally.

The paper also looks at how Lloyd's Register plans to support the marine industry in meeting sustainability goals through the publication of timely and appropriate *Rules, Regulations* and guidance.

2. ENERGY DEMAND

2.1 EFFICIENT SHIPS

Although this paper focuses mainly on future power generation technologies likely to contribute in achieving sustainable shipping, it should not be overlooked that very significant reductions in both fuel consumption and emissions can be achieved using a range of existing technologies.

A recent study estimates that fuel consumption could be reduced by up to 30% in new ships by including a range of technical features in the design of the ship as a whole, features such as waste heat recovery, improved steering configurations, improved hull form and antifouling, for example.

Equally large reductions, of up to 30%, are estimated from a range of operational improvements, such as enhanced weather routing, optimised trim and ballasting [3].

Clearly, the adoption of such measures alone would be a massive step towards sustainable shipping.

3. ENERGY CONVERSION

3.1 GAS FUELLED ENGINES

Major engine manufacturers have been delivering engines capable of running on natural gas for some time. Switching to natural gas has several advantages compared to burning HFO or even MDO. Significant reductions in all emissions are claimed [4], including:

- 30% lower CO_2;
- 85% lower NO_x (due to high air/fuel ratio)
- no SO_x (due to sulphur removal from fuel)
- very low particulates
- no visible smoke
- no sludge deposits.

The large reductions in CO_2 compared with HFO and MDO are due quite simply to the fact that the main component of natural gas, methane (CH_4), contains significantly less carbon than HFO or MDO. Indeed, methane is the most efficient hydrocarbon when comparing energy content against carbon content.

Disadvantages include the relatively limited worldwide availability of natural gas and the lower volumetric energy density of the fuel compared to MDO, for example. Even when liquefied, the storage space required for liquefied natural gas (LNG) could be up to four times greater than equivalent MDO tanks. Even more limited is the worldwide availability of LNG.

With a clear understanding of the risks associated with gas-fuelled engines, Lloyd's Register has been working closely with industry to develop *Rules and Regulations* for using methane gas as a fuel in order to facilitate its introduction [5].

3.2 PHOTOVOLTAIC CELLS

Under pressure to reduce CO_2 emissions from cars over their entire lifecycle including shipment, Pure Car and Truck Carrier (PCTC) ships are likely to emerge as some of the first examples of energy efficient ships.

In demonstrating the potential contribution of solar power, a 40 kW photovoltaic (PV) array comprising 328 modules of PV cells has recently been installed on the upper deck of an operational PCTC. Connected to the ship's 440 V AC electrical distribution network, the performance of the array will be evaluated in sea-going conditions with particular regard to the effects of salt water exposure and vibration.

Since they are capable of harnessing renewable solar energy, the advantages of solid state photovoltaic arrays are clear. The primary disadvantage, however, is the very large exposed surface area required per kW of power generated.

3.3 WIND ENGINES

With claims of a potential reduction in shipboard fuel consumption of 30%, the contribution of wind engines, better known as 'Flettner rotors', to sustainable marine power generation could be very significant. They utilise a phenomenon known as the Magnus effect, in which the force of the wind on a rotating vertical cylinder creates a low pressure on one side, generating thrust in much the same way that a sail does, only with a magnitude which is 10 to 14 times greater.

At least two full scale demonstration projects are currently underway. Lloyd's Register is currently working closely with the Wind Assisted Ship Propulsion (WASP) project, with designs for four 2.3-metre diameter and 17-metre high rotors currently undergoing review. Following review, testing will be carried out ashore, followed by their installation on board a bulk carrier [6].

3.4 ON-SHORE POWER SUPPLIES

The use of on-shore power supplies for 'cold-ironing' while in port may become a de facto facet of port operations in the future. Regulators have begun to encourage the use of such installations. 'Cold-ironing' is the US Navy's way of describing the practice of connecting a ship to a shore-side power supply in port, allowing the ship's machinery to be shut down and causing the installation to become 'cold'.

The term is now commonly used to describe a new generation of different high-voltage shore connections with fast plug connections and seamless load transfer without blackouts, which allow the full range of in-port activities to continue while the ship is discharging and loading cargo.

Already, a variety of equipment manufacturers and on-shore power supply designers are offering a variety of different solutions and configurations. Major differences between these installations which could have an impact on ship safety and operability include:

- Operating frequency – many of the world's on-shore electrical systems operate at 50 Hz, while most ship systems operate at 60 Hz, making these incompatible without expensive frequency conversion.
- Voltage levels – transformers are normally required to change the shore voltage to the ship voltage. Different ships have different operating levels (11 kV, 6.6 kV and 440 kV being common), necessitating transformers with multiple tapings or similar.
- Power rating – different ships have differing power-use profiles in port.
- Cable and connector types – there are currently no construction or test standards for flexible marine cables or high voltage plug and socket outlets.

- Cable management and lifting appliances – for the power levels required, cables and connectors will be too heavy for simple manual handling. Cable reels or cranes can be installed on board to extend ship cables to shore sockets or shore cable reels and cranes can be used to extend shore cables to shipboard sockets.
- Control and safety arrangements – the available solutions have been diverse, ranging from simple to highly sophisticated. They can range from manual operation with no automatic safety measures, to automatic connection and disconnection of submersible electrical equipment, fully integrated into the ship and shore-side emergency shutdown systems.

Where shore power is provided by renewable energy, typically local wind turbines, the benefits are greater and obvious. Where power is provided from the national power distribution network, in addition to the local benefits of reduced emissions and noise, it may be expected that such power consumed has been generated with higher efficiency than if it were generated on board.

With a clear understanding of the risks associated with shore power, Lloyd's Register has been working closely with industry to develop *Rules and Regulations* for the connection of on-shore power in order to facilitate its introduction [7].

3.5 FUEL CELLS

Fuel cells share many of the characteristics and utilise many of the same components as the cells of a battery. Both fuel cells and batteries convert stored chemical energy into electricity in a silent, efficient electrochemical reaction. Despite the similarities, however, one fundamental difference between a fuel cell and a battery suggests that a more appropriate comparison may be with that of a conventional generator set. Unlike a battery, in which the reactants consumed in the energy conversion process are stored internally and are eventually depleted, the reactants consumed by the fuel cell are stored externally and are supplied to the fuel cell in the same way as a conventional generator set is supplied with fuel and air. Such an arrangement means that a fuel cell, unlike a battery, has the potential to supply power as long as the supply of reactants, hydrogen and oxygen is maintained.

The ability of the fuel cell to provide a continuous supply of electrical power has important implications. Sharing characteristics of batteries and generators, the fuel cell has the potential to displace virtually all sources of shipboard power, ranging from batteries providing just a few watts of power intermittently, through to main and auxiliary power generating plant delivering megawatts of power continuously. The relatively low power of individual fuel cells requires the use of multiple cells to achieve usable power levels. Such a replication of components lends itself to high volume production and the design of modular fuel cell power plant with the potential for high reliability, good fault tolerance and potentially low capital cost.

The benefits of fuel cell technology are greatest when the fuel cell is operated on high purity hydrogen and oxygen and when the by-products of the energy conversion reaction (heat and water) can be utilised. In such circumstances, the power plant is relatively simple, extremely efficient and produces no undesirable emissions. Such an ideal operating environment is exemplified by manned space and sub-sea applications.

Although the ultimate goal, a number of considerations make the use of hydrogen as a fuel for marine fuel cell power generation unlikely in the near term, in particular its worldwide availability and its very low volumetric energy density, which necessitates unfeasibly large storage spaces. The operation of fuel cells on conventional marine fuel oils, however, is a problem. The fuel cell would need to be capable of converting the marine fuel oil into hydrogen. The development of fuel processing equipment capable of converting such fuels into hydrogen is unlikely to be realised in the near term. Despite considerable investment by the automotive industry, a reliable fuel reformer capable of converting gasoline into hydrogen proved elusive. It is, therefore, unlikely that reformation of heavier marine fuel oils would be realised by the marine industry, the only possible exception being US Naval research programmes.

A much more realistic scenario for near term marine fuel cell power generation is operation on natural gas. A number of 'high temperature' fuel cells are capable of operating directly on natural gas, converting methane into hydrogen within the fuel cell itself. Unfortunately, while feasible, (many megawatts of power are currently generated worldwide by natural gas-fuelled fuel cells) the use of any fuel other than hydrogen means that the fuel cell becomes significantly larger and substantially more complex than the highly efficient hydrogen-oxygen-fuelled fuel cell and, in consuming hydrocarbon fuels such as natural gas, will produce some undesirable emissions. Arguably more significant, however, is that the overall efficiency of the power plant will be significantly lower than the efficiency delivered by the hydrogen-oxygen-fuelled fuel cell power plant. Such a reduction in efficiency means that early marine fuel cell power plants are likely to operate at efficiencies not dramatically greater than those achievable using conventional power generation technologies and well below the maximum theoretical efficiency of the fuel cell.

The process and physical arrangements by which the energy is converted within the fuel cell are similar to those of a battery and are essentially the same regardless of the type of fuel cell. Two reactants, hydrogen and oxygen, combine within the fuel cell to produce water, releasing both electrical energy and thermal energy in the process. The reaction proceeds as long as hydrogen and oxygen, both of which are consumed within the reaction, are supplied to the fuel cell.

The desire for particular operating characteristics and improved fuel cell performance has led to the development of several different types of fuel cell which are individually identified by the electrolyte material they use. All offer particular advantages when compared. However, of the five basic types currently under development, the high temperature solid oxide (SOFC) type, operating at temperatures between 700 and 1000 deg C, and, to a lesser extent, the low temperature proton exchange membrane type (PEMFC), are perhaps most suited to the marine operating environment.

It is expected that performance will gradually improve, and the introduction of combined cycle techniques, combining fuel cells with gas turbines, will result in a substantial additional increase in the overall efficiency of the plant. In the longer term, however, it is the operating environment that is expected to change in favour of the fuel cell. Driven by concerns about the stability and, ultimately, the availability of fossil fuel supplies, it is hoped that 'green' hydrogen, generated using renewable energy ashore and consumed in hydrogen fuelled fuel cells on board ships, will provide the eventual solution. In such an ideal operating environment, the benefits of fuel cell technology will be fully exploited.

Lloyd's Register is currently working closely with industry as part of the EC METHAU project, the ultimate aim of which is to install and evaluate the performance of a methanol fuelled SOFC on board an operational PCTC [8].

4. FACILITATING CHANGE

4.1 RULES, REGULATIONS AND GUIDANCE

In order to support the marine industry in meeting the challenges of sustainable power generation and sustainable shipping generally, Lloyd's Register has developed, and continues to develop, *Rules and Regulations* to facilitate the introduction of new technologies on board ships.

Where Lloyd's Register has sufficient understanding, expertise and knowledge of the risks associated with the technologies proposed for installation on board Lloyd's Register classed ships, application-specific *Rules and Regulations* are published accordingly. To facilitate the introduction of technologies for which Lloyd's Register may not necessarily have sufficient understanding and knowledge to justify the publication of specific *Rules and Regulations*, a set of generic, systems engineering-based *Rules and Regulations* have been published. These allow Lloyd's Register to assess the safety and reliability of such technologies, while allowing the industry the freedom to evaluate radically new solutions under seagoing conditions.

4.2 RULES AND REGULATIONS FOR ON-SHORE POWER

To facilitate the uptake of on-shore power, Lloyd's Register has recently published application-specific *Rules for On-Shore Power Supplies* and currently supports the development of complementary international standards by TC18 of the International Electrotechnical Commission (IEC) in cooperation with the International Standards Organisation (ISO).

Although the environmental benefits are many, the technical risks for the ships themselves and the safety risks for those who work on board and ashore need to be given equal consideration. Further, as such shore-side power systems proliferate, adequate standards are needed to ensure effective operation and compatibility between systems.

The potential environmental benefits of on-shore power supplies should not take precedence over ship safety. The technical difficulties, hazards and potential for serious injury and damage introduced are not to be underestimated. The aforementioned *Rules for On-shore Power Supplies* were created to assist in addressing these hazards, along with a corresponding class notation, OPS. The requirements in the *Rules and Regulations* were developed in close consultation with a wide variety of industry stakeholders.

4.3 RULES AND REGULATIONS FOR METHANE GAS FUELLED SHIPS

To enable shipyards and owners to assess the class-related implications of a gas-fuelled ship, Lloyd's Register has published its *Provisional Rules for the Classification of Methane Gas Fuelled Ships*. The development process has involved a wide cross-section of industry experts, including ship designers and engine builders.

The requirements provide a structured approach for design and assessment. Ships complying with the requirements will be eligible for the assignment of a class notation, GF. The *Rules* have encompassed applicable requirements from current standards, including the draft IMO requirements, IACS Unified Requirements (UR) and Lloyd's Register's requirements for offshore installations.

One of the key aspects of the *Rules* is the designation and assessment of hazardous areas and the location of machinery and equipment, consistent with current practice and terminology. Particular care is required in the design of ventilation and safety arrangements for safe and reliable operation of gas-fuelled machinery, and these issues are fully addressed in the *Rules*.

The requirements cover all types of gas-fuelled machinery including both single and dual fuel engines, as well as gas turbine machinery and boilers.

4.4 RULES AND REGULATIONS FOR MACHINERY AND EQUIPMENT OF UNCONVENTIONAL DESIGN

Reliance on in-service feedback, incidents and failures as a process for identifying the risks associated with new technologies is not realistic in today's society. Equally unacceptable, however, is prohibiting or delaying the installation on board ships of the technologies desperately needed to meet the challenges of sustainable power generation while the regulators acquire the necessary knowledge and experience to develop prescriptive requirements for their design and construction. Accordingly, the requirements described in this paper outline the pragmatic, process-based, systems engineering approach taken by Lloyd's Register to the assessment of the safety and dependability of systems, machinery and equipment, making use of new technologies and systems of unconventional design.

As a means by which Lloyd's Register may satisfy itself of the safety and dependability of engineering systems of unconventional design proposed for installation on board Lloyd's Register classed ships, and for which Lloyd's Register may very likely have no in-service experience, a set of process-based requirements has been developed based on established and internationally recognised systems engineering principles.

In accordance with the aims of the IMO guidelines for Formal Safety Assessment (FSA), the requirements aim to ensure that risks to maritime safety and the environment, stemming from the introduction of new technologies, are addressed in so far as they affect the scope of ship classification.

The requirements apply to machinery and engineering systems intended to be installed on board Lloyd's Register classed ships and considered by Lloyd's Register to be of an 'unconventional' design, and which, as a result, are not directly addressed by the extant *Rules and Regulations*. It should be noted, however, that the general requirements of the *Rules and Regulations* remain to be satisfied as applicable.

The underlying principle behind the requirements is that formal controls are required to be employed for all development-related activities which include certain key systems engineering processes, including:

- project management
- requirements definition
- quality assurance
- design definition
- risk management
- configuration management
- verification
- integration
- validation (certification and survey).

Assessment by Lloyd's Register involves examination of the procedures for the application of the processes, together with all records associated with their application. For each of the processes, the procedures and their associated records are to provide evidence as described here.

4.4 (a) Project Management

A project management procedure is required to be established, documented and followed, in order to define and manage the key project processes. For the entire project, and each of the processes within the project, project management procedure documentation is to define the activities to be carried out, the required inputs and outputs, the roles and responsibilities of key personnel, the competence of key personnel and a schedule for the activities.

4.4 (b) Definition of Requirements

A requirements definition procedure is needed to be established, documented and followed, in order to define the required functional behaviour and performance of the machinery or engineering system in the environments to which the machinery or engineering system are likely to be exposed, under both normal and foreseeable emergency conditions. Account is required to be taken of the requirements of all key stakeholders, including the shipowner, the ship's crew, the shipyard, equipment suppliers and regulators. The requirements definition procedure documentation is required to specify the functional behaviour and performance requirements and is to identify the source of the requirements.

Lloyd's Register's requirements include compliance with statutory regulations and Lloyd's Register's existing *Rules and Regulations* as far as they are applicable to the fuel cell system. Additionally, where internationally recognised standards, codes of practice or guidance, relevant to the design and construction of marine fuel cell systems exist, due account is to be taken of the provisions of such documents. Typical of such standards are the international standards IEC60092 – *Electrical installations in ships – Part 101 Definitions and general requirements;* and IEC60721 – *Classification of environmental conditions Part 3: Classification of groups of environmental parameters and their severities – ship environment* which together provide a relatively complete definition of the environment in which a new power generation technologies would be expected to operate.

4.4 (c) Quality Assurance

A quality assurance procedure is required to be established, documented and followed, in order to ensure that the quality of the machinery or engineering system is in accordance with a defined quality management system. The specific quality controls to be applied during the project, in order to satisfy the requirements of the quality management system, are to be defined. The quality management system itself is required to satisfy the requirements of ISO9001:2000 – *Quality management systems – Requirements* or an equivalent acceptable national standard.

4.4 (d) Design Definition

A design definition process is required to be established, documented and followed, in order to define the requirements for the design of machinery or an engineering system which satisfies the stakeholder requirements, the quality assurance requirements and complies with basic internationally recognised design requirements for safety and functionality. The design definition process is required to ensure that the design of the machinery or engineering system satisfies statutory legislation, classification requirements and international standards and codes of practice where relevant and is to take account of stakeholder requirements and the quality assurance requirements. Design definition procedure documentation is required to specify the design requirements, identify the source of the requirements and ensure that the requirements for the design of major components and subsystems of the machinery or engineering system can be verified before and after integration.

4.4 (e) Risk Management

A risk management process is required to be established, documented and followed, in order to ensure that any risks stemming from the introduction of the machinery or engineering system are addressed, in particular: risks affecting the structural strength and integrity of the ship's hull; the safety of shipboard machinery and engineering systems; the safety of shipboard personnel; the reliability of essential and emergency machinery and engineering systems and the environment. Consideration is required to be given to the hazards associated with installation, operation, maintenance and disposal, both with the machinery or engineering system functioning correctly and, following any reasonably foreseeable failure, taking account of stakeholder requirements and design requirements.

Hazards are required to be identified using acceptable and recognised hazard identification techniques. The process is to ensure that risks are eliminated wherever possible. Risks which cannot be eliminated are to be mitigated as necessary. Details of risks, and the means by which they are mitigated, are required to be included in the operating manual.

Guidance on selecting and performing the various risk assessment techniques is widely available, with certain techniques being more suited for particular applications than others, as indicated in the international standard IEC60300 *Dependability management – Part 3-1: Application guide – Analysis techniques for dependability – Guide on methodology.* The IMO's Formal Safety Assessment (FSA) process serves as one such technique, as do those described in several international standards including*:* IEC61882 – *Hazard and operability studies (HAZOP studies) – application guide;* and IEC60812 – *Analysis techniques for system reliability – Procedure for failure mode and effects analysis (FMEA).*

4.4 (f) Configuration Management

A configuration management process is required to be established, documented and followed, in order to ensure traceability of the configuration of the machinery or engineering system, its subsystems and its components. Items essential for the safety or operation of the machinery or engineering system, and which could foreseeably be changed during the life time of the machinery or engineering system are to be identified such as documentation, software, sensors, actuators, instrumentation modules, boards and cards. The process is required to take account of the design requirements and any items used to mitigate risks. Configuration management procedure documentation is required to ensure that any changes to configuration control items are identified, recorded, evaluated, approved, incorporated and verified.

The international standard ISO10007 – *Quality management systems -- Guidelines for configuration* *management* is available as a guide in the development of a configuration management process.

4.4 (g) Verification

A verification process is required to be established, documented and followed, in order to ensure that subsystems and major components of the machinery or engineering system satisfy their design requirements. The process is to be based on one of, or a combination of, the following activities, as appropriate: design review; product inspection; process audit; and product testing. Verification procedure documentation is required to identify the requirements to be verified, the means by which they are to be verified, and the points in the project at which verification is to be carried out.

4.4 (h) Integration

An integration process is required to be established, documented and followed, in order to ensure that the machinery or engineering system is assembled in a sequence which allows verification of individual subsystems and major components following integration in advance of validating the entire machinery or engineering system. The process is required to take account of the verification requirements. Integration procedure documentation is to identify the subsystems and major components, the sequence in which they are to be integrated, the points in the project at which integration is to be carried out and the points in the project at which verification is to be carried out.

4.4 (i) Validation (Certification and Survey)

A validation process is to be established, documented and followed, in order to ensure the functional behaviour and performance of the machinery or engineering system meets its functional and performance requirements. The process is to validate stakeholder requirements, arrangements required to mitigate risks and the traceability of the configuration control items. Validation procedure documentation is to identify the requirements to be validated, the means by which they are be validated and the points in the project at which validation is to be carried out, including factory acceptance testing, integration testing, commissioning, sea trials and though-life survey.

It may be said that the key processes described above are simply good engineering practice, much of which is, or ought to be, established practice in a sector as mature as the marine industry – a sentiment which is shared by the author. The requirements described above have been published by Lloyd's Register as an additional chapter in the *Rules and Regulations for the Classification of Ships* [9].

To support the application of these *Rules and Regulations*, it is planned to develop application specific guidance. An early example of this will be for fuel cell systems providing electrical power for essential services, using knowledge gained through its participation in both commercial fuel cell demonstration projects and research and development projects, such as the EU projects METHAPU, FCSHIP and FCTESTNET. The publication of guidance rather than *Rules and Regulations* requiring verification allows Lloyd's Register to pass on such knowledge for the benefit of the industry. At a point when Lloyd's Register has sufficient knowledge and understanding of the risks associated with fuel cell technology application, specific *Rules and Regulations* will be published, as is done for conventional machinery and equipment.

5. CONCLUSIONS

The energy demands on board a large modern ship make the challenge of sustainable shipping appear daunting. However, as can be seen, several near-term solutions would appear to have the potential to make a significant contribution to the sustainability of shipping. Together, these suggest that a dramatic reduction in both emissions and fuel consumption can be expected in the not too distant future.

There are several other power generation scenarios in existence, not included in this paper, which could play an equal, or even greater, role in the provision of shipboard energy. However, there remains considerable debate as to their place in a sustainable society, whatever their role at this point in time.

6. REFERENCES

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