

Classifying the Innovation: The Certification of New Designs for Power Generation, Conversion and Energy Storage Focusing on the Reduction of Ships Emissions

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Abstract. In recent times the ship building and yacht industries have seen a surge in the requests for the application to the power generation, conversion and energy storage of technologies which were previously reserved to land-based uses or to niche sectors such as space, military, and scientific research. Such requests are often driven by seeking cleaner exhaust emissions, more efficient fuel consumption and higher passenger and crew comfort. Among these novel technologies we can mention fuel cells and (large) batteries based on Li-ion chemistries. These solutions are not only unconventional per se, they also carry along the necessity for advanced electrical system integration (even more so if combined in a hybrid architecture) or, for fuel cells, the need for the storage of dedicated fuels, e.g., liquid, or compressed hydrogen or methanol, and fuel treatment, e.g., evaporators and chemical reformers. The lack of prescriptive regulations covering such innovative solutions, both in terms of equipment and fuel, adds in challenge to their acceptance and certification from Regulatory Bodies and Flag Administrations. Furthermore, although high-level guidelines are provided, they often need to be tailored on a case-by-case basis and integrated with risk assessment exercises. The aim of this work is to give a comprehensive overview of the Classification tools available to date – be it prescriptive or risk-based – for the approval of novel designs and how do they relate to the existing statutory guidelines and to the established risk analysis instruments. The discussion will be corroborated by insights into some hands-on case studies in the yacht and cruise ship industry segments.

Keywords. Lloyd's Register, Classification, Alternative Design, Risk-based certification, Passenger ship, Yacht, Natural gas, Hydrogen, Methanol, Ammonia, Lithium battery, Fuel cell, Hybrid, Power generation, Power conversion, Energy storage.

1. Introduction

In the search for cleaner exhaust gas emission, several energy sources other than oil-based are currently being investigated for maritime applications. Some of these are

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reviewed below, both from the fuels perspective (such as hydrogen, ammonia, methanol) and power equipment one (fuel cells, lithium batteries, hybrid power systems). The available Flag Administration and Class approval tools and resources are then discussed for such solutions. For certain applications, an Alternative Design and/or risk-based certification approaches need to be followed, and they are accordingly described.

2. Unconventional fuels and power equipment

2.1. Unconventional fuels

Current day ships operate mostly on residual fuel such as HFO (heavy fuel oil) or distilled fuels like MDO (marine diesel oil). Various grades of such fuel exist. However, they are all hydrocarbon fuels based on oil. This aspect has promoted the investigation of alternative fuels to eliminate or at least reduce the carbon dioxide (CO₂) emissions. These fuels shall either be zero-carbon fuels, i.e., containing no carbon at all, thus ruling out all hydrocarbons; or net-zero fuels, i.e., fuels whose carbon content, released in the atmosphere during the combustion, is compensated by capturing it with technologies such as carbon capture or biofuels, where the plants would do that through photosynthesis.

Among zero carbon fuels hydrogen, H₂, is one of the most promising. It is a light, non-toxic, colourless and odourless gas, easily flammable in air between 4% and 75%. It liquefies at atmospheric pressure at abt. -254 °C and its critical point is at abt. -240 °C, making it difficult to liquefy and keep liquid due to the small liquid range. It maintains its lightness in the liquid state with a density of abt. 71 kg/m³. Alternatively, chemical storage solutions exist for hydrogen, such as metal hydrides and LOHC (Liquid Organic Hydrogen Carriers), with the aim to reduce the risks and technical issues in storage while preserving and, if possible, improving the fuel storage density.

Another option is ammonia: with a chemical formula NH₃ it contains no carbon, and a given volume of ammonia contains almost twice as much hydrogen than pure hydrogen. It liquefies at -33 °C at atmospheric pressure and it is the most widely produced chemical in the world. This makes it an ideal candidate for fuel; however, it has some drawbacks: it is highly toxic, in concentrations in the range of PPM in air and to be used with fuel cells it must be cracked first, separating the hydrogen from nitrogen. It is also typically dangerous to fuel cells, therefore even traces of it after cracking must be removed.

Perhaps the most known net-zero fuel is methanol. It contains carbon, but it can be distilled from biomass: this means that the amount of carbon released into the atmosphere during the combustion phase matches that captured by the plant – source of the biomass – throughout its life, hence giving a zero balance. At atmospheric pressure and room temperature it is a liquid (volatile, with a boiling point of 65°C) and can be stored and handled as such.

All these fuels are in principle free of Sulphur therefore SO_x are not released. Regarding NO_x emissions, they depend on power generation technology rather than on fuel itself. In general, improvements over traditional hydrocarbon fuels can be obtained, especially using fuel cells, even though the amount of nitrogen contained in the ammonia may require some attention.

2.2. Unconventional power equipment

The motivations which push towards the move to unconventional fuels (e.g., hydrogen, methanol, ammonia, etc.) versus the well-established HFO, MDO carry along the need to modify the existing electric power generation and propulsion equipment or even develop entirely novel solutions.

In fact, the chief power generation equipment is represented by the internal combustion engine (ICE) running on oil-based fuels. This is providing mechanical propulsion power – either directly or through gearing – or electrical power when driving an alternator since the beginning of 1900. While ICEs can in principle run on the unconventional fuels, no market-ready solutions are available to date.

A parallel route consists in developing equipment that currently have less (if at all) heritage in merchant shipping. A candidate in this respect is represented by the fuel cell – a thermodynamic engine capable of directly converting to electrical work the energy released by the same oxidation reactions which can be exploited in ICEs [1]. Among the advantages of fuel cells to ICEs we can mention higher efficiency, virtually no moving parts, and silent operation. Several types of fuel cells are available, with the most common being the polymer electrolyte membrane fuel cell (PEMFC) running on hydrogen and air. Hydrogen can either be directly fed from a storage onboard or obtained from other fuels such as methane or methanol by steam reforming, and from ammonia by cracking [2]. Furthermore, other fuel cell types running on different fuels (direct methanol PEMFC, ammonia fuel cell, SOFC (solid oxide fuel cell) with internal reforming of methane, etc.) are available or under development.

Another approach when it comes to the availability of electrical power onboard is focusing on storage. Electric batteries are a promising solution: recent advances in Lithium-ion cells technology have improved the combination of available power produced and energy available with respect to lead-acid and nickel cadmium cell chemistries [3]. Applications can range from peak shaving and optimising the operating point of generators, to backup uninterruptible power supply (UPS), energy storage from recovery or renewables, booster of power (e.g., for tugs) or even being the sole source of main electrical power. This last application represents a huge attraction as giving the chance to sail (even though for a limited and brief period) into areas where zero-emissions are imposed by local authorities (e.g., Norwegian fjords) and enhancing the comfort of the yachts' guests by having absence of noise.

Lastly, it is worth mentioning that also hydrogen can be viewed from an energy storage perspective. It can be obtained by water electrolysis when extra electrical energy is available (e.g., excess energy from running generators or from renewables) and then stored and be employed as fuel.

3. Statutory and Class approval tools

3.1. Statutory tools

With the introduction of the LNG-as-fuel concept for non-LNG carrier ships (already covered by the IGC code) some regulatory tools were needed. The first comprehensive

tool was the IMO Resolution MSC.285(86) introduced in 2009. It was then developed into the IMO Resolution MSC.391(95) (adopted on 11 June 2015) also known as the IGF Code [4]. This goal-based code provides general goal and functional requirements valid for any low-flashpoint fuels, plus a considerable extent of specific requirements for LNG.

The IGF code has been widely adopted in the LNG-as-fuel ships and it is now under development to provide specific and detailed requirements for other gases and low flashpoint fuels, such as hydrogen and methanol. In this respect, on 7 December 2020, the IMO has published the MSC.1/Circular.1621 Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel [5] aiming to provide provisions for the arrangement, installation, control and monitoring of machinery, equipment and systems using methyl/ethyl alcohol as fuel to minimize the risk to ship, crew, and environment.

In a similar fashion, the IMO is developing, through the MSC Sub-Committee on Carriage of Cargoes and Containers (CCC), interim guidelines for ship using fuel cells. At the time of writing, they have been drafted [6] on CCC7 meeting in September 2021 and will be forwarded to the Maritime Safety Committee - MSC - for approval at its 105th session scheduled for April 2022. It is to be noted that all these regulations are goal-based and rely on risk assessment processes to identify and mitigate, if necessary, the risks introduced using alternative fuels. This represents a difference with traditional, prescriptive approach rules. Part of the reason is that these rules are meant to cover many diverse types of ships, from tugs to tankers, from ferries, to cruise vessels, making therefore particularly difficult to introduce requirements that are applicable to all these different ships.

3.2. Class tools

The Lloyd's Register (LR) Group Ltd. was established for the purpose of producing a faithful and accurate classification of merchant shipping and now, as other Class Societies, primarily produces classification Rules. Ships, Crafts and Yachts built in compliance with the Rules are accordingly assigned a Class. As such, it is of prominent importance that technological innovations are captured in the Rules while at the same time promoting industrial improvements for the safety of navigation and personnel and the respect of the environment.

When it comes to machinery and equipment to be installed on classed ships, the Rules often refer to a relevant and acceptable National or International Standard. A fundamental tool available for the assurance of equipment compliance is provided by the Type Approval, an impartial Certification system that provides independent third-party certification to a product's conformity with specific standards or specifications.

Currently the LR Rules cover fuel cell power installations [7] and the fuel cell power system and modules are required to comply with the relevant parts of the International Electrotechnical Commission (IEC) standard IEC 62282 [8] and [9], respectively. The LR Rules for Fuel Cell power installation capture and are consistent with the IMO interim guidelines.

Batteries based on Li-ion chemistry are covered by the LR Rules [10] and are required to be designed and tested according to IEC 62619 [11] and IEC 62620 [12] and to satisfy the requirements of the dedicated LR Type Approval System Test Specification [13].

It is to be noted that both fuel cells and large batteries installations, but also in general other sources of electrical power, are likely to be integrated onboard within each other and with other types of power sources such as diesel-driven generators to supply the overall main electrical power demand. This is defined as a hybrid electrical power system, and relevant requirements [14] are in place to ensure that dependability targets and safety are achieved.

Furthermore, LR Rules and Requirements [15] are available for the use of gases (e.g., natural gas, hydrogen, ammonia) or low-flashpoint fuels (e.g., methanol, ethanol – refer also to [16]). These capture and are consistent with the IMO IGF Code. Currently, functional requirements for natural gas fuel are included. For other fuels, the compliance to the requirements for natural gas must be demonstrated through alternative design/risk-based certification.

4. Alternative design and risk-based certification

4.1. Alternative design

As described in above paragraphs, the expanding market of the cruise and yacht industry, together with the adoption of new technologies, novel and unconventional arrangements, equipment and systems, requires suitable statutory regulatory tools for ensuring that the SOLAS safety objectives and relevant functional requirements are suitably and effectively met.

When new technologies are proposed to be installed on board, it is quite typical that the current applicable regulatory framework does not provide specific prescriptive requirements, or the current regulatory framework is not developed for considering this new technology solution. Cases should also be mentioned, where the traditional shipboard arrangements and systems are installed in configurations alternative to those prescribed by existing requirements e.g., main vertical zones extending more than the SOLAS limitations, lifeboat with carrying capacity exceeding the maximum capacity of 150 persons and fire doors larger than those actually fire tested.

Where fire safety design or arrangements deviate from the prescriptive requirements of the SOLAS Chapters (Ch. II-1, Ch. II and Ch. III), Alternative Design and Arrangement (hereinafter “AD & A”) shall be carried out in accordance with applicable regulations (SOLAS Reg. II-1/55, Reg. II-2/17 and Reg. III/38) and dedicated IMO MSC Circulars. The process for analysing the safety equivalency for alternative designs and arrangements is extensively outlined in IMO circulars MSC/Circ. 1002 “Guidelines on Alternative Design and Arrangements for Fire Safety”, its Corrigendum MSC.1/Circ. 1002/Corr.1, MSC.1/Circ. 1212 “Guidelines on Alternative Design and Arrangements for SOLAS Chapters II-1 and III” and MSC.1/Circular.1455 “Guidelines for the Approval of Alternatives and Equivalents as Provided for in Various IMO Instruments”.

The fundamental requirement of AD & A is to demonstrate an equivalent level of safety for the adopted solution. AD & A can facilitate design innovation by providing an alternative methodology to demonstrate that an adequate level of safety has satisfactorily been achieved. AD & A can be considered a form of goal-based legislation and it is generally based on a holistic risk assessment.

AD & A can extend to the whole arrangement of the ship, or alternatively it can be focused on items, systems or individual components, part of an equipment.

Currently only the IGF Code includes detailed and specific prescriptive requirements for natural gas applications, but all other low flashpoint fuels or gases must generally demonstrate an equivalent level of safety following the Alternative Design methodology and applicable processes, as specified in SOLAS Reg. II-1/55 and relevant IMO guidelines (MSC.1/Circ.1212 or MSC.1/Circ.1455).

However, where other specific IMO guidelines exist for particular gases or other low flashpoint fuels and are based on a prescriptive regulatory framework, (e. g. MSC.1/Circ.1621, the Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel), upon being agreed among the stakeholders and the Flag Administration, these guidelines might be applied in lieu of the Alternative Design criteria.

4.2. Lloyd's Register risk-based certification

As a mean to demonstrate the suitability and acceptability of a design also in the light of SOLAS requirements, LR has developed a structured tool of risk assessment process that in its last release has been defined Risk-based certification (RBC).

This process is published in the dedicated Lloyds Register ShipRight document [17]. It is a unique guide for designers, owners, operators, and shipbuilders who need to embrace a process of certification for projects where a comprehensive set of detailed prescriptive requirements has not been developed yet in the international rules and regulations, such as for example the alternative fuels installations which are subject of the present article.

The process is defined in stages, summarized in **Figure 1**, and the stages as well as the overall process given by RBC are consistent with the requirements described in the IMO MSC.1/Circular.1455 and MSC.1/Circular.1212/Rev.1.

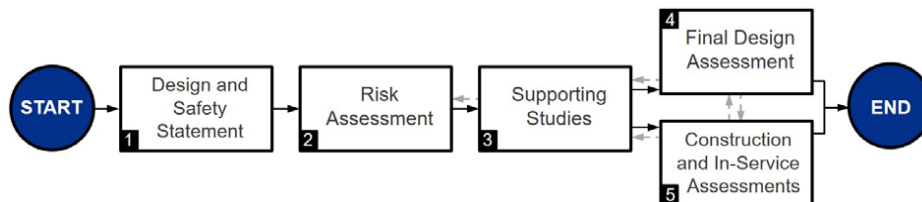


Figure 1. Risk Based Certification (RBC) process

RBC-1 – Design and Safety Statement is the basis of the definition of a project where the boundaries of the investigation are set, and the stakeholders are identified.

RBC-2 – Risk Assessment is a Hazard Identification (HazId) type risk assessment. This means that the likelihood of events is estimated, for example, a fuel leak from a damaged valve, in addition to identifying causes, recording prevention and mitigation measures, and estimating consequences (i.e., harm to persons). Consequences and their likelihood are also individually categorized and combined to provide risk ratings. These risk ratings are then compared against criteria to judge if the risk of an event is ‘low’ or has been ‘mitigated as necessary’ (refer to Ch. 3 Risk Criteria). Only if the risk is shown to be ‘low’ or ‘mitigated as necessary’ it can be ‘accepted’ (i.e., a ‘high’ risk can never be accepted).

Normally from the outcome of the stage RBC-2 but often also in the light of other inputs, a stage RBC-3 – Supporting Studies may be considered necessary to further investigate some aspects of the design. For example: to help address details that were unknown at the RBC-2 stage or uncertainties in risk assessment inputs; and to confirm the suitability of design options or changes. Gas dispersion and explosion analysis can be examples of supporting studies for hydrogen installation. The type and depth of the study needs to be commensurate with the ‘level’ of risk and the severity of potential consequences.

The RBC-4 – Final Design Assessment is to be performed on a mature design and its purpose is to determine if further modifications or refinements are required for ‘acceptance’ of the risks presented by the design, summarizes the justification of why the design should be accepted by LR and/or the regulator (e.g., National Administration), and provides input to design appraisal and the normal rigors of third-party certification.

5. Case studies

We are currently participating in several projects of different types, such as classification, risk assessment and research in collaboration with other partners.

Among the research projects, RESHiP [18] aimed to the identification, concept engineering and risk-based certification of a ship whose main power demand could be supplied by a combination of fuel cells and lithium batteries. Current Direct [19] is a project focusing on the development and certification of a Li-ion based, swappable containerized solution as a main source of electrical power.

Several Yachts with lithium batteries and hybrid power systems have been recently delivered and classified (Cerri Cantieri Navali MY Vanadis, Benetti MY Luminosity) while other projects are ongoing. Other current Yacht projects are considering the installation of PEMFC fueled by H₂ obtained from methanol reforming or generating sets running on methanol fuel.

The cruise industry is no exception to the trend. In addition, it is expected that some areas of particular interest for cruise routes, such as the Geirangerfjord in Norway, will become restricted to zero-emissions ships only in the near future. This has pushed cruise vessel owners, together with yards, designers, OEMs, Class and other partners into the development of ships, which can sail for some time in zero-emissions conditions. To meet these goals, for certain projects, technologies such as multi-MW fuels cells and matching LH₂ storage and handling arrangements have been chosen and are currently being developed for the purpose.

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