MARINE PRACTICE GUIDELINES FOR FUEL CELL APPLICATIONS

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This paper focuses on the implementation of fuel cells in marine systems as a propulsion system and energy source. The objective is to provide an overview of the pertinent legislation for marine applications of fuel cells. This work includes a characterization of some guidelines for the safe application of fuel cell systems on ships. It also describes two ships that have implemented fuel cells to obtain energy, the Viking Lady, the first marine ship to include this technology, and Greentug, a reference for new tugs.

***Keywords**:* fuel cell, guidelines, marine applications, prototypes, system implementation

1. INTRODUCTION

In recent years, there has been increased public concern about the potential environmental impact of shipping [1]. Always maritime industry has responded to the restrictions imposed to protect the environment through optimization and development of different systems of internal combustion engines. Recently, the environmental concern is made evident by the use of new technologies and/or fuels for marine applications. Some examples of the interest to produce energy with lower environmental cost would be the cases presented below:

- The Company Balèaria, which operates between the Balearic Islands and the Iberian Peninsula, intends to re-engine four of its high speed vessels for using LNG instead of diesel. It aims to reduce maintenance and operating costs as well as to comply with future environmental standards. Using natural gas reduces 25% of CO_2 emissions and eliminates other emissions types [2].
- The ports of Rotterdam and Gothenburg, two of the largest in Europe, will sign an agreement to promote use of LNG as fuel for shipping. Both ports belong to the "Sulphur Emission Control Area" (SECA) in northern Europe, where from 2015 will begin to take effect very strict regulations regarding the sulfur content in fuels. In the case of the port of Gothenburg the construction of a new terminal that will include the supply of LNG has begun to be studied. The aim is to have infrastructure for LNG bunkering available once the sulphur regulations come into effect. Sulphur and particle emissions would be reduced to almost zero, nitrogen oxide emissions by 85-90 per cent and net greenhouse gases by 15-20 per cent [3].

In many cases, the primary aim is to minimize the environmental footprint of ships operating in densely populated coastal regions and biologically sensitive marine areas. With this idea in mind, an alternative solution to traditional propulsion systems to produce electricity without emissions of SOx, NOx and CO_2 proposes using fuel cells [4]. The needs that require the installation of fuel cells involve investing large amounts of money in addition to the need for more experience in what relates to the field of application and the safety. Also the hydrogen low density states important storage problem, which add additional safety problems.

2. MARINE GUIDELINES

The guidelines for the safe application of fuel cell systems on ships are summarized and compared in Table 1.

Table 1: Comparison of guidelines [5, 6, 7]

	Bureau Veritas	Germanischer Lloyds	Det Norske Veritas
General requirements			
Guidelines applying to the use of fuel cell systems installed on ships. (Applicability to new ships to be determined by the classification society.)	✓	✓	✓
Documentation to be submitted			
-Description of the equipment.	✓	✓	✓
-Electric circuit diagrams.	✓	✓	✓
-Automation concept.	✓	✓	✓
-Fire extinguishing concept.	✓	✓	✓
-Plans of hazardous areas and safety and emergency concept.	✓	✓	✓
-Physical environment and operating conditions.	✓		✓
Testing and trials	✓	✓	
Ship arrangement and system design			
Materials used in gas installations must be in accordance with the Rules for the Classification of Ships.	✓	✓	✓
Austenitic stainless steel shall be used for materials in contact with hydrogen. Other materials may be approved after special consideration.	✓	✓	✓
The geometry of the arrangement and location of spaces must be simple.	✓	✓	✓
The ventilation system used for hazardous spaces must be separate from the system used for non-hazardous spaces.	✓	✓	✓
Fire safety			
Detection system in tank room and FC spaces.	✓	✓	✓
Definition of hazardous zones.	✓	✓	✓
Fire extinction.	✓	✓	✓
Control, regulating, monitoring and alarm devices			

Gas tank monitoring.	✓	✓	✓
Gas compressor monitoring.	✓		✓
Fuel cell power system monitoring.	✓	✓	✓
Monitoring of chemical reactions.		✓	
Electrical systems			
Area classification.	✓		✓
In general, electrical equipment and wiring must not be installed in hazardous areas unless essential for operational purposes.	✓		✓
Power supply connections must not allow the ingress of gaseous mixtures where gas fuel leaks are possible.	✓		✓
Manufacture, workmanship and testing.			
Liquefied gas tank.	✓	✓	✓
FC fuel piping systems.	✓	✓	✓
Onboard testing of FC plant.	✓	✓	✓

One set of guidelines, from ***Bureau Veritas***, is described in greater detail below. These are the marine guidelines applied to **'Greentug'**, the reference for new tugs.

-Materials

Components containing natural gas or hydrogen must comply with the provisions of the IGC Code (the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk). For non-cryogenic gas, particularly compressed gas, other non-metallic materials may be applied subject to special examination.

Components in contact with hydrogen must be made of materials having good compatibility with respect to embrittlement and hydrogen attack phenomena. The normal operating temperature range for materials used in hydrogen components should be -40℃ to +85℃ (normal conditions including filling and disc harging). References to hydrogen-compatible materials and suitability demonstration testing are included in the guidelines. Non-metallic piping carrying hydrogen gas may accumulate electrostatic charge along its exterior surface. Discharges from the external surface of the pipe may be sufficient to ignite a flammable mixture of gas or vapor in the surrounding environment. Care must be taken to effectively mitigate this risk.

-General arrangement

Machinery spaces characterized by its geometry and distribution system design safety control should be such that in case of leakage without loss of vessel's essential functions (propulsion, government and maneuver).

The main distribution of spacious for fuel, distribution, storage, processing and use must comply with the conditions so that the extent of the danger zones is kept to a minimum. Besides presenting a simple geometry to avoid trapping explosive mixtures. Gas fuel storage, gas compressors, fuel processing systems, fuel cell modules and power conditioning systems must be located in different areas. Spaces containing fuel processing equipment must comply with the same requirements as machinery spaces housing fuel cell stacks.

-Gas fuel supply

All gas supply piping within gas-safe machinery space boundaries must be contained by a gas-tight enclosure, i.e., double-wall piping or ducting. Low-pressure gas supply piping (under 10 bar) located within ESD-protected machinery spaces equipped with an individual exhaust ventilation system may be accepted without a gas-tight external enclosure if the areas occupied by flanges, valves and other components of the gas supply system are gas-tight enclosed. (Arrangements in machinery spaces are such that the spaces are considered non-hazardous under normal conditions, but under certain abnormal conditions may have the potential to become hazardous.)

Ventilation systems for gas supply line ducts must always be in operation when there is gas in the pipe system. Continuous gas detection is recommended for each gas supply line to indicate leaks and to trigger shutdown of the gas supply to the machinery space. The master gas fuel valve must close automatically if the air flow is not established and maintained by the exhaust ventilation system.

Arrangements for provision of the necessary flexibility must be demonstrated to maintain the integrity of the piping system in all foreseen service situations. The guidelines pay special attention to the application of different types of valves and their location in the gas piping system.

-Gas fuel storage

The fuel gas can stored in liquid or high pressure, in these cases the gas storage tank must be of type C, thus fulfilling the conditions of the IGC Code. It must be possible to empty and purge gas and vent bunker tanks with gas piping systems. Inerting must be performed prior to venting to avoid an explosion in hazardous atmospheres in storage tanks and gas pipes. If hydrogen is used, fuel inerting is preferably achieved using helium, which cannot freeze and form a plug when exposed to cold hydrogen. Air must be prevented from entering the piping system and storage tanks in order to prevent the formation of flammable mixtures. The system must be designed to withstand at least twice the anticipated number of filling cycles.

The design and construction of compressed gas storage tanks must be in accordance with recognized standards (e.g. BV Rules, Pt C, Ch 1, Sec 3). Applicability of the standards chosen for the containment system to seagoing conditions must be demonstrated. Pressure relief valves must be fitted. The system must be designed to withstand the anticipated filling cycles for the lifetime of the ship.

The guidelines provide specific recommendations for the onboard location of gas fuel storage tanks and batteries to protect them in the event of a collision or grounding, with 760 mm as the absolute minimum inboard distance from the side shell. For liquid hydrogen storage, the inner pressure vessel must be designed to operate at a temperature of -253℃. In this state, liquid gas can be stored at a maximum acceptable working pressure of 10 bar. Storage of compressed gas below deck may be permitted after special consideration if requirements are met regarding relief valve settings, thermal protection, gas detection, ventilation and fixed fire extinguishing. The storage tank and associated valves and piping must be located in a space designed to act as a second barrier for liquid or compressed gas leakage. On ships where essential services depend on the fuel cell system, fuel storage must be divided between two or more tanks of approximately equal size, located in separate compartments.

-Electrical equipment

In general, electrical equipment and wiring may not be installed in hazardous areas (areas where an explosive gas atmosphere or a flammable gas (flash point below 60℃) is or may be expected to be present) unless necessary for operational purposes. The type of equipment and installation requirements must comply with the relevant area classification, considering three types of dangerous zones (0, 1 and 2; see IEC 60079-10 and IEC 60092-502).

-Ventilation systems

Ventilation is a key safety feature of gas-fueled power systems. Good air circulation in all spaces is of paramount importance, particularly for preventing the formation of explosive gas mixture pockets in the space. The guidelines provide extensive recommendations for the forced ventilation of gas-related spaces and gas pipe ducting, and for the location of ventilation inlets and outlets and pressure relief outlets. The ventilation system for machinery spaces containing gas utilization equipment must be independent of all other ventilation systems. Ventilation must be monitored, including alarms. Electrical installations must be disconnected if ventilation cannot be restored for an extended period. Any ducting used for the ventilation of hazardous spaces must be separated from that used for the ventilation of non-hazardous spaces. Means must be provided to indicate any loss of the required ventilation capacity.

-Detection, monitoring and control

In order to provide the operator (or operating system) with the required information to safely operate the fuel cell power system, several detection and monitoring systems must be installed. Typical examples are gas detectors (at different levels of the Lower Flammable Limit (LFL) of the gas considered), loss of ventilation detectors, fire detectors, and gas pressure monitoring systems. The guidelines provide a detailed table (monitoring the fuel cell installation), highlighting the use of the different monitoring and detection systems, associated alarms, and follow-up actions (automatic shutdown of the main tank valve or automatic shutdown of the gas supply to the affected machinery space). For gas detection at 40% LFL, two independent gas detectors located close together are required for redundancy reasons, unless the gas detector is the self-monitoring type. Redundancy for the detection of critical hydrogen concentration is also considered in order to account for possible detector failure.

-Risk analysis

A risk analysis of the fuel cell installation systems must be performed to assess the consequences of a failure affecting the relevant systems and/or a gas leak. The required analysis can be an FTA (Fault Tree Analysis), FMEA (Failure Modes and Effects Analysis), HAZOP (Hazard and Operability Study), a combination of these techniques, or another type of analysis providing equivalent information. The risk analysis must be based on the single failure concept, which means that only one failure must be considered at the same time. Both detectable and non-electable failures must be considered. Consequence failures, i.e., failures of any component caused directly by a single failure of another component, must also be considered.

-Tests and trials

Factory testing is required for materials, components and system assemblies. The complete installation must be tested on board. Lists and descriptions of tests that must be performed, or were already performed (for type-approved equipment), must be defined and submitted for approval. Specific tests are needed for components in contact with hydrogen. (The relevant tests could be derived from approval tests for car hydrogen tanks.)

The guidelines provide test recommendations for gas tanks and gas piping in accordance with the IGC Code and the interim BLG (Bulk Liquids and Gases) guidelines, including welding tests, post-assembly hydrostatic tests, and onboard system tests.

-Operational recommendations

The guidelines provide specific operational and training requirements with regard to system operation and maintenance. Recommendations are provided for the operating manual and maintenance manuals and for the special training of crew members with direct responsibility for gas-related operations [5].

3. PROTOTYPES AND APPLICATIONS

Capabilities for improving fuel cell technology are currently growing, along with the use of fuel cells in practical cases (i.e., ship propulsion systems and electrical systems). These are the reasons for developing practical guidelines for marine applications. We know of different cases where this technology has been employed, and have described the applicable guidelines in previous sections. To illustrate the above, we have included a description of the ships we consider most relevant to our paper.

- ***Viking Lady***

The Viking Lady, Fig. 1 and Table 2, a supply ship, was the first ocean-going ship to use fuel cells. It is equipped with hydrogen fuel cells, extracted from LNG, and batteries providing sufficient electrical power for its electrical systems. It uses a diesel engine for main propulsion, Fig. 2.

The FellowSHIP Project started in 2003, and focused on finding new solutions to reduce CO_2 emissions by 50% and NO_x and SO_x emissions by 100% in marine applications. It also sought to reduce fuel consumption by 30-35%. The project had three phases:

- One (2003): Initial studies and designs.
- Two (2007-2010): Once the fuel cells were studied, they were integrated into the electrical system and the new control system developed for this prototype ship. Construction of the Viking Lady took place during this phase.
- Three (2010-2013): After the ship was built and launched, a research program began using informatics tools and different kinds of estimators to predict fuel cell behavior under marine conditions, based on the ship's performance.

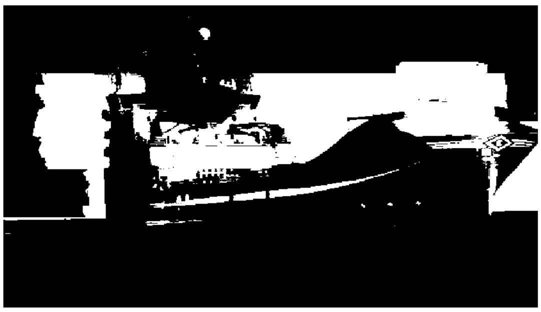

Fig. 1. Viking Lady (http://vikinglady.no/technology/)

Several tests found that the ship was only able to operate with fuel cells and batteries at low speed and low power, which are therefore advisable for use in port. This capacity is of great interest because the ship is designed to sail in the North Sea, where there are strict regulations on gas emissions. We can also see that fuel cells provide valuable support to the main engine when the ship is supplying fuel. Another important advantage was the reduction of vibrations, of particular interest when the ship is using the dynamic positioning system.

Table 2: Viking Lady specifications

Delivery (year)	2009
Length	92.2 m
Width	21 m
Depth	7.6 m
Gross tonnage	6100 tm
Dead weight	5900 tm
Berths	25 persons
IMO no.	9409675
Class	DNV 1A1 Supply Vessel
Ship owner	Eidesvik Offshore

The system for generating electrical power, Fig. 2, consists of fuel cells and a series of batteries by Corvus Energy (Canada). These are comprised of 6.5 kW lithium-polymer modules. This group of batteries is monitored by a control system that indicates when they are charged or empty, on or off. There is also, Fig. 3, a monitor to indicate the starting and stopping parameters.

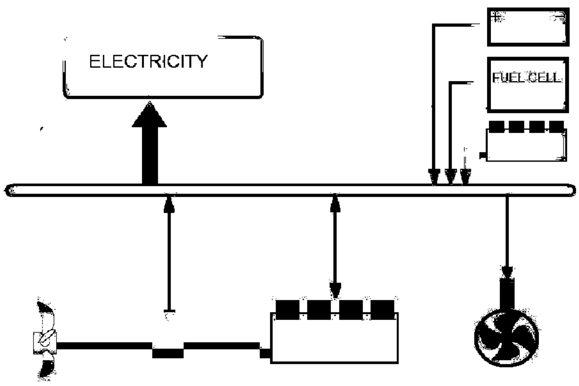

Fig. 2. The electricity network and distribution (electricity is produced by batteries and fuel cells), along with the independent propulsion system

The fuel cell pack on the Viking Lady has roughly 18.5 hours of autonomy while operating at up to 500 kW of power. In the beginning, the minimum power established was 320 kW.

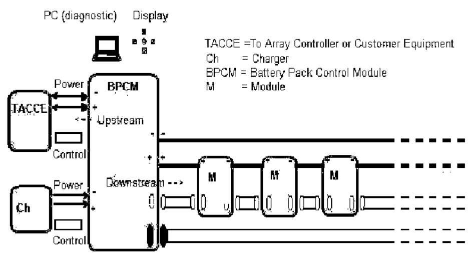

Fig. 3. Battery system

These are Molten-Carbonate Fuel Cells (MCFC). They operate at high temperatures, making it necessary to reach 550-650ºC. This could be an advantage: no external transformation of LNG into hydrogen is necessary because it is directly dissociated. Because it is a basic electrolyte cell (Li_2CO_3/Na_2CO_3), the carbon ions travel rather than the protons. Their yield is about 54%, and they can supply 200 to 2000 kW of power, supporting temperatures up to 600-800ºC. CO_2 is generated during the electrical reactions. However, the CO_2 produced is the same that was taken from the atmosphere.

This type of cell has several advantages. They are very efficient because they take advantage of the high temperatures in gas and steam turbines to increase efficiency. There is no CO_2 poisoning in the anodes because no CO_2 is generated. Finally, they allow for the use of a wide range of fuels. However, there are also some disadvantages. These include the need to increase the temperatures (which can also be an advantage, as explained above), high costs, and the instability and fragility of the electrolyte [8, 9].

The Viking Lady project involved an investment of 5 million Euros, of which only 60% was contributed by shareholders and 40% was provided by the Norwegian government. The Viking Lady had some supporters without which it could not have been completed:

- DNV (Det Norske Veritas): A classification society that safeguards the safety of persons and the environment, which promotes the certification and classification of services for the global market (Table 3).
- Eidesvik Offshore, a specialized shipping company with a fleet of supply ships that fully supported the project.
- Wärtsilä, a leading marine propulsion company that designed the ship's electrical power plant.

The project also received support from the Norwegian Ministerial Council and the German Departments of Innovation, Economy, Environment and Technology.

It was determined that a decrease in CO_2 emissions equivalent to 22,000 cars per year can be achieved through this project. NO_x emissions are decreased by 180 tons. A decrease in fuel consumption has also been observed. The project offers greater operational safety, requires less maintenance, and can result in decreased vibrations. The problem with this technology is the high cost, due to its limited development, although it is estimated that the ship will become profitable two years after construction [10].

- ***Greentug***

Greentug, Table 3 and Fig. 4, still in draft form, is a reference for new tugs. Greentug is a hybrid ship with an electrical system powered by a fuel cell and main propulsion provided by diesel engines. It is capable of reducing SO_x and NO_x production by 90% and CO_2 by 50%. Like the Viking Lady, it is designed to operate in the North Sea, in the ports of Rotterdam and Amsterdam.

Table 3. Greentug specifications

Length	30.95 m
Width	12.00 m
Depth	5.3 m
Velocity	13 kn
Dead weight	65 tm

The power generator set consists of a fuel cell system, and the fuel cell system is comprised of a series of lithium-ion batteries with a range of about eight and a half hours.

The battery packs are used to handle power peaks, while the remaining electrical demand will be covered by the fuel cell system.

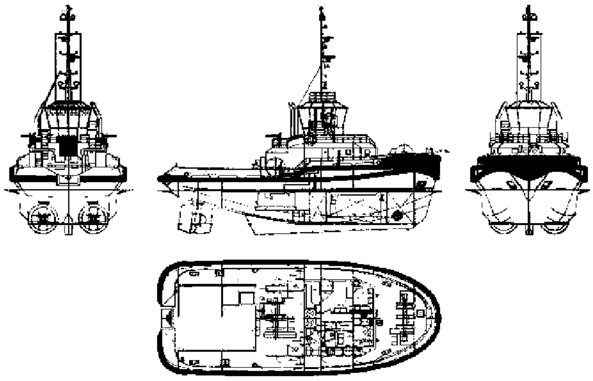

Fig. 4. Plans for Greentug [12]

The fuel cell system is comprised of two generator sets capable of generating 100 kW of power each. The PEM cell was supplied by NedStack Fuel Cell Technology, and provides an efficiency of 34%. These fuel cells use a solid polymer electrolyte and a platinum catalyst. They have an operating temperature range of 60-120°C. In this type of stack, the elements transferred from the anode to the cathode are protons (H^+) [8, 9].

The fuel used is hydrogen, stored in 1000 kg (833 m^3) tanks at a storage pressure of 430Ba. This type of fuel cell provides a fast start feature, operates at low temperatures and is low-corrosion, but requires hydration and is very sensitive to CO [11].

Propulsion power is supplied by a series of diesel combustion engines, two of which are capable of providing 950 kW of power and two providing 1200 kW. It is equipped with a 113 m^3 fuel oil tank. Because it is a tugboat, an optimization study was conducted to determine the weight distribution of the fuel cells.

Electrical power will be used for relief efforts. When the vessel sails in green mode, it will achieve zero emissions during operations and will stop browsing for about one hour at a speed of 7 knots.

The project is supported by: Smit Engineering, Bakker Sliedrecht, Electro Industrie, MARIN, Bureau Veritas, Nedstack Fuel Cell Technology, TNO Science and Industry, and LindeGas Benelux.

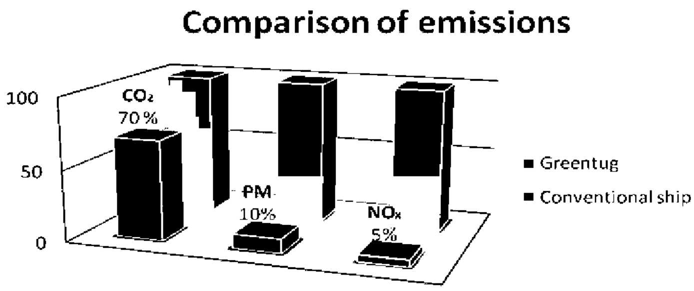

Fig. 5. Graph comparing emissions from Greentug and conventional ships (adapted from [13])

Greentug will be capable of reducing emissions to 0 during temporary green operations, and will operate using only fuel cells 85% of the time. Emissions will be considerably reduced in other operating modes, Fig. 5, and significant fuel savings will be achieved. However, as with any new technology, costs will be high [11, 12, 13].

4. CONCLUSIONS

Fuel cell power supplies show high potential for growth, and efforts by classification societies to develop guidelines are an indicator of future expectations for fuel cells. The development of guidelines is dependent on future demand for such power supplies and improvements to certain technical aspects, as well as the contribution of current regulations to ship safety. However, time is needed to respond to these challenges. Another problem that conditions this technology is the source of the fuel (hydrogen), which must be economically viable and provided by renewable energy sources.

This paper introduces two innovative projects, Viking Lady and Greentug that shed light on the viability of such systems from a safety and economic perspective. This provides information on the possibilities of these systems as an alternative to traditional petroleum-based propulsion systems.

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The learning system requests trainers and lecturers capable to offer the necessary learning materials for the process. Constanta Maritime University started programs dedicated to the life long learning, based on a series of online courses and in parallel in order to improve its capacities for this learning method, training lecturers to be able to offer in the future the requested knowledge and information for the people involved in the maritime industry.

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