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# PROJECTE FINAL DE CARRERA

# Les piles de combustible al sector naval

**Titulació: ETN, especialitat en Propulsió i Serveis del Vaixell, Pla 2000**

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**Desembre 2011**

# Annex A. BV Guidelines for the safe application of fuel cell systems on ships

# Guidelines for the safe application of fuel cell systems on ships

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## Introduction

Over the last years a clear increase in public interest with regard to the environmental impact of shipping can be observed. There is mounting pressure on the maritime industry to reduce exhaust gas emissions of ships such as carbon-oxides, nitrogen-oxides (NOx), sulphur-oxides (SOx) and particulate matter. The revised MARPOL Annex VI, when entering into force in July 2010, will progressively reduce the permissible emission limits on NOx and SOx. At the same time discussions are underway within the IMO and the EU to regulate and reduce the emission of greenhouse gases. In addition, the volatile development of the (fuel) oil price, which saw record highs in the second half of 2008, as well as the predicted depletion of fossil resources is driving the industry to reduce its dependency to hydrocarbon based energy.

The maritime industry has been active in responding to the environmental challenges by optimizing internal combustion engines and developing exhaust gas cleaning (e.g. scrubbers and catalytic reduction) and recirculation systems. In addition, there is a growing focus on alternative propulsion and powering systems; primarily aiming at the minimizing the environmental footprint of ships operating in densely populated coastal regions and biologically sensitive marine areas (e.g. arctic waters).

A promising solution for alternative powering is the use of fuel cells to generate electrical power without NOx, SOx and PM emissions. The higher efficiency of fuel cells compared to diesel generators allows reduction of $CO_2$ emissions. In combination with hydrogen (ideally produced from non-fossil energy) as a non-polluting and carbon-free stockable energy carrier, fuel cells could drastically reduce air emissions, while simultaneously reducing the dependency to hydrocarbons.

The current main challenges for application of fuel cell installations (i.e. fuel cell power system, fuel storage and fuel processing system) are the high cost of the equipment, the lack of experience on their long term performance in a marine environment and the mastering of safety issues. The latter are mainly related to the use of highly flammable fuels. In addition, when using hydrogen, its low energy volume density (about one third of natural gas) requires storage either as cryogenic liquid, as high pressure compressed gas (usually at more than 300 bars) or in other specific gas form (e.g. use of metal hydride storage), which each present additional safety concerns.

Although safety issues have been addressed for terrestrial applications, for which commercial systems are available off the shelf, and are subject to extensive research for road applications, civilian applications at sea are still limited to a few pilot projects. As a matter of fact, the key hurdle for the wider application of fuel cells in ships is the lack of a comprehensive regulatory framework covering the technology. Acting on this level would allow breaking the vicious circle in which the lack of regulatory framework limits the possibilities of building and testing prototype applications, which in turn are essential for qualifying and improving the performance of the systems and for gaining a better insight in the safety issues, which is necessary for establishing rules …

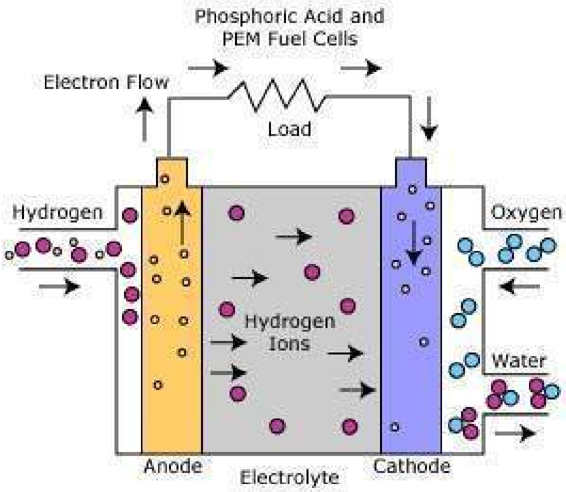
Bureau Veritas acknowledges this point and has responded by developing a set of comprehensive guidelines for the safe application of fuel cells on ships, taking into account relevant existing IMO conventions and guidelines, a wide range of non-maritime international standards (ISO, IEC, SAE, EU) as well as BV's in-house developed expertise. Gas storage and distribution, fuel cell power systems, fire detection & fire fighting, ventilation and monitoring systems are considered in-depth, providing a unique holistic approach to ship design. This paper presents the key points of the guidelines and their application to a real-life project with particularly green intentions in which Bureau Veritas is participating.

Following the **Introduction** section, the section **Fuel cell technologies** explains the basic principles and describes the different types of fuel cells and their possible applications. In addition, a brief economic assessment of fuel cell systems is given, followed by an assessment of fuels for fuel cells. The **Prototypes and applications** section will outline the current fuel cell projects in the maritime industry. Special attention is paid to the Hydrogen Hybrid Harbour Tug, a joint industry project in which Bureau Veritas is participating. The **Safety and regulations** section considers the main safety issues as well as the regulatory context for application of fuel cells on ships, while the section **Bureau Veritas guidelines** will describe the objectives, background and contents of the proposed guidelines. Finally the **Closure** section will provide the main conclusions and recommendations.

**Fuel cell technologies**

*Fuel Cells*
According to the IEC (International Electro technical Commission), a fuel cell is "an electrochemical device that converts the chemical energy of a fuel, such as hydrogen rich gases, alcohols, hydrocarbons and oxidants to DC power, heat and other reaction products". The basic operating principle of a fuel cell is illustrated in Figure 1 for the case of a Proton Exchange Membrane Fuel Cell (PEMFC), which is one of today most common technologies.

Figure 1: Fuel cell basic operating principle for a Proton Exchange Membrane Fuel Cell (PEMFC)




(Source: www.chmltech.com)

The fuel cell is primarily composed of two electrodes separated by an electrolyte. Hydrogen is channelled to the anode. Thanks to the catalyst (usually platinum) present on the anode, the di-hydrogen molecule is split into protons and electrons. The electrolyte properties are such that the protons can travel through it towards the cathode, whereas the electrons are flowed through the electrical circuit to power. Hydrogen protons, electrons and oxygen (possibly from ambient air), which is channelled to the cathode, recombine again, thanks to the presence of a catalyst, to produce water.

These oxidation-reduction reactions can be written as:

Anode reaction: $2\ H_2 \rightarrow 4\ H^+ + 4\ e^-$
Cathode reaction: $O_2 + 4\ H^+ + 4\ e^- \rightarrow 2\ H_2O$
Overall cell reaction: $2\ H_2 + O_2 \rightarrow 2\ H_2O$

These reactions are exothermic and therefore also produce heat.

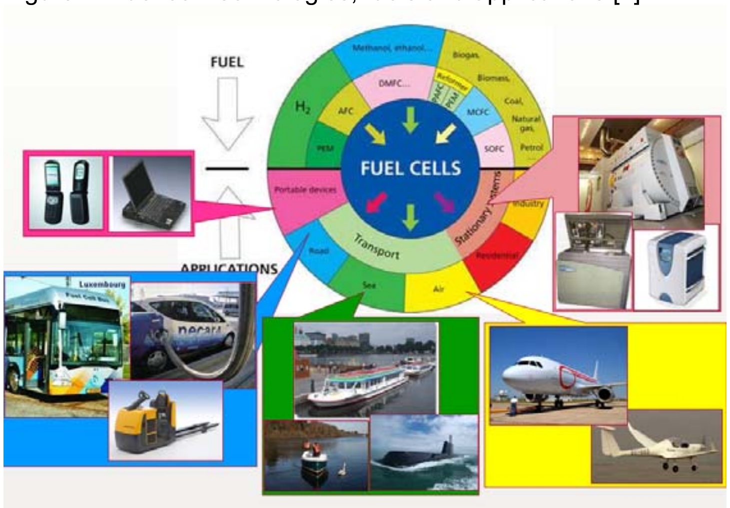
In the case of the PEMFC, the electrolyte is a polymer membrane which needs to have several properties:

- As high proton conductivity as possible in order to reduce losses associated to the voltage drop from internal resistance;
- Provide a good chemical and thermal strength in an acid medium during several thousands of hours for mobile or light transportation applications and up to several tens of thousands of hours for stationary applications;
- Be completely tight to oxygen and hydrogen to avoid their mixing;
- Provide mechanical properties combining strength and flexibility, allowing the use of very thin membranes (around 100 to 200 microns or even 10 to 20 microns depending on the membrane construction).

Fuel cells are assembled into a fuel cell stack, in series or in parallel in order to obtain the required intensity and/or voltage.

As illustrated by Figure 2 today there is not one single technology, but rather several fuel cell technologies, which can use different types of fuels and can be used for a wide range of industrial applications.

Figure 2: Fuel cell technologies, fuels and applications [1]




The various fuel cell technologies existing today make use of different electrolytes, with several types of ions flowing through the electrolyte, and operate in different temperature ranges. The main categories of current fuel cells are summarised in Table 1.

Table 1: Various types of fuel cell technologies

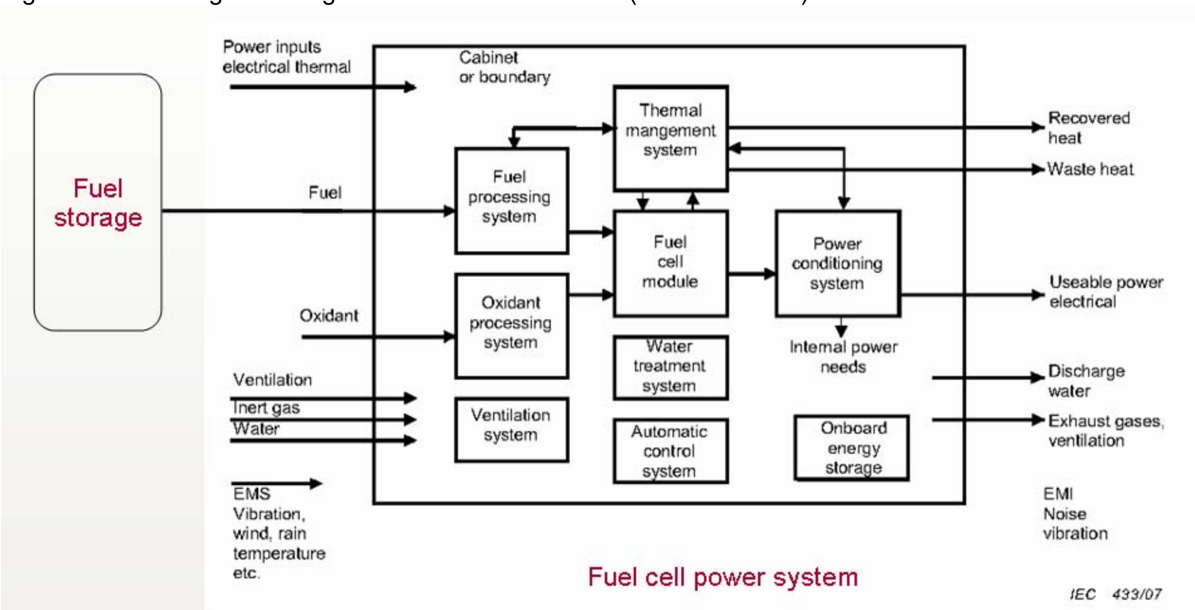
| **Fuel Cell type** | **Main Specificities** | **Temp. (°C)** | **Application and power range** |
|---|---|---|---|
| Direct Methanol Fuel Cell (DMFC) | Same technology as PEMFC; consumes methanol and oxygen<br>More energy by unit of volume stored, less efficient | 90 – 120 | Mobile, transport, stationary<br>10 mW – 100 kW |
| Alkaline Fuel Cell (AFC) | Oldest type of FC used in spatial application<br>Consume hydrogen and oxygen<br>Easily poisoned by CO2 | 50 – 90 | Space, transport<br>1 – 100 kW |
| Proton Exchange Membrane Fuel Cell (PEMFC) | Most common FC for transport application/small stationary<br>Consume hydrogen and oxygen<br>Poisoned by CO, membranes need hydration | 70 – 120 | Mobile, transport, stationary<br>10 mW – 100 kW |
| Phosphoric Acid Fuel Cell (PAFC) | Used in continuous in stationary application<br>Consume hydrogen and oxygen<br>Need preheating, less sensitive to CO | 150 – 200 | Stationary, transport<br>200 kW – 10 MW |
| Molten carbonate Fuel Cell (MCFC) | Used in stationary application<br>Consume hydrocarbons or hydrogen and oxygen<br>Not poisoned by impurities, possibility of cogeneration | 600 – 650 | Stationary<br>500 kW – 10 MW |
| Solid Oxide Fuel Cell (SOFC) | Transportation and stationary application<br>Consume methane, LNG or hydrogen and oxygen<br>Not poisoned by impurities, cogeneration possible | 700 – 1000 | Stationary, transport<br>1 kW – 10 MW |

As can be seen from the above table, two categories of fuel cells operate at high temperature: MCFC and SOFC. This allows to use them for Combined Heat and Power (CHP) generation and thus increase their overall power efficiency. However, achieving their thermal equilibrium requires some time (typically several hours). These features make them particularly suitable for stationary applications. Other interesting aspects of these fuel cells are their reduced sensitivity to the quality of the fuel and their use of non noble catalyst.

The output voltage of a fuel cell is linked to the intensity of the current produced. The intensity of maximum power does not usually coincide with the one of maximum efficiency and a compromise must be made. The operating point of most fuel cells is selected with an efficiency of around 50%. In the case of hot fuel cells with CHP, the overall efficiency (electrical and thermal power) can reach up to 70% or more.

A fuel cell installation is not limited to the fuel cell stack. As a matter of fact, it may correspond to a complex system with many components covering the fuel storage, distribution and the fuel cell power system. A generic block diagram of such an installation is presented in Figure 3.

Figure 3: Block diagram of a generic fuel cell installation (IEC 62282-3-1)




The fuel storage and distribution covers the fuel tank, the piping system for refuelling and for distributing the fuel to the fuel cell power system, as well as all the safety related components (valves, sensors, detectors, monitoring system). The fuel cell power system is generally composed of the following main sub-systems:

- Fuel cell module: assembly of one or more fuel cell stacks, electrical connections for the power delivered by the stacks, and means for monitoring and/or control;
- Oxidant processing system: the system that meters, conditions, processes and may pressurize the incoming supply for use within the fuel cell power system;
- Fuel processing system: catalytic or chemical processing equipment plus associated heat exchangers and controls required to prepare the fuel for utilization within a fuel cell;
- Thermal management system: provides cooling and heat rejection to maintain thermal equilibrium within the fuel cell power system, may provide for the recovery of excess heat (in particular for Combined Heat and Power production) and assists in heating the power train during start-up;
- Water treatment system: provides the treatment and purification of recovered or added water for use within the fuel cell power system (e.g. for membrane hydration of PEMFC);
- Power conditioning system: equipment which is used to adapt the electrical energy produced to the requirements as specified by the manufacturer;
- Automatic control system: assembly of sensors, actuators, valves, switches and logic components that maintains the fuel cell power system parameters within the manufacturer's specified limits without manual intervention;
- Ventilation system: provides, by mechanical means, air to a fuel cell power system's cabinet;
- Onboard energy storage: Internal energy source intended to aid or complement the fuel cell module in providing power to internal or external loads.

Fuel cells are still expensive technologies, with current average prices ranging from 3000 €/kW to 5000 €/kW (source: AFH2, www.afh2.org). This is mainly due to the use of noble material as catalysts to the electrolytes for some fuel cell types (e.g. PEMFC), and to the fact that mass production has not been achieved yet.

The industry objective for stationary applications is to reach 1500 to 2000 €/kW, which seems realistic once mass production has been achieved. However, the life duration of fuel cells will have to be increased from 5000 h today to more than 40 000 h. For bus applications, the industry objective is to reach a price range of 300 to 500 €/kW which is expected to be achieved within 10 years. For the car industry, even larger price reduction is needed, with a target around 30 to 50 €/kW, which does not seem feasible without making technological jumps, in particular on the membrane and the catalyst.

*Fuels*

Although fuel cells primarily use di-hydrogen (which will be called hydrogen for convenience in the remainder of the present paper) as fuel, other fuels can also be used in conjunction with a chemical conversion to di-hydrogen. This can be done either externally with a reforming process, or internally, in particular for hot fuel cells (MCFC, SOFC). In fact, fuel cells have been tested with three main types of fuel:

- Hydrogen;
- Alcohols (methanol, ethanol);
- Hydrocarbons (natural gas, butane, propane, petroleum distillates, fermentation gas, gasified biomass).

The physical properties of di-hydrogen are presented in Table 2. Comparison of the properties to methane, which is already used as fuel for transportation (e.g. in natural gas fuelled ships), shows some similarities (lighter than air, Lower Flammable Limit).

Table 2: Physical properties of hydrogen, methane and propane

| | Valid at | Unit | Hydrogen[1] | Methane | Propane |
|---|---|---|---|---|---|
| **Boiling point** | 1.013 Bar | K | 20.4 | 111.6 | 231.1 |
| **Critical temperature** | | K | 33.19 | 119.6 | 396.8 |
| **Critical pressure** | | Bar | 13.15 | 46.0 | 42.4 |
| **Density of liquid** | Boiling point | $kg/m^3$ | 70.8 | 422.5 | 580.7 |
| **Density of gas** | Boiling point | $kg/m^3$ | 1.338 | 1.818 | 2.419 |
| **Density of gas** | 1.013 Bar, 0°C | $kg/m^3$ | 0.090 | 0.717 | 2.011 |
| **Diffusion coefficient in air** | 1.013 Bar, 20°C | $cm^2/s$ | 0.69 | 0.22 | 0.12 |
| **Limits of flammability[2]** | 1.013 Bar, 20°C | Vol. % | 4.0-75.0 | 5.0-15.4 | 2.1-9.5 |
| **Limits of detonability[2]** | 1.013 Bar, 20°C | Vol. % | 13.0-65.0 | 6.3-13.5 | 3.0-8.0 |
| **Autoignition temperature[2]** | 1.013 Bar | °C | 560 | 595 | 470 |
| **Minimum ignition energy[2]** | 1.013 Bar, 20°C | mJ | 0.019 | 0.28 | 0.26 |
| **Theoretical temperature of flame[2]** | 1.013 Bar | °C | 2045 | 1875 | 2040 |
| **Energy density** | | MJ/kg | 120 | 50.3 | 120.6 |
| **Human health risk** | | | Asphyxiation, Non toxic | Asphyxiation, Non toxic | Asphyxiation, Non toxic |
| **Corrosion** | | | Non corrosive | Non corrosive | Non corrosive |
| **Heat radiation during fire** | A hydrogen fire radiates very little heat compared to a petroleum fire | | | | |

1. Normal hydrogen (75% ortho and 25% para)
2. Combustion with air

The use of hydrogen presents a number of advantages:

- There is unlimited resource in atomic form (H);
- It delivers a high chemical energy per unit mass (120 to 140 MJ/kg, 2.2 to 2.8 more than natural gas);
- Hydrogen is non-polluting, non-toxic and non-poisonous;
- It is very light, with a large coefficient of diffusion in air (3 to 4 more than natural gas); this feature is interesting from a safety point of view since it reduces the probability of having a hydrogen rich (inflammable or explosive) mixture in open air;
- Hydrogen fire has little radiation, which limits its capability of burning or igniting material and equipment to the close vicinity of the flame;
- It is a well known gas (e.g. in the beginning of the 20$^{th}$ century gas for street lighting containing 60% hydrogen was used). Presently its worldwide consumption reaches 45 million tons per year, which corresponds to 1.5% of the annual worldwide energy consumption;
- In combination with a fuel cell, hydrogen is a very clean means of electrical power production since only water is released;
- Although today hydrogen is mainly produced from hydrocarbons, it can be produced with a very small environmental footprint by electrolysis, providing a good electrical power storage solution to intermittent renewable sources of energy (wind mills, hydropower, solar cells, and energy recovering from sea, …).

However, hydrogen also presents a series of drawbacks which need to be correctly addressed to enable large deployment:

- Di-hydrogen does not exist in molecular form, and therefore needs to be produced (requires energy);
- Because of its very light weight, its volume energy density is low (about one third compared to natural gas), which is a concern for its storage;
- Hydrogen presents a wide range of flammability and detonability in air. At the same time it should be noted that gasoline vapour for instance can be explosive at an even lower concentration (1.1 to 1.3%);
- The minimum ignition energy of a hydrogen mixture is as low as 20 µJ at 30% concentration. However, at their lower flammable limit, hydrogen and natural gas have similar minimum ignition energy of the order of 10 mJ;
- Hydrogen is colourless and odourless, which makes it hard to detect a leak. In addition its flame is not visible in day light;
- Its molecular size is very small, hence it has a strong tendency to leak (e.g. at joints);
- Some metals and metallic materials, when in contact with hydrogen, can exhibit an increased susceptibility to hydrogen-assisted material property degradation, commonly known as “hydrogen embrittlement” and “hydrogen attack”. The first phenomenon corresponds to a decrease of the metal ductility. That is, a lower fracture resistance, due to the solubility and diffusion of hydrogen atoms in the metal. The second phenomenon can be encountered at high (around 500°C) temperature with some low-alloyed structural steels.

*Fuel Storage*

Hydrogen storage is currently performed mainly in compressed gas form and in cryogenic liquid form. Novel methods such as metal hydride storage and sodium borohydride storage are also under development and already applied in very specific installations.

Compressed hydrogen is stored and transported at pressures ranging from 200 bars up to 700 bars and more. Metallic bottles are used in the lower pressure range, whereas composite (filament winded) pressure vessels are used for higher pressures. The typical hydrogen mass to containment ratio is on the order of 7 to 8% for this type of storage and the volume energy density (per tank unit volume) ranges from about 560 to 1900 $kWh/m^3$ for pressures ranging from 200 bars to 700 bars respectively.

Liquid hydrogen is stored under its boiling point, which is 20 K at atmospheric pressure. The tank should have a very good thermal insulation to limit the liquid boil-off. The typical hydrogen mass to containment ratio is on the order of 6 to 7% for this type of storage and the volume energy density is about 2800 $kWh/m^3$.

Metal hydrides seem a promising technology for storing energy at high density with reduced (ambient to moderate) pressure compared to compressed storage and higher temperature compared to liquid storage, therewith reducing safety issues from these points of view. The principle is that hydrogen can be reversibly absorbed into the lattice of a large number of metal alloys, forming a hydride. Cooling is needed during absorption and heating during desorption, which provides a means to control hydrogen leakage by temperature control. Since tanks are filled with the metal alloy, the weight of the containment is important, hence typical hydrogen mass to containment ratio on the order of 2 to 3%. There is a large variety of alloy under investigation today. It should be noted that some alloys can react with air and/or water, which needs to be considered from a safety point of view.

The Sodium Borohydride ($NaBH_4$) is a particular case of a hydride. In presence of a catalyst (Cobalt or Ruthenium based) it reacts with water to produce hydrogen and Sodium Borate. This technique is not well developed yet, mainly because of the catalyst cost and of difficulties to recycle the Sodium Borate.

As explained before other fuels than hydrogen may be used, provided that a conversion to hydrogen is performed, either before the fuel cell by using a reformer, or inside the fuel cell under the effect of temperature and a catalyst. A common technique is the reforming of hydrocarbons (e.g. natural gas), which can be performed by means of different processes (steam reforming, partial oxidation and auto thermal reforming).

*Market and perspectives*

The market for fuel cell power systems and hydrogen is not very developed yet because of the lack of maturity of the fuel cell technologies, the lack of hydrogen production and distribution infrastructures and last, but not the least, the current lack of clear regulations for exploiting fuel cell installations, even for prototype testing.

The European Commission has initiated in October 2002 a High Level Group for Hydrogen and Fuel Cells Technologies, which developed a short to long term European vision [1], which can be summarised as follows:

From 2000 to 2020 developments are based on public incentive and private efforts, with fundamental, applied research and with demonstrations:

2010:

- Local clusters of hydrogen filling stations, hydrogen transported by road or produced locally at the refuelling stations;
- First hydrogen fuel cell fleets, series production of fuel cells for fleets (direct hydrogen or onboard reforming) and other transport fuel cell auxiliary power units (boats);
- Stationary low temperature fuel cell systems (PEMFC) with power up to 300 kW; stationary high temperature fuel cell systems (MCFC/SOFC) with power up to 500 kW; demonstration fleets of fuel cell powered buses.

2020:

- Hydrogen produced from fossil fuels with carbon sequestration, interconnection of local hydrogen distribution grids, significant hydrogen production from renewable fuels including biomass gasification;
- SOFC systems atmospheric and hybrid commercial with power up to 10 MW, fuel cell vehicles competitive for passenger cars, fuel cells commercial in micro-application, low-cost high temperature fuel cell systems.

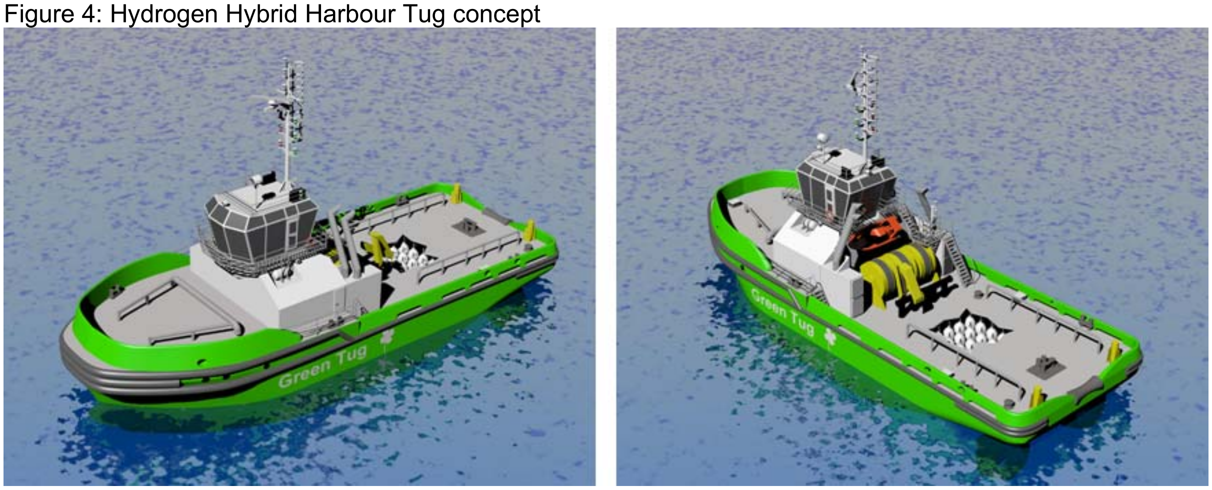
From 2020, large scale commercialisation of hydrogen and fuel cell starts. Hydrogen becomes the prime fuel choice for fuel cell vehicles in 2030. Fuel cells become the dominant technology in transport, distributed power generation and in micro-applications around 2040, and are used, with hydrogen, in aviation in 2050.

This vision is in line with communications from major car manufacturers indicating a targeted public deployment of fuel cell cars around 2025-2030.

**Prototypes and applications**

It is commonly acknowledged that prototype demonstrations are necessary in order to assess the performance of the fuel cell technologies, improve them, and gain knowledge and experience in dealing with the related safety issues. To this end many projects have already been initiated for the different types of applications described previously (see Figure 2) and a few experimental installations are running today. In addition some industrial systems exist. For instance, in the marine sector there are Air Independent propulsion of the German types U212 & U214 submarines (PEMFC 9x34 kW / 2x120 kW, metal hydride hydrogen storage and liquid oxygen storage), the inland passenger ship “Zemship” on the Alster Lake near Hamburg (Hybrid battery and PEMFC 2x50 kW main propulsion system, compressed hydrogen storage) and a shuttle ship in Amsterdam (Hybrid battery and PEMFC 2x30 kW main propulsion system, compressed hydrogen storage).

Figure 4: Hydrogen Hybrid Harbour Tug concept



Bureau Veritas is currently collaborating with a Dutch Green Design project called Hydrogen Hybrid Harbour Tug (HHHT). This project will be the first real application of the Bureau Veritas preliminary guidelines which are presented later in this paper. The aim of the project is to design and build a 65 t bollard pull harbour tug with minimized exhaust emissions by applying a hybrid propulsion system involving both diesel generators and hydrogen fuelled fuel cells. The diesel generator sets are generating the required power output (4400 kW, driving two rudder propellers according to the Azimuth Stern Drive concept) for berthing and unberthing operations. The fuel cell power system, in combination with batteries, can provide sufficient power during standby and mobilization & demobilization periods. The 2x100 kW fuel cell stacks can deliver sufficient thrust for manoeuvring the tug at a speed of 7 kn. An artist impression of the HHHT is shown in figure 4.

In this way a substantial reduction in exhaust emissions can be achieved. An additional benefit of fuel cell powering is that the propulsion efficiency is about 70% higher compared to conventional diesel-direct drive installations [2]. This effectively causes a reduction in the mineral fuel consumption when the tug operates in the fuel cell mode.

The environmental footprint of the HHHT is further reduced by a number of features:

- The number and power of the diesel generators is chosen such as to ensure efficient engine operation in all operational modes (corresponding to the power need);
- The Electrical motors driving the main rudder propellers are mounted directly on top of these units, therewith reducing mechanical losses;
- Power regeneration technology is applied in two situations:
  1. Paying out of the towing winch;
  2. Using the inactive propeller as dynamo in the dynamic breaking or steering mode.
- Bunkering of low sulphur fuel to minimize SOx emissions;
- Applying Selective Catalyst Reduction (SCR) to reduce NOx emissions;
- Applying sooth filters for reducing the emission of particulate matter (PM).

Based on the application of the fuel cell technology and the additional features, the estimated overall reduction in exhaust gas emissions of the HHHT is depicted in Table 3.

Table 3: Estimated overall reduction in exhaust emissions of the HHHT [2]

| | |
|---|---|
| NOx (nitrogen-oxides) | - 90 % |
| SOx (sulphur-oxides) | - 90 % |
| $CO_2$ (carbon-dioxide, one of the greenhouse gases) | - 30 to 50 % |
| PM (particulate matter, e.g. sooth) | - 90 % |

The key issues currently addressed in the project are the onboard storage of high pressure compressed hydrogen, the safe distribution and processing of hydrogen and the design of the hydrogen venting system in view of the tug assisting in the berthing of ships carrying dangerous (flammable) cargo (e.g. chemical tankers). In addition, the risk analysis, as required by the guidelines, will provide valuable insight into the risks and the effectiveness of risk mitigating measures of applying fuel cell technology onboard commercial ships.

Based on the feedback of the project the preliminary guidelines will be further refined. Special attention will be paid to the application of the guidelines to non-SOLAS vessels and the use of hybrid propulsion systems.

The HHHT project is run as a partnership between the following companies:

- Offshore Ship Designers (design)
- Smit Harbour Towage (owner/operator)
- Iskes Towing & Salvage (owner/operator)
- Nedstack (fuel cell technology)
- Bakker Sliedrecht (electrical systems)
- MARIN (maritime research)
- Bureau Veritas (classification & safety guidance)

The project is financially supported by SenterNovem, an agency of the Dutch Ministry of Economic Affairs.

The ultimate aim of the project is to actually build two prototype HHHTs: one for Smit (Port of Rotterdam) and one for Iskes (Port of Amsterdam).

**Safety and regulations**

The primary safety issue to be addressed concerns the use of inflammable gas and/or fuel with low flashpoint (< 60°C). The main hazard to be prevented is the creation of explosive mixture pockets in case of gas release in any part of the system containing gas (leakage, accidental release). A second hazard to be considered is the impact of external fire on a part of the system containing gas (gas tank in particular).

The secondary safety issue concerns the gas storage, each type of storage presenting its specific hazards:

- Compressed gas storage: the main hazard to be considered is gas tank failure. This can result from internal overpressure (e.g. error during refuelling, pressure rise due to external temperature rise in case of external fire) or from tank fatigue (e.g. effect of fatigue, embrittlement in case of hydrogen). The primary consequences of such a failure are a gas release with possibility of fire or explosion in presence of an ignition source, and the blast of (possibly ruptured) tank parts. Pressure vessels are already used onboard but they are made of steel. Due to its lower energy volume density, the storage of compressed hydrogen requires very high pressure levels for obtaining sufficient energy storage capacity, for which composite tanks are required. The long term behaviour of such tanks in a marine environment is not very well known today and therefore requires special attention;
- Liquid gas storage: the safety issues are similar to the ones encountered with cryogenic natural gas storage, but more severe in the case of liquid hydrogen due to its lower boiling point and due to the embrittlement phenomenon if a metallic containment is used. In case of liquid gas spill, the main hazards are ship steel structure embrittlement and cold burn to personnel.

The above hazards are also relevant to the parts of the fuel cell power system which contain gas. In addition, specific hazards should be considered when relevant:

- Presence of hot surfaces and/or hot fluids (e.g. in hot fuel cells and in reformer), which may represent an ignition source in case of gas release, and a source of burning for personnel;
- Presence of high electrical intensity or voltage, which may again represent a source of ignition and give a risk of electrocution of personnel.

Additionally, the presence of toxic substances may need to be addressed, either as primary fuel (e.g. methanol), or as by product/intermediate product (carbon monoxide created in fuel processing).

If the fuel cell installation is used to power an essential service of the ship (e.g. main propulsion), then the consequence of a failure of the installation needs to be considered as well.

To our knowledge, there are no published Flag State rules for marine installations of fuel cell systems. No international (i.e. IMO) rule exist either. As a matter of fact, the future International Code of safety for Gas-fuelled Ships (IGF Code), which is briefly described later in this paper, should cover the use of other gases than natural gas, and in particular of hydrogen, but does not intend to cover the fuel cell power system. Moreover, the date of completion and adoption for this new code are not known. It is worth noting that for the automotive industry, Japan has established legislation on Hydrogen and Fuel Cell Vehicles (HFCV). In addition, a worldwide regulation for hydrogen cars is in preparation (Global Technical Regulations of United Nations Economic Commission for Europe), and a proposal for a regulation of the European Parliament and of the Council on type-approval of hydrogen powered motor vehicles has been approved.

Having said that, a number of standards have been issued or are under development for different aspects which are relevant to the use of hydrogen and fuel cells. The international committees in charge of these questions are the ISO/TC 197 “Hydrogen technologies” and IEC/TC105 “Fuel cells”. In addition, links exists with other technical committees, such as:

- ISO TC11 on boilers and pressure vessels;
- ISO TC22 on road vehicles;
- ISO TC58/SC3 on gas cylinder/cylinder design;
- ISO TC220 on cryogenic vessels;
- ISO TC31 on electrical equipment for explosive atmospheres.

In the automotive sector, many standards for hydrogen and fuel cells have been established by the SAE organisation too.

Although a number of initiatives has been taken to regulate the industrial use of fuel cell technologies, their consistency and scope of application onboard ships is not fully clear. Put in other words: what works on land does not necessarily work at sea, where ship motions and a sea environment have to be accounted for. In addition, there is limited real life (and long term) experience with fuel cell power systems on ships. In order to further develop fuel cell technologies and improve the associated regulations, it is essential to develop new prototypes and demonstration models. In turn, a clear regulatory framework will guide the industry in developing new prototypes.

As classification societies are being consulted by their clients to provide guidance on safety and regulatory issues related to fuels and fuel cells, some European societies have developed requirements on the basis of their knowledge and experience. Additional long term experience is required to refine and complete such guidance. Once sufficient knowledge and experience has been accumulated by the different class societies, this could be combined to create a uniform safety standard and a level playing field for the marine industry.

**Bureau Veritas guidelines**

In response to the observed lack of consistent and traceable standards for the application of fuel cells on ships, while acknowledging the increasing interest in alternative powering systems, Bureau Veritas has decided to research the topic and create guidelines to support safe design, manufacturing, operation and maintenance of fuel cell power systems onboard ships. The objective of the guidelines is to provide criteria for the arrangement and installation of machinery for propulsion and auxiliary purposes, using fuel cell installations, which have an equivalent level of integrity in terms of safety, reliability and dependability as can be achieved with (new and) comparable conventional oil fuelled main and auxiliary machinery.

Presently the guidelines have preliminary status and are subject to internal and external review. Internal comments have been received and feedback analysis is in progress. At the same time the preliminary version of the guidelines is used for application to real projects, which provides additional opportunities for refinement and completion. After taking into account all the feedback the guidelines will be published as a Bureau Veritas Guidance Note under the name “Guidelines for fuel cell systems onboard commercial ships”.

The guidelines apply to fuel cell systems on ships using a gas as fuel and oxygen from ambient air as oxidant. The use onboard of both gas (in particular hydrogen) and hydrocarbon based fuel is subject to special examination to take into account the specificities of hybrid powering systems (e.g. safety issues associated with the possible interactions between the different fuel systems). The guidelines are primarily intended for application to new ships, but can be used for retrofitting fuel cell systems on existing ships as well (extent of application of the guidelines to be decided on a case-by-case basis). The guidelines are to be applied in addition to the relevant provisions of the SOLAS Convention, as applicable.

There is no limitation on the type or power of the applied fuel cell power system. There is also no limitation on the type of gas used, although the guidelines mainly focus on natural gas and hydrogen as fuels. The gas may be stored in both gaseous and liquid state, while gas reforming is covered as well. Other types of processes, such as metal hydride storage of hydrogen and storage and use of pure oxygen as oxidant are not explicitly covered and are therefore subject to special examination.

The guidelines are primarily based on the “Interim Guidelines for Natural Gas-Fuelled Engine Installations in Ships”, as prepared by the IMO’s Sub-Committee on Bulk Liquids and Gases (BLG), which in the future is expected to be replaced by the International Code of safety for Gas-fuelled Ships (IGF Code). In addition to natural gas, the IGF Code should also address other gas fuel types such as hydrogen. The Bureau Veritas Rule Note “Safety Rules for Gas-Fuelled Engine Installations in Ships” (NR529, February 2007) has been used as the main reference document for drafting the guidelines for fuel cells, where necessary updated with the latest revisions of the above mentioned IMO’s interim guidelines. These documents, as well as the present guidelines, make reference to various parts of the IGC Code. Hydrogen and fuel cell specificities have been integrated into the guidelines by including parts of, or making reference to, the documents listed in Table 4.

Table 4: References used for incorporating hydrogen and fuel cell technology into the guidelines

| | |
|---|---|
| 1 | ISO 23273-1:2006: Fuel cell road vehicles – safety specifications; Part 1: Vehicle functional safety |
| 2 | ISO 23273-2:2006: Fuel cell road vehicles – safety specifications; Part 2: Protection against hydrogen hazards for vehicles fuelled with compressed hydrogen |
| 3 | ISO/TR 15916:2004: Basic considerations for the safety of hydrogen systems |
| 4 | ISO 11114-4: Transportable gas cylinders – Compatibility of cylinders and valve materials with gas contents; Part 4: Test methods for hydrogen compatibility with metals |
| 5 | EN ISO 14726-1:2001: Ships and marine technology. Identification colours for the content of piping systems; Part 1: Main colours and media |
| 6 | IEC 60092-502: Electrical Installations in Ships – Tankers – Special Features |
| 7 | IEC 60079-10: Electrical apparatus for explosive gas atmospheres; Part 10: Classification of hazardous areas |
| 8 | IEC 60079-17: Explosive atmospheres; Part 17: Electrical installations inspection and maintenance |
| 9 | IEC 62282-3-1: Fuel cell technologies; Part 3.1: Stationary fuel cell power systems – Safety |
| 10 | IEC 62282-3-2: Fuel cell technologies; Part 3.2: Stationary fuel cell power systems – Performance test methods |
| 11 | SAE J2578 (December 2002): Recommended practice for general fuel cell vehicle safety |
| 12 | SAE J2579 (January 2008): Technical Information Report for fuel systems in fuel cell and other hydrogen vehicles |
| 13 | Proposal for a regulation of the European Parliament and of the Council on type approval of hydrogen powered motor vehicles and amending Directive 2007/46/EC, COM(2007)593 2007/0214(COD) |
| 14 | Draft ECE Compressed Gaseous Hydrogen Regulation, revision 12b, 12/10/2003 (EIHP2) |

In addition reference is made to various parts of the Bureau Veritas Rules for the Classification of Steel Ships, see Table 5.

Table 5: References to Bureau Veritas Rules for the Classification of Steel Ships (BV Rules)

| | |
|---|---|
| 15 | Pt C, Ch 1: Machinery |
| 16 | Pt C, Ch 2: Electrical Installations |
| 17 | Pt C, Ch 3: Automation |
| 18 | Pt C, Ch 4: Fire protection, detection and extinction |
| 19 | Pt E, Ch 6: Comfort on board (COMF) |
| 20 | Pt D, Ch 21: Ships not covered by SOLAS |

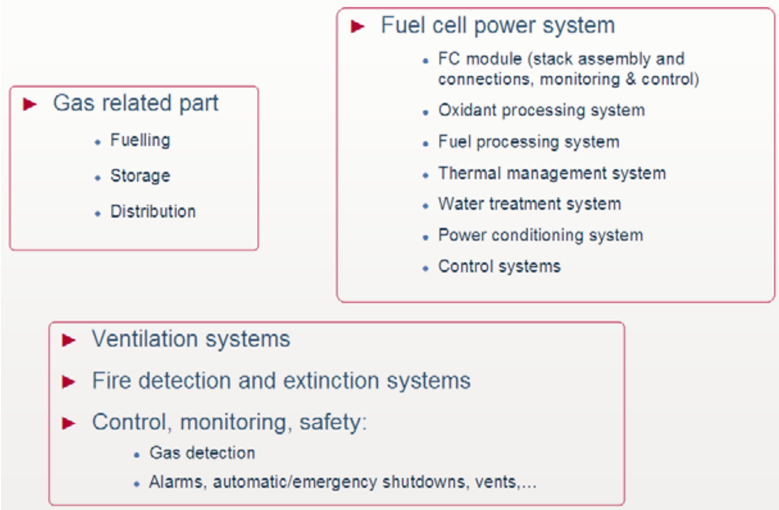
In the guidelines an overview of the functional requirements embodied in the guidelines to achieve its objective is presented, together with an extensive list of documents and procedures to be submitted. The guidelines contain prescriptive recommendations, risk analysis, tests & trials and operational recommendations. In order to assess all aspects of the fuel cell technology in a practical way, the guidelines have been divided into eight chapters and one appendix as depicted in Figure 5. A functional breakdown of the installation is provided for easy reference, see Figure 6. The remainder of this section provides an overview of the key points of the guidelines.

Figure 5: Table of the contents of the guidelines

Chapter 1 – General
Chapter 2 – Ship Arrangements and System Design
Chapter 3 – Fire Safety
Chapter 4 – Electrical Systems
Chapter 5 – Control, Monitoring and Safety Systems
Chapter 6 – Fuel Cell Power System
Chapter 7 – Manufacture, Workmanship and Testing
Chapter 8 – Operational and Training Requirements

Appendix 1 – Scope of the Risk Analysis

Figure 6: Breakdown of the installation




*Materials*

Components containing natural gas or hydrogen are to comply with the provisions of the IGC Code (metals). For non cryogenic gas, in particular compressed gas, other non-metallic materials may be applied subject to special examination.

Components in contact with hydrogen should 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°C to +85°C (normal conditions including filling or discharging). 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 vapour in the surrounding environment. Care is to be taken to effectively mitigate this risk.

*General arrangement*

The arrangement and number of machinery spaces and the design of the safety control systems should be such that in case of leakage in a gas supply pipe, making shutdown of the gas supply necessary, this will not lead to the loss of essential functions of the ship (propulsion, electrical production).

The arrangement and location of spaces for gas fuel storage, distribution, processing and use should be such that the number and extent of hazardous areas is kept to a minimum. The spaces are recommended to have as simple geometrical and internal arrangement as possible in order to minimize the possibility of entrapping explosive mixtures. Gas fuel storage, gas compressors, fuel processing systems, fuel cell modules and power conditioning systems should be located in different spaces. Spaces in which fuel processing equipment is located are to comply with the same requirements as machinery spaces in which fuel cell stacks are located.

Machinery spaces can be categorized into two configurations:

1. Gas safe machinery spaces: arrangements in machinery spaces are such that the spaces are considered gas safe under all conditions, normal as well as abnormal conditions, i.e. inherently gas safe;
2. ESD protected machinery spaces: 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. In the event of abnormal conditions involving gas hazards, emergency shutdown (ESD) of non-safe equipment (ignition sources) and machinery is to be automatically executed while equipment in use or active during these conditions are to be of a certified safe type.

Recommendations for means of access to the gas dangerous spaces described above are provided. In addition, recommendations for the protected location of gas tanks and supply lines are given.

*Gas fuel supply*

All gas supply piping within gas safe machinery space boundaries should be enclosed in a gas tight closure, i.e. double wall piping or ducting. Low pressure gas supply piping with (pressure less than 10 bars) located within ESD protected machinery spaces equipped with an individual exhaust ventilation system may be accepted without gas tight external enclosure if the areas occupied by flanges, valves and other components of the gas supply system are gas tight enclosed.

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

The thickness of the gas piping should be in conformity with formulae specified in the guidelines (general pipe design and arrangement). Gas pipes should not be located less than 760 mm from the ship's side and should not pass through accommodation spaces, service spaces or control stations. Gas fuel piping may pass through or extend into other spaces provided that the piping is double walled or ducted and additional requirements regarding ventilation, prevention of mechanical damage and gas detection are complied with, while protective measures need to be taken to minimize the risk of injury to personnel in case of rupture of a high pressure pipe.

The gas piping should be installed with sufficient flexibility to account for hull deflections. Arrangements for provision of the necessary flexibility should 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*

Gas fuel can be stored in liquid or compressed state. The storage tank for liquefied gas should be an independent tank type C in accordance with the IGC Code, including pressure relieve valves. It should be possible to empty, purge gas and vent bunker tanks with gas piping systems. Inerting should be performed prior to venting to avoid an explosion in hazardous atmosphere in storage tanks and gas pipes. If hydrogen is used as, fuel inerting is preferably done using helium, which cannot freeze and form a plug when exposed to cold hydrogen. Air should be prevented from entering the piping system and the storage tanks in order to prevent formation of flammable mixtures. The system should be designed to withstand at least twice the anticipated number of filling cycles.

The design and construction of compressed gas storage tanks should be in accordance with recognized standards (e.g. BV Rules Pt C, Ch 1, Sec 3). The applicability of the chosen standards for the containment system to seagoing conditions is to be demonstrated. Pressure relieve valves are to be fitted. The system should be designed to withstand the anticipated filling cycles during 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 case of a collision or grounding, with 760 mm as the absolute minimum inboard distance from the side shell. Gas in liquid state can be stored with a maximum acceptable working pressure of 10 bars. Storage of compressed gas below deck may be permitted upon special consideration if requirements regarding relief valve settings, thermal protection, gas detection, ventilation and fixed fire extinguishing are complied with. The storage tank and associated valves and piping should be located in a space designed to act as a second barrier in case of liquid or compressed gas leakage. For ships for which essential services depend on the fuel cell system the fuel storage should be divided between two or more tanks of approximately equal size, which are located in separate compartments.

The supports and fixation of independent storage tanks, either for compressed or liquefied gas storage, should be designed in order to prevent movement of the tank under static and dynamic loads associated to the ship motions, while allowing contraction and expansion due to tank temperature and internal pressure variations, as well as hull deflections, without undue stressing of the tank and the hull structure. The design loads for the tank supports and fixations are to be derived from an evaluation of the ship motions providing the most probable largest loads the ship will encounter during its operating life (normally $10^8$ wave encounters, corresponding to an operating life of about 20 years).

Suitable supports are to be provided to withstand collision forces acting in different directions on the tank. In addition, suitable arrangements are to be provided to keep the gas storage tanks in place in the event of flooding of the tank room to prevent damages resulting from buoyancy forces acting on the tanks. Depending on the design characteristics a fatigue analysis of the tank supports and fixations may be necessary.

*Electrical equipment*

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

*Ventilation systems*

Ventilation is a key safety feature of gas fuelled power systems. Good air circulation in all spaces, in particular with respect to preventing the possibility of the formation of explosive gas mixture pockets in the space is of paramount importance. The guidelines provide extensive recommendations for enforced ventilation of gas related spaces and gas pipe ducting, as well as for the location of ventilation inlets and outlets and pressure relief outlets.

The ventilation system for machinery spaces containing gas utilization equipment should be independent of all other ventilation systems. Ventilation should be monitored, including alarms. Electrical installations should be disconnected if ventilation cannot be restored for an extended period. Any ducting used for the ventilation of hazardous spaces should be separated from that used for the ventilation of non-hazardous spaces. Means should be provided to indicate any loss of the required ventilation capacity.

*Detection, monitoring & 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 need to 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 of the fuel cell installation), highlighting the use of the different monitoring and detection systems, the associated alarms and the follow up actions (automatic shutdown of the main tank valve or automatic shutdown of the gas supply to the concerned machinery space). For gas detection at 40% LFL two independent gas detectors located close to each other are required for redundancy reasons, unless the gas detector is of self monitoring type. Redundancy for the detection of critical hydrogen concentration is also considered to account for possible detector failure.

*Risk analysis*

A risk analysis of the fuel cell installation systems should be performed to assess the consequences of a failure affecting the concerned systems and/or a gas leakage. The required analysis can be a FTA, FMEA, HAZOP analysis, a combination of these techniques or another type of analysis providing equivalent information. The risk analysis should be based on the single failure concept, which means that only one failure needs to be considered at the same time. Both detectable and non detectable failures are to be considered. Consequences failures, i.e. failures of any component directly caused by a single failure of another component, are also to be considered.

The scope of the risk analysis should be as follows:

1. Identify all the possible failures in the concerned systems which could lead to a loss of the assigned function;
2. Evaluate the consequences;
3. Identify the failure detection method;
4. Identify the corrective measures:
    a. In the system design, such as redundancies or safety devices, monitoring or alarm provisions which permit restricted operation of the system;
    b. In the system operation, such as initiation of the redundancy or activation of an alternative mode of operation.

As a minimum, the risk analysis should be performed for the following systems and functions:

- Fuel gas piping system;
- Fuel gas containment systems (gas pipe ducts) and associated ventilation systems;
- Gas detection systems;
- Control, monitoring and safety systems;
- Fuel cell power system, containing the fuel cell module, oxidant processing system, fuel processing system, thermal management system, water treatment system, water discharge system, power conditioning system and their control systems. The analysis should cover failure of any of these subsystems, as well as change in air and gas fuel quality and deviation of any process parameter (HAZOP analysis);
- Gas leakage;
- Black-out;
- Human factor (procedures requiring human action).

The results of the risk analysis should be documented and confirmed by a practical test.

*Test and trials*

Factory testing is required for materials, components and for system assemblies. The complete installation should be tested onboard. Lists and descriptions of tests that should be performed, or already performed (for type approved equipment), should be defined and presented as for agreement. Specific tests are needed for components in contact with hydrogen (relevant tests could be derived from approval tests for cars hydrogen tanks).

The guidelines provide test recommendations for gas tanks and gas piping in accordance with the IGC Code and the interim BLG guidelines, including welding tests, after assembly hydrostatic tests and onboard system tests. In addition, test recommendations for valves intended operating at a working temperature below -55°C are included. Prototypes for expansion bellows in gas piping, including joints, should also be tested. The fuel cell power system tests should be derived from extensive type approval and routine tests as described in IEC 62282-3-1 et -2.

Prior to servicing, a complete set of installation trials should be performed. The program of trials should be documented and presented for approval and should at least cover tests of the following items:

- All control, monitoring and safety systems;
- All procedures;
- All protective measures installed following the risk analysis results.

BV rules for regulatory machinery tests onboard should also be considered for establishing the trials program (Pt C, Ch 1, Sec 15).

*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, as well as for special training of crew members with direct responsibility on gas related operations.

**Closure**

As a consequence of the increasing awareness with regard to the environmental impact of shipping, the industry is looking for ways to reduce exhaust gas emissions (NOx, SOx, GHG and PM). In addition, the recent volatility in the oil price, combined with the notion that fossil fuel will become increasingly scarce, is driving ship owners and operators to consider alternative ways to generate power onboard.

To this end, fuel cells appear to be a promising solution for clean and efficient electrical power generation onboard ships. If hydrogen is used as energy carrier (fuel), the onboard electricity production is fully independent of fossil fuel and therefore very clean. When hydrogen is produced by non-fossil fuel as well, the total energy cycle will become very clean.

Today, fuel cell technologies have not yet fully matured to a level enabling large scale deployment. Important issues are the lack of experience on long term performance, the control of gas related safety issues, the high acquisition price, the limited availability and fuel distribution network and, importantly, the lack of comprehensive regulatory framework covering the application of fuel cell technologies onboard ships (marine environment).

Prototype testing is of paramount importance to resolve these issues. At the same time it is recognised that it is difficult to develop these prototypes without regulatory guidance. In response Bureau Veritas has developed a comprehensive set of guidelines for fuel cell systems on commercial ships to assist clients interested in using such pioneering technologies. The guidelines combine existing regulations for gas fuelled ships with regulations for terrestrial fuel cell power systems adapted to the application onboard ships.

The guidelines are now tested on a number of pilot projects, of which the Hydrogen Hybrid Harbour Tug is a good example. The experience feedback of using the guidelines in a practical situation will be used to refine and further complete the guidelines. Bureau Veritas is looking forward to work together with partners within the industry to further develop the use of clean technologies in shipping.

### References

[1] European Commission; “Hydrogen Energy and Fuel Cells – A vision of our future”; Final Report of the High Level Group; European Commission; 2003

[2] Wijsmuller, M.; “How Green Can You Make a Tug?”; 20th International Tug & Salvage Convention and Exhibition; Day 2, Paper 8; Singapore, 19th-23rd May 2008

# Annex B. Característiques Viking Lady

# MS Viking Lady


**MS Viking Lady – 92m Platform Supply Vessel/LNG. Delivery in March 2009 by West Contractors AS, Ølensvåg, Norway as yard no. 30 to Eidesvik, Norway. The design is by Vik & Sandvik AS, Fitjar, Norway.**

**Principal particulars**

| | |
|---|---|
| Length o.a.: | 92 m |
| Length p.p: | 84 m |
| Breadth mid: | 21,00 m |
| Depth to main deck: | 9,60 m |
| Gross tonnage: | 6125 GT |
| Speed: | 15,5 knots |
| Class: | DNV +1A1, supply vessel, SF, E0, DP AUTR, Gas fuelled, LFL*, Oil Rec, Clean Design, COMF-(V3), NAUT-OSV(A), Ice C. FiFi-1, dk (+) and HL(p) |

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NO-5582 Ølensvåg, Norway
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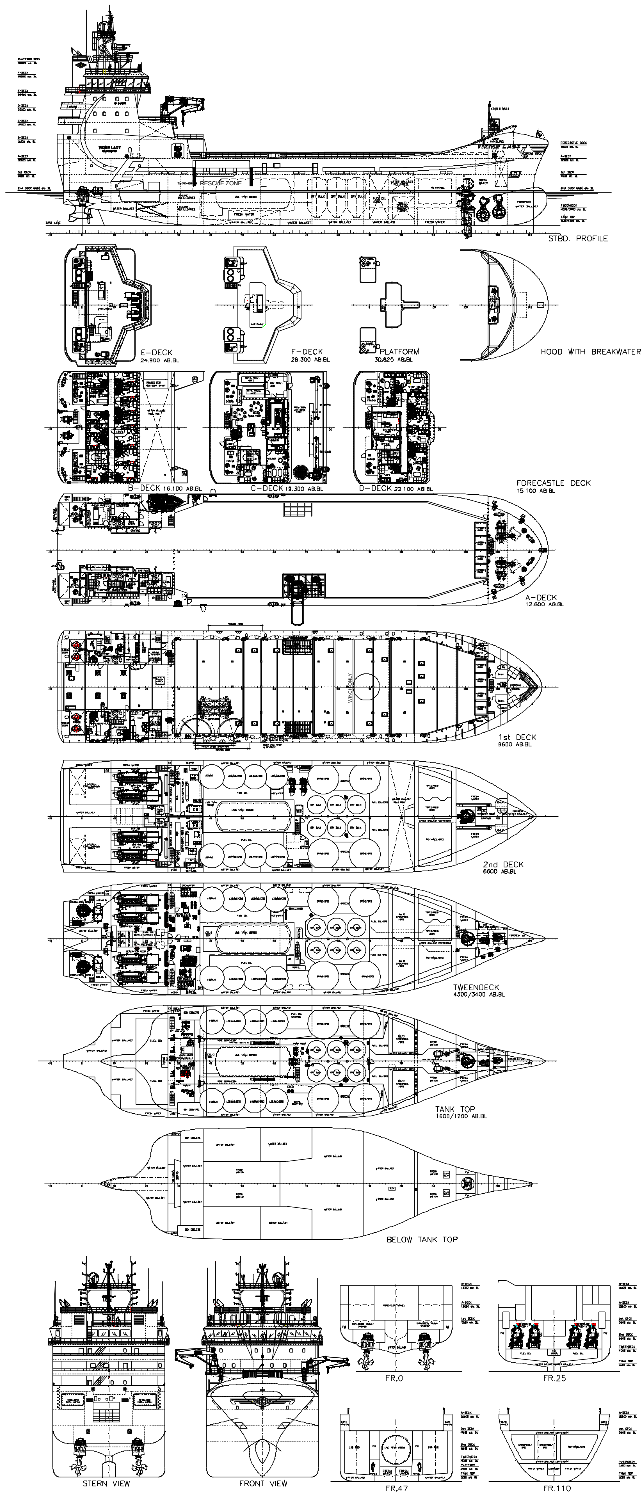
# Vessel information

# MS Viking Lady




***Dieselelectric Propulsion system***

Main Motors: 4 x Wärtsilä 6R32DF 2010kW
Main Generators: 4 x Alconza NIR 6391 A-10LW 1950kW
Propeller system: 2 x Rolls Royce AZP 100FP
Electric motor: 2 x Alconza QD 560 M2-6W 2300kW
Sidethrusters: 2 x Rolls Royce TT2200 DPN FP 1200kW
Azimuth thruster: 1 x Rolls Royce ULE 1201 FP, 880 kW
Emergency diesel generator: Volvo Penta D9-MG-RC 160 kW

***Electronical equipment***

Radar 10 cm: Furuno FCR-2837S
Radar 3 cm: Furuno FCR-2837
ECDIS: Telchart Tecdis T2137
Autopilot: Simrad AP-9
Gyrocompass: Simrad GC-80
Speed log: Furuno DS-800
Dyn Pos System: Kongsberg K-Pos 2
Radar Transponder Jotron, Tron SART
Echo Sounder: Furuno FE 700
Sat Phone/fax Telenor V-Sat 4996
PA System: Zenitel type ACM
AIS: Furuno FA-150
GPS: Furuno GP-150
VDR: Furuno VR-5016
Sound reception sys.: Sento VSS-111
VHF: Sailor RT2048
Radio plant: Furuno GMDSS A3
MF/HF: FS-1570
VHF/DSC: FM-8800S
Inmarsatt C
Weather faximile: Furuno Fax-208A
VHF direction finder: TD-L 1550 A
Navtex receiver: NX700B
VHF Motorola GM360

***Ship systems***

Separators: Alfa Laval
Bulk Compressors: 2 x Atlas Copco TMS 200
Oily water separator: Ocean Clean EB 2,5
Vent./AC-arrangement: Aeron AS
Watermist plant: Marioff
Main alarm system: Wärtsilä Norway
Mob boat: Mako 655
Liferafts: 4 x Viking 25 DK
Bulk storage system Randaberg Sveiseindustrier AS
Ballastmonitoring: Wärtsilä Norway
Searchlights: Norselight 2000 W
Fire alarm: Eltek
Steering Gears: Rolls-Royce
Switchboard: 690, 440, 230V - Wärtsilä

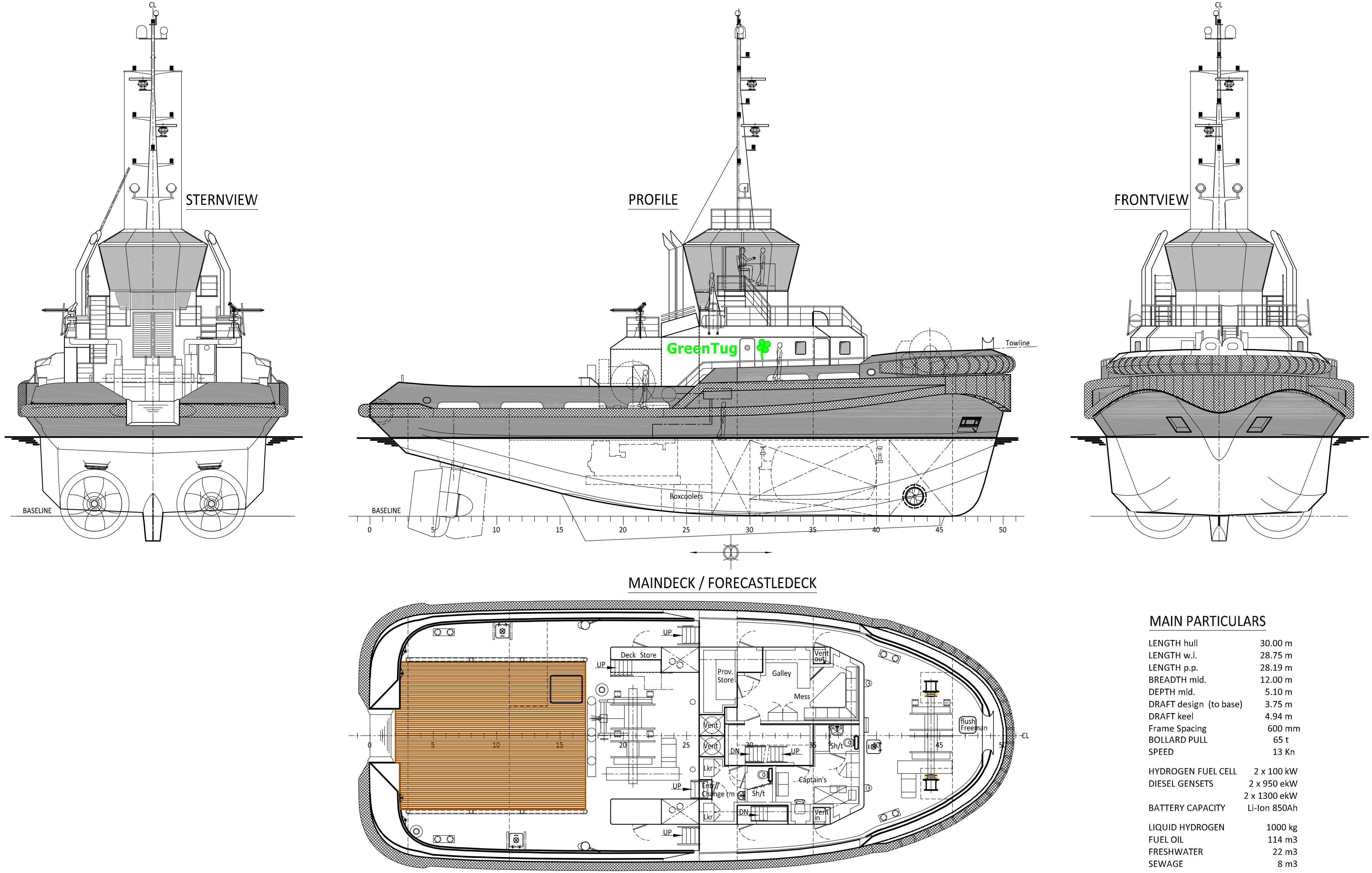
***Capacities***

Fuel oil: 1000 m3
Fresh water: 993 m3
Methanol: 167 m3
Water Ballast: 3518 m3
Dry bulk: 318 m3
Accommodation: 25 men
Deck area: 945 m2
Deck load: 3450 tonnes

***Deck equipment***

Deck Crane: TTS 1 x GPK-80, 1 x GPK 260
Tugger winch: Karmøy Winch
Anchor windlass: Karmøy Winch

# **Annex C. Greentug**




## MAIN PARTICULARS

| | |
|---|---|
| LENGTH hull | 30.00 m |
| LENGTH w.l. | 28.75 m |
| LENGTH p.p. | 28.19 m |
| BREADTH mld. | 12.00 m |
| DEPTH mld. | 5.10 m |
| DRAFT design (to base) | 3.75 m |
| DRAFT keel | 4.94 m |
| Frame Spacing | 600 mm |
| BOLLARD PULL | 65 t |
| SPEED | 13 Kn |
| HYDROGEN FUEL CELL | 2 x 100 kW |
| DIESEL GENSETS | 2 x 950 ekW |
| | 2 x 1300 ekW |
| BATTERY CAPACITY | Li-Ion 850Ah |
| LIQUID HYDROGEN | 1000 kg |
| FUEL OIL | 114 m3 |
| FRESHWATER | 22 m3 |
| SEWAGE | 8 m3 |

# Annex D. Equacions de les piles de combustible

## 10.4 Equacions de les piles de combustible

Podem classificar les equacions que regeixen les piles de combustible en diverses àrees segons la seva naturalesa:

1) Equacions termodinàmiques
2) Equacions de transferència de calor
3) Equacions electroquímiques
4) Equacions del transport de càrrega
5) Equacions del transport de massa
6) Equacions generals

## 1.Equacions termodinàmiques

Un dels conceptes és el potencial de Nernst (recordar que es tracta del potencial ideal en circuit obert de la pila). Destacar que per cada tipus de pila de combustible tindrem condicions diferents de treball.

Així que el potencial de Nernst és:

$$E = E_r - \frac{R \cdot T}{n \cdot F} \ln\left[\prod_i \left(\frac{p_i}{p_0}\right)^{vi}\right] \quad [1]$$

$E$ és el voltatge real de la pila, $E_r$ és el voltatge en condicions estàndard, $R$ és la constant universal dels gasos, $T$ és la temperatura absoluta, $n$ és el nombre d'electrons intercanviats a la reacció, $F$ és la constant de Faraday, $p_i$ és la pressió parcial del gas "i", $p_0$ és la pressió de referència.

Per formular aquesta equació es considera que els gasos es comporten com a gasos ideals, ja que les pressions a les que treballen són baixes. També es pot extreure que el potencial d'una pila de combustible és funció de la temperatura i la pressió dels gasos reactius.

## 2.Equacions de transferència de calor

Una forma d'augmentar l'eficiència general de la pila de combustible és aprofitant la calor generada durant la reacció electroquímica per a cogeneració. Però per a que aquest fet es pugui aprofitar la pila ha de treballar a altes temperatures.
Suposem una pila de combustible qualsevol, el combustible i el comburent (oxigen) en condicions T i P. L'oxigen té una certa fracció molar ( $X_{O_2}$ ) a més d'un flux màssic determinat. Quan els gasos entren a la pila reaccionen formant diòxid de carboni i vapor d'aigua, per tant:

$$C_aH_b + \left(a + \frac{b}{4}\right)O_2 \Rightarrow aCO_2 + \frac{b}{2}H_2O \text{ [2]}$$

Tindrem que el balanç energètic de la pila de combustible serà:

$$\sum \left(h_i\right)_{entrada} = \sum \left(h_i\right)_{sortida} + W_{elèctric} + Q \text{ [3]}$$

L'energia d'entrada al sistema són les entalpies del combustible i del comburent. L'energia de sortida consta de 3 termes: les entalpies dels productes de la reacció, el treball elèctric produït i la calor que es genera durant les reaccions electroquímiques.

L'entalpia d'un gas es calcula mitjançant:

$$h = \dot{m} \cdot c_p \cdot T \text{ [4]}$$

$\dot{m}$ és el cabal màssic del gas ( $kg \cdot s^{-1}$), $c_p$ és la calor específica ( $J \cdot kg^{-1} \cdot K^{-1}$ ), T és la temperatura (K). Recordar que la pila de combustible és un sistema obert, la massa dels gasos no és constant però el cabal màssic sí, i l'entalpia es dóna en watts (W).

## 3.Equacions electroquímiques

Són les diverses equacions electroquímiques que es necessiten per modelar les corrents i els potencials de la pila de combustible.

### Cinètica de l'elèctrode

El desenvolupament de les reaccions electroquímiques en les capes del catalitzador es manifesta amb la transferència d'electrons i en un canvi de l'energia lliure de Gibbs. El ritme al que es desenvolupen aquestes reaccions ve donat pel corrent elèctric. Segons la Llei de Faraday, la densitat de corrent és proporcional a la càrrega transferida i al consum reactiu per unitat d'àrea.

$i = n \cdot F \cdot j$ [5]

$i$ és la densitat de corrent ($A \cdot m^{-2}$), $n \cdot F$ és la càrrega transferida per unitat de massa ($C \cdot mol^{-1}$), $j$ és el flux de reactiu per unitat d'àrea ($mol \cdot s^{-1} \cdot m^{-2}$). En l'equilibri, les reaccions de reducció i d'oxidació són simultànies (els reactius es consumeixen al mateix temps).

El consum del reductor i de l'oxidant és proporcional a la seva concentració, de manera que es pot escriure.

$$j_f = k_f \cdot C_{Ox}$$
$$j_b = k_b \cdot C_{\mathrm{Re}}$$
[6]

$k_f$ és el coeficient de velocitat de la reacció d'oxidació ($s^{-1}$), $k_b$ és el coeficient de la reacció de reducció ($s^{-1}$), $C_{Ox}$ i $C_{\mathrm{Re}}$ són les concentracions superficials dels reactius ($mol \cdot m^{-2}$). La diferència entre els electrons cedits i els electrons consumits és el corrent generat, que és:

$i = n \cdot F \cdot (k_f \cdot C_{Ox} - k_b \cdot C_{\mathrm{Re}})$ [7]

En l'equilibri les dues reaccions tenen la mateixa velocitat, així que la densitat de corrent és 0. D'altra banda tenim que la velocitat a la que les dues reaccions es desenvolupen en l'equilibri s'anomena densitat de corrent d'intercanvi. Els coeficients de velocitat de la reacció depenen de l'energia lliure de Gibbs:

$$k = \frac{k_B \cdot T}{h} \cdot \exp\left(-\frac{\Delta G}{R \cdot T}\right)$$ [8]

$k_B$ és la constant de Boltzmann ($1{,}3805 \cdot 10^{-23} J \cdot K^{-1}$), h és la constant de Planck ($6{,}621 \cdot 10^{-34} J \cdot s^{-1}$). Aplicades a les reaccions de reducció i d'oxidació, l'energia lliure de Gibbs es pot expressar com:

$$\Delta G = \Delta G_{ch} - \alpha_{Ox} \cdot F \cdot E$$
$$[9]$$
$$\Delta G = \Delta G_{ch} + \alpha_{\mathrm{Re}} \cdot F \cdot E$$

$\Delta G_{ch}$ es refereix a la part química de l'energia lliure de Gibbs, $\alpha$ és el coeficient de transferència, F és la constant de Faraday, E és el potencial. Substituint finalment obtenim:

$$k_f = k_{0,f} \cdot \exp\left(-\frac{\alpha_{\mathrm{Re}} \cdot F \cdot E}{R \cdot T}\right)$$
$$[10]$$
$$k_b = k_{0,b} \cdot \exp\left(-\frac{\alpha_{Ox} \cdot F \cdot E}{R \cdot T}\right)$$

Aquestes equacions les substituïm a $i = n \cdot F \cdot (k_f \cdot C_{Ox} - k_b \cdot C_{\mathrm{Re}})$ i així obtenim:

$$i = n \cdot F \left[ k_{0,f} \cdot C_{0x} \cdot \exp\left(-\frac{\alpha_{\mathrm{Re}} \cdot F \cdot E}{R \cdot T}\right) - k_{0,b} \cdot C_{\mathrm{Re}} \cdot \exp\left(\frac{\alpha_{0x} \cdot F \cdot E}{R \cdot T}\right)\right] [11]$$

Sabent que la densitat de corrent val 0 i el potencial val $E_r$, la densitat de corrent d'intercanvi val:

$$i_0 = n \cdot F \cdot k_{0,f} \cdot C_{Ox} \cdot \exp\left(-\frac{\alpha_{\mathrm{Re}} \cdot F \cdot E_r}{R \cdot T}\right) = n \cdot F \cdot k_{0,b} \cdot C_{\mathrm{Re}} \cdot \exp\left(-\frac{\alpha_{Ox} \cdot F \cdot E_r}{R \cdot T}\right) [12]$$

Per obtenir finalment:

$$i = i_0 \cdot \left[ \exp\left(-\frac{\alpha_{\mathrm{Re}} \cdot F \cdot (E - E_r)}{R \cdot T}\right) - \exp\left(-\frac{\alpha_{Ox} \cdot F \cdot (E - E_r)}{R \cdot T}\right)\right] [13]$$

La darrera fórmula es coneix com l'equació de Butler-Volmer, i explica la relació existent entre la densitat de corrent i el potencial de la pila de combustible. $E - E_r$ s'anomena sobrepotencial (diferència de potencial necessària per que la pila pugui generar corrent elèctric).

**<u>Pèrdues de voltatge</u>**

La resposta de la pila de combustible es veu afectada per una sèrie de pèrdues, tals com les pèrdues d'activació, pèrdues de transferència màssica i pèrdues òhmiques. Les pèrdues d'activació estan relacionades amb el sobrepotencial de la pila que és necessari per superar l'energia d'activació i iniciar així la reacció electroquímica. Les pèrdues per activació a l'ànode i el càtode són:

$$\Delta V_{act,a} = E_a - E_{r,a} = \frac{R \cdot T}{\alpha_a \cdot F} \cdot \ln\left(\frac{i}{i_{0,a}}\right)$$

[14]

$$\Delta V_{act,c} = E_c - E_{r,c} = \frac{R \cdot T}{\alpha_c \cdot F} \cdot \ln\left(\frac{i}{i_{0,c}}\right)$$

La densitat de corrent d'intercanvi a l'ànode és de $10^5 A \cdot m^{-2}$, mentre el del càtode és de $1 A \cdot m^{-2}$, així que tenim que el sobrepotencial a l'ànode és molt més petit, així que les pèrdues per activació també ho seran. El fet que el sobrepotencial del càtode sigui alt implica que la reacció de reducció de l'oxigen sigui molt més lenta que no pas la reacció d'oxidació de l'hidrogen.

**<u>Pèrdues per corrents interns i corrents creuats</u>**

L'electròlit o membrana és un medi que no condueix electrons ni permet la difusió dels gasos reactius. Tot i així la impermeabilitat no és perfecta i hi ha una petita part de l'hidrogen que va directament al càtode. Així els electrons troben una via de pas alternativa a la del circuit amb la càrrega, disminuint el rendiment de la pila. Aquestes pèrdues són negligibles durant el funcionament de la pila i són importants quan les densitats de corrent són molt petites o si la pila es troba en situació de circuit obert.

## <u>4.Equacions del transport de càrrega</u>

**<u>Pèrdues de voltatge</u>**

Aquest tipus de pèrdues són ocasionades pel transport de càrrega, i es manifesten en la resistència al pas de ions per part de l'electròlit i a la resistència al pas dels electrons per part dels components conductors elèctrics de la pila. Aquestes pèrdues es poden formular amb la Llei d'Ohm:

$\Delta V_{act} = i \cdot R_e$ [15]

$i$ és la densitat de corrent ($A \cdot m^{-2}$), $R_e$ és la resistència equivalent ($\Omega \cdot m^2$). La resistència equivalent és la suma de la resistència elèctrica, la resistència iònica (valor típic de $0{,}15 \Omega \cdot m^2$) i la resistència de contacte (valor típic de $0{,}15 \Omega \cdot m^2$). Si comparem els valors de les 3 resistències anteriors veiem que el valor de la resistència elèctrica es pot menysprear.

**Transport iònic**

Els ions es mouen a través de la membrana utilitzant dues alternatives. Per un costat, es mouen a través de l'estructura química del Nafion gràcies als grups d'àcid sulfònic que proporcionen un lloc pel transport dels protons. D'altra banda els protons tenen un mètode alternatiu per a moure's a través de la membrana: les molècules d'aigua. Ja sigui mitjançant la hidratació dels gasos reactius o aprofitant la mateixa aigua formada al càtode, els protons es poden enganxar a les molècules d'aigua per formar ions hidroni sent transportats dins la fase aquosa. Per això és tant important que la membrana estigui ben humida, sinó la seva conductivitat es veuria reduïda molt.

**5.Equacions del transport de massa**

El transport màssic dels reactius és un aspecte essencial per millorar la resposta d'una pila de combustible, ja que la concentració dels reactius a les capes del catalitzador en depèn directament. El transport en massa es pot dividir en dos grups: el transport de canals de flux (circulen els gasos reactius per arribar fins a l'elèctrode) i el transport d'elèctrodes. L'equació de Nernst mostra la influència de la pressió en el voltatge de la pila, és a dir, a mesura que es consumeixen els reactius disminueix la seva concentració i això implica una reducció en la seva pressió i per tant de voltatge. Si no s'alimenta adequadament la pila amb reactius, el rendiment es veu afectat, així que les pèrdues de voltatge per transport de massa segueixen l'equació de Nernst:

$$\Delta V_m = \frac{R \cdot T}{n \cdot F} \ln\left(\frac{C_0}{C_i}\right) \text{ [16]}$$

$C_0$ és la concentració del gas reactiu [$mol \cdot m^{-3}$], $C_i$ és la concentració del gas a la capa del catalitzador ($mol \cdot m^{-3}$). Pel que fa al transport dels gasos en els elèctrodes, es considera que es mouen per difusió segons la Llei de Fick:

$$N = A \cdot D \cdot \frac{\left(C_0 - C_i\right)}{\delta} \text{ [17]}$$

$N$ és el flux de gas reactiu ($mol \cdot s^{-1}$), $A$ és l'àrea activa de l'elèctrode ($m^2$), $D$ és el coeficient de difusió ($m^2 \cdot s^{-1}$), $\delta$ és el gruix de material que travessa el gas durant la difusió. En una pila en estat estacionari, el consum de reactius en la reacció electroquímica és proporcional al flux difusiu:

$$N = \frac{i \cdot A}{n \cdot F} \quad [18]$$

Combinant les dues darreres equacions tenim:

$$i = n \cdot F \cdot D \cdot \frac{\left(C_0 - C_i\right)}{\delta} \quad [19]$$

Es veu que la densitat de corrent i la concentració a la superfície estan relacionades de manera que si una augmenta, l'altre decreix. En el cas límit, la densitat de corrent no pot créixer més si $C_i$ és 0, perquè no hi hauria gas per poder dur a terme la reacció. Aquest corrent es coneix com corrent límit:

$$i_L = \frac{n \cdot F \cdot D \cdot C_0}{\delta} \quad [20]$$

Si dividim les 2 últimes equacions tenim que:

$$\frac{i}{i_L} = \frac{C_0 - C_i}{C_0} = 1 - \frac{C_i}{C_0}$$
$$ó \quad [21]$$
$$\frac{C_0}{C_i} = \frac{i_L}{i_L - i}$$

Si substituïm el quocient de $\Delta V_m = \frac{R \cdot T}{n \cdot F} \ln\left(\frac{C_0}{C_i}\right)$ [22] tenim:

$$\Delta V_m = \frac{R \cdot T}{n \cdot F} \cdot \ln\left(\frac{i_L}{i_L - i}\right) \quad [23]$$

Aquesta equació és l'expressió bàsica per les pèrdues de voltatge degut al transport màssic. S'observa que les pèrdues comencen a ser importants a mesura que la densitat de corrent s'acosta al seu valor límit. Per a valors petits de la densitat de corrent les pèrdues són gairebé nul·les.

**La corba de polarització**

Aquesta corba és la forma gràfica de resumir les pèrdues en una pila de combustible. Com es veu a la següent figura, tenim 3 zones:

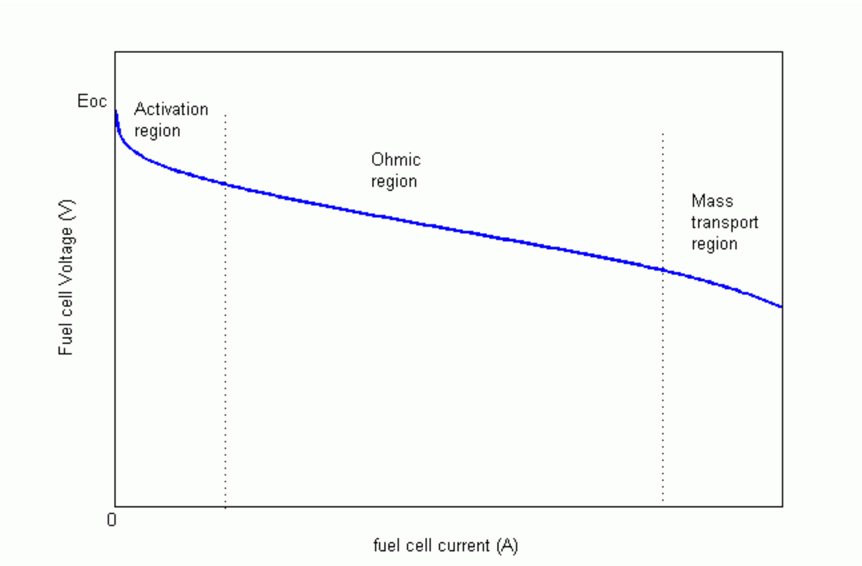



***Figura 1: Corba polarització d'una pila de combustible. Font: mathworks.es***

A la primera zona tenim una forta reducció del potencial de la pila per a densitats de corrent pràcticament 0, aquesta zona és la corresponent a les pèrdues per activació. La segona zona és molt lineal i correspon a les pèrdues òhmiques. Finalment, i per a densitats de corrent elevades, hi ha una reducció de potencial gran, corresponent a les pèrdues per transport màssic.

**6.Equacions generals**

Aquestes equacions es poden aplicar a qualsevol tipus de pila sense considerar la seva geometria.

**Conservació de la massa**

La següent equació expressa la conservació de la massa d'una pila de combustible:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = S_m \quad [24]$$

$\rho$ és la densitat ($kg \cdot m^{-3}$), $v$ és la velocitat ($m \cdot s^{-1}$), $S_m$ es refereix a una font de massa addicional. Aquesta equació és apta pels processos interns de la pila, tals com les reaccions electroquímiques.

**Conservació del moment**

Aquest fenomen es representa amb l'equació de Navier-Stokes.

$$\frac{\partial(\rho v)}{\partial t} + \nabla \cdot (\rho v) = -\nabla p + \nabla \cdot (\mu_{mescla} \nabla v) + S_M \text{ [25]}$$

$\mu_{mescla}$ és la viscositat dinàmica mitjana de la mescla $(kg \cdot m^{-1} \cdot s^{-1})$, p és la pressió del fluid en Pa, $S_M$ és el conjunt de forces externes al cos.

**Conservació de l'energia**

Les propietats dels materials de la pila i els ritmes de les reaccions depenen fonamentalment de la temperatura. Les variacions de la temperatura venen descrites per l'equació:

$$(\rho c_p)_{eff} \frac{\partial T}{\partial t} + (\rho c_p)_{eff} (v \cdot \nabla T) = \nabla \cdot (k_{eff} \nabla T) + S_e \text{ [26]}$$

$c_p$ és la capacitat calorífica específica mitjana $(J \cdot kg^{-1} \cdot K^{-1})$, T és la temperatura (K), k és la conductivitat tèrmica $(W \cdot m^{-1} \cdot K^{-1})$, $S_e$ és el terme de font d'energia.

**Conservació de les espècies**

Aquesta equació representa la conservació màssica de les espècies per a cada reactiu. Per la fase gas és:

$$\frac{\partial(\varepsilon \rho x_i)}{\partial t} + \nabla \cdot (v \varepsilon \rho x_i) = (\nabla \cdot \rho D_i^{eff} \nabla x_i) + S_{s,i} \text{ [27]}$$

$\varepsilon$ és la porositat de la capa de difusió gasosa, GDL (Gas Diffusion Layer), $x_i$ és la fracció molar de l'espècie gasosa, $D_{eff}$ és el coeficient de difusió de la GDL $(m^2 \cdot s^{-1})$, $S_{s,i}$ és la font addicional d'espècies. Aquest últim terme és zero en totes les parts de la pila excepte en les capes del catalitzador, on les espècies són consumides i creades en les reaccions electroquímiques.

**Conservació de la càrrega**

Aquesta equació descriu el transport del corrent en una pila de combustible. Pel corrent elèctric es té:

$$\nabla \cdot (\sigma_s^{eff} \nabla \phi_s) = S_{\phi s} \text{ [28]}$$

Pel corrent iònic es té:

$$\nabla \cdot (\sigma_m^{eff} \nabla \phi_m) = S_{\phi m} \text{ [29]}$$

$\sigma_m^{eff}$ i $\sigma_s^{eff}$ són la conductivitat iònica a la fase electrolítica i la conductivitat elèctrica en fase sòlida ($Sm^{-1}$), $\phi_s$ és el potencial elèctric de la fase sòlida (V), $S_\phi$ és el terme de font, que representa el corrent volumètric de transferència i que és nul fora de les capes del catalitzador.

**Transport màssic i elèctric als elèctrodes**

Hi ha 3 models per explicar aquest cas.

1) Llei de Fick

   Aquest és el model més simple de difusió, ja que només contempla el cas de difusió amb dues espècies gasoses.

   $N_i = -cD_{ij}\nabla x_i$ [30]

   $c$ és la concentració molar total (mol $m^3$), $D_{ij}$ és la difusivitat ($m^2 s^{-1}$), $x_i$ correspon a la fracció molar del gas, $N_i$ correspon al flux màssic difusiu ($kg \cdot m^{-2} \cdot s^{-1}$).

2) Model D'Stefan-Maxwell

   Aquest model s'utilitza en cas de tenir sistemes amb diversos components (N espècies diferents).

   $\nabla x_i = -\sum_{j=1}^{N} \frac{1}{cD_{ij}}(x_j N_i - x_i N_j)$ [31]

3) Dusty Gas

   Aquest model és una variant del model D'Stefan-Maxwell.

Pel que fa al transport de càrrega, les equacions que modelen el moviment dels electrons a través dels elèctrodes i el moviment dels ions a través de l'electròlit es basen en la Llei d'Ohm, un balanç de càrrega i les equacions de conservació de la càrrega. Es defineix el corrent elèctric i el corrent iònic com:

$$\begin{aligned} i_e &= -\sigma_s^{eff} \cdot \nabla\phi_s \\ i_i &= -\sigma_m^{eff} \cdot \nabla\phi_m \end{aligned} \quad [32]$$

Aquestes dues equacions es troben escrites en forma diferencial. $i_e$ correspon al corrent elèctric i $i_i$ al corrent iònic. $\phi$ correspon al potencial, $\sigma^{eff}$ és la conductivitat.

**Annex E. Normativa GL**

# Rules for Classification and Construction

# VI Additional Rules and Guidelines

## 3 Machinery Installations

## 11 Guidelines for the Use of Fuel Cell Systems on Board of Ships and Boats

OPERATING 24/7

Edition 2003

**The following Guidelines come into force on March 1st, 2003**

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"General Terms and Conditions" of the respective latest edition will be applicable
(see Rules for Classification and Construction, I - Ship Technology, Part 0 - Classification and Surveys).



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**Section 7 Explosion Protection**



**Section 8 Control, Regulating, Monitoring and Alarm Devices**



**Section 9 Protective Devices and Protective Systems**



**Section 10 Trials of the System**

# Section 1

# General

## A. Scope of Application

**1.** These Guidelines apply to the use of fuel-cell systems (FC systems) permanently installed on ships and boats. They describe the technical requirements for the safe operation of FC systems.

**2.** In the case of FC systems which are used as the sole means of propulsion, for the emergency electrical supply or for the supply of essential consumers in accordance with the GL Construction Rules, the additional requirements will be determined within the scope of an individual examination.

**3.** Designs which deviate from these Guidelines or from the applicable Rules may be approved if they are examined by GL for suitability and then approved as being equivalent.

**4.** Deviating designs are necessary to some extent for submersibles. These can be approved by GL, especially with regard to the ventilation systems and pressure relief devices.

**5.** For water craft with FC systems conforming to these Guidelines and having a rated output greater than or equal to 10 % of the rated output of the machinery installation the class notation **FC-xxx** will be assigned. The wild-card symbol **"xxx"** designates the percentage share of the FC system in relation to the rated output of the machinery installation.

For FC systems having a rated output lower than 10 % of the rated output of the machinery installation the class notation **with FC** will be assigned.

## B. Applicable Rules

### 1. Rules for Classification and Construction

In addition to these Guidelines, the following Rules for Classification and Construction shall apply, if applicable:

– Main Group I – Ship Technology
  Part 1 – Seagoing Ships
  Chapter 1 – Hull Structures

– Main Group I – Ship Technology
  Part 1 – Seagoing Ships
  Chapter 2 – Machinery Installations

  Here the following apply in particular:

  Section 1 General Rules and Instructions

  Section 8 Pressure Vessels

  Section 9 Oil Firing Equipment

  Section 10 Storage of Liquid Fuels, Lubricating, Hydraulic and Thermal Oils as well as Oil Residues

  Section 11 Piping Systems, Valves and Pumps

  Section 12 Fire Protection and Fire Extinguishing Equipment

  Section 15 Special Rules for Tankers

– Main Group I – Ship Technology
  Part 1 – Seagoing Ships
  Chapter 3 – Electrical Installations
  Chapter 4 – Automation

– Main Group I – Ship Technology
  Part 2 – Inland Waterway Vessels
  Chapter 2 – Machinery Installations
  Chapter 3 – Electrical Installations

– Main Group I – Ship Technology
  Part 3 – Special Craft

– Main Group II – Materials and Welding
  Part 1 – Metallic Materials
  Part 2 – Non metallic Materials
  Part 3 – Welding

### 2. Other rules

National and international regulations, such as **SOLAS-74, MARPOL 73/74**, IEC standards etc. shall be observed, if applicable.

## C. Definitions

### 1. Alarm system

System for generating an alarm when the upper or lower limiting values are transgressed. There is no automatic intervention in the system.

### 2. Fuel cell

A fuel cell is a source of electrical power in which the chemical energy of a fuel is converted directly into electrical energy by electrochemical oxidation (also known as "cold combustion").

### 3. Fuel cell stack

A fuel cell stack (FC stack) is a unit consisting of several fuel cells that are electrically connected in series, with internal interconnections for electricity and gas/liquid. An FC stack in the terms of these Guidelines also includes the pipe connection fittings as well as the connections required to supply the electrical energy.

### 4. Fuel cell system (FC system)

An FC system in terms of these Guidelines can comprise the following components:

– fuel cell stacks

– arrangements for the transfer and storage of fuel, including the necessary auxiliary equipment (e.g. heating/cooling)

– arrangements for fuel distribution

– arrangements for fuel conditioning, including any reformer systems, gas humidifiers etc.

– installation spaces, including the ventilation systems

– conditioning and storage of the oxidants (air or oxygen)

– electrolyte systems

– arrangements for the conditioning of residual gas and exhaust gas

– cooling systems

– interconnections between the systems

– safety, regulating and monitoring equipment

– electrical inverter systems

– other auxiliary systems

– other energy converters integrated into the system, e.g. gas turbines in systems with high-temperature fuel cells

### 5. Hazardous areas (Ex zones)

These are areas in which the accumulation of flammable gases or vapours in a hazardous concentration or quantity may be expected. Depending on the probability of an explosive atmosphere, hazardous areas are classed as explosion zone 0, 1 or 2 according to Section 7, B.

### 6. Protective devices

Protective devices detect critical deviations from limit values and prevent an immediate risk to persons, ship or machinery. In the event of a failure, protective devices transfer the system into a safe state and prevent uncontrolled restarting.

### 7. Protective systems

A protective system consists of the grouping of several protective devices to form a functional unit.

### 8. Safe areas

Safe areas are the zones outside of the hazardous areas of a ship.

## D. Environmental Conditions

In the selection, design and arrangement of all components of FC systems on seagoing ships, the environmental conditions described in the GL Construction Rules, Main Group I – Ship Technology, Part 1 – Seagoing Ships, Chapter 2 – Machinery Installations, Section 1, C. shall be applied.

For FC systems on inland waterway vessels and pleasure craft, the environmental conditions as per Main Group I, Part 2, Chapter 2, Section 1, C.3. and C.4. or Main Group I, Part 3, Chapter 3, Section 1, C.2. shall apply.

## E. Fuels

**1.** Fuels in terms of these Guidelines are the fuels kept in the storage tanks of the FC system as well as the fuels available after conditioning or distribution.

**2.** With the corresponding conditioning through the reforming process, FC systems can be supplied both with conventional marine fuels (flashpoint above 60 °C) and with fuels which have a flashpoint below 60 °C. The latter fuel types include, for example, methanol, liquefied gases such as LPG, the cryogenic liquefied gases LNG and LH2, as well as pressurized gases such as CNG, compressed hydrogen or propane.

**3.** For the use of fuels with a flashpoint of 60 °C or lower, the technical requirements specified in these Guidelines shall apply. Additional requirements may be stipulated by GL. Furthermore, the consent of the competent approval authority (e.g. Flag State Administration) is required.

**4.** For the use of fuels with a flashpoint above 60 °C, the requirements specified in the GL Construction Rules, Main Group I, Part 1, Chapter 2, Section 10 and 11, shall apply.

## F. Documents to be Submitted

### 1. General

The technical documents shall permit an assessment of the compliance of the system and its components with the applicable requirements of these Guidelines and of other rules that must be met. Insofar as needed for the assessment, the documents shall cover the design, production and functional principles, and shall permit a check that actual construction is in compliance with the documentation.

Once the documents submitted have been approved, they shall be binding. Any subsequent modifications require GL approval prior to implementation.

### 2. Safety concept

It shall be demonstrated that

- the FC systems function safely when used for their intended purpose including the maintenance activities
- malfunctions can be prevented with the aid of the monitoring, alarm and protective devices
- dangerous operational situations which according to general experience can arise, even though the time of occurrence cannot be predicted (e.g. critical deviations from limit values), and/or which occur as a result of possible negligence (e.g. foreseeable misuse) are brought under control
- the effects of damage are limited by appropriate precautionary measures

### 3. Safety functions

The documents submitted must show what technical safety measures or solutions are effective for the operational situations stated under 2. In addition, it shall be verified that the safety measures were selected according to the following sequence of the criteria:

- directly acting safety functions
- indirectly acting safety functions
- organizational safety precautions

### 4. Documents

The following documents shall be submitted in triplicate.

Before production of the FC system commences:

- description of the process and function of the FC system
- piping and instrumentation diagrams, with block circuit diagrams of the overall system, including parts lists or equipment lists
- technical documents of the components, including the fuel cell stacks themselves (descriptions, specifications, verification of suitability according to existing standards and rules, approvals and inspection certificates)
- electrical circuit diagrams, including the circuit diagrams of the alarm system and the protective system
- automation concept
- fire extinguishing concept
- plans of the hazardous areas (Ex zones)
- safety and emergency concept, including a safety analysis according to recognized procedures, e.g. fault tree analysis, see F.2. and F.3.

Before the trials according to Section 10:

- operation manual
- trials programme

## G. Testing and Trials

### 1. General

**1.1** FC systems are subject to the construction supervision and acceptance testing by GL. Compliance with the approved documents, the workmanship, the suitability of the material and the documentation of the material characteristics as well as conformance with the specification are checked.

**1.2** GL reserves the right to extend the scope of the tests, and also to subject to testing those parts which are not explicitly to be tested according to the Rules. For parts produced in series, the prescribed tests may be replaced by other tests agreed with GL.

### 2. Test steps

The testing of an FC system by GL comprises the following steps:

- evaluation of the technical concept

- examination of the system documentation, the technical documents for the components subject to mandatory testing, and the technical documents of the alarm and protective systems
- manufacturing tests, pressure tests and – if applicable – functional tests of parts and components
- factory test of control, regulating and protective devices, and of protective systems, at the manufacturer
- functional test and completeness check of the alarm and protective systems
- functional test and acceptance test of the overall system, including pressure and tightness tests and completeness checks, see Section 10
- determination of the periodical tests, insofar as these are not stipulated by the GL Classification Rules

On successful execution of the above-mentioned test steps, the proper construction and workmanship of the system in accordance with the provisions of these Guidelines is certified, and the Class Notation **FC** is assigned.

### 3. Pressure and tightness test

**3.1** The piping systems and components shall be subjected to a hydrostatic pressure test with a test pressure equal to 1,5 times the maximum working pressure as well as a tightness test with a test pressure equal to 0,9 times the maximum allowable working overpressure.

**3.2** The shut-off valves must be tested additionally for tightness with 1,1 times the maximum allowable working overpressure.

**3.3** A deviating procedure is only permissible if this is necessary for technical reasons and if it has been examined and approved by GL.

## H. Power supply of Essential Consumers

If the FC system is used to supply essential consumers as per Main Group I, Part 1, Chapter 3, Section 1, B.2., B.3. and B.4., then verification of adequate reliability and fail-safety of the FC system shall be provided. The scope and type of the required verification is specified in each individual case by GL.

## I. Installation

**1.** FC systems shall be located in separate spaces. Installation in conventional machinery spaces is not permitted.

The requirement for a separate space can also be met by a suitable form of enclosure for the components transferring the fuel. In such a case, installation in conventional machinery spaces is admissible.

**2.** Spaces in which fuel storage tanks are located shall be separated from conventional machinery spaces and the other parts of the FC system.

**3.** Spaces in which components of the FC system are installed shall be equipped with a mechanical ventilation system or other suitable ventilation devices of the extraction type as per Section 5. The spaces shall be monitored by gas detection systems as per Section 8, C. Special attention shall be paid to areas with a low rate of air circulation.

Alternative constructions approved by GL as being equivalent are permissible for submersibles and pleasure craft.

# Section 2

# Materials

## A. General Requirements

The materials shall be suitable for the intended application and shall comply with recognized standards. Their suitability shall be proven to GL. The use of flammable materials is not allowed outside the FC stack. The Rules for Materials issued by GL shall be observed. The use of flammable materials inside the FC stack requires the approval of GL. Section 4, B.1. shall be observed.

## B. Approved Materials and Material Tests

For pressure vessels, piping, valves and pumps, the following requirements shall apply:

– seagoing ships:

  Main Group I, Part 1, Chapter 2, Section 8 and Section 11

– Inland waterway vessels:

  Main Group I, Part 2, Chapter 2, Section 7 and Section 10

– pleasure craft:

  Main Group I, Part 3, Chapter 3, Section 5

Pipes for flammable liquids or gases shall be constructed of suitable metallic materials. The use of other materials requires the consent of GL.

# Section 3

# Fuel Systems

## A. Fuel Transfer System

**1.** The fuel transfer systems include all components needed for filling the fuel tanks/containers. The connections to exchangeable tanks/containers shall be regarded as part of the fuel storage system.

Fuel transfer systems shall be permanently installed, completely separated from other pipeline systems, and clearly marked.

**2.** The bunkering station shall be located on the open deck.

**3.** The bunkering station and fuel transfer pipes shall be provided with shut-off valves located directly at the transfer point and directly before the distribution manifold to the fuel tanks. The shut-off valves shall be designed in a way that they can be closed manually and by remote control. The position of the shut-off valve shall be indicated locally and in the control room.

Remote-controlled valves and the position indicator in the control room are not required in the following cases:

– fuel transfer systems with pipes up to 10 m in length, if the nominal diameter is less than or equal to 12 mm

– systems where a suitable non-return valve is integrated into the pipe at the fuel transfer point

**4.** A suitable fire extinguishing device shall be provided in the vicinity of the bunkering station.

**5.** If the fuel transfer system is installed in a safe area according to Section 1, C.8., then measures shall be taken to ensure that the fuel transfer pipe can be gas-freed after use. Openings of blow-off pipes for gas-freeing shall be arranged at points where no sources of ignition exist.

**6.** During fuel transfer the requirements of zone 1 as per Section 7 shall apply for the immediate vicinity of the bunkering station. The immediate vicinity is defined as the space within a spherical radius of 3 m around the transfer connection. A reduction of this distance is only permissible with the approval of GL.

**7.** Entrances, ventilation openings and openings leading to accommodation and service spaces, machinery spaces, and control rooms shall be located outside hazardous areas. They shall not face the bunkering station.

**8.** Openings to spaces which are located up to 10 m away from the transfer connection shall be kept closed during fuel transfer. Appropriate warning notices shall be displayed.

## B. Fuel Storage

**1.** Fuel shall be stored in suitable tanks or containers. Tanks/containers shall be secured against the ship movements occurring during operation at sea. Proof of the suitability of the tanks/containers and their securing arrangements shall be submitted to GL.

**2.** The installation spaces for tanks/containers shall be located outside of accommodation, service and machinery spaces and of control rooms, and shall be separated from such spaces by gastight bulkheads. If the installation space is adjacent to a space with potential fire load, separation by means of an A-60 bulkhead is required. Tanks, which are part of the ship structure, shall be separated from other spaces by means of cofferdams.

If it is necessary to deviate from this provision on board small craft, the approval of GL is required.

**3.** Entrances, openings and ventilation openings to accommodation, service and machinery spaces and to control rooms shall be arranged at a distance of at least 3 m from the openings of the installation space.

If it is necessary to deviate from this provision on small craft, the approval of GL is required.

**4.** The ventilation and blow-off pipes of the tanks shall be routed to the open air and so arranged that the exhaust vapours and gases can be discharged without any danger. Up to a spherical radius of 3 m around the outlet opening, there shall be no sources of ignition or openings which lead to spaces containing sources of ignition.

Technically equivalent solutions are permissible, if it is not possible to vent vapours and gases to the open air.

**5.** Fuel tanks intended for liquefied and pressurized gases and subjected to overpressure shall be protected against inadmissible temperature increases resulting from a fire in the vicinity. Fire loads are not permissible within the installation space. The installation space shall be protected against inadmissible heating in the event of fire, by means of a water sprinkler system or, alternatively, through A-60 fire insulation.

If it is necessary to deviate from this provision on small craft, the approval of GL is required.

## C. Fuel Conditioning

### 1. General

**1.1** All components for conditioning the fuel – such as preheaters, compressors, filters, reformers etc. – shall be located in a closed space or a suitable enclosure. This space or enclosure shall be ventilated according to Section 5 and shall be equipped with a gas detection system according to Section 8, C. and Section 9.

**1.2** The installation spaces of the fuel conditioning system shall be separated from the spaces used for storage of the fuel. Doors between the spaces used for fuel storage and those used for fuel conditioning are not permitted.

**1.3** In the pipes to the fuel conditioning system, remote-controlled shut-offs, which can be closed from outside the spaces, shall be arranged at the bulkheads.

**1.4** The installation space shall be situated outside of accommodation, service and machinery spaces and control rooms, and shall be separated from such spaces by means of a cofferdam or an A-60 bulkhead. Installation in a conventional machinery space is admissible, on condition that a suitable enclosure is provided.

**1.5** Entrances, openings and ventilation openings to accommodation, service and machinery spaces and to control rooms shall be arranged at a distance of at least 3 m from the openings of the installation space used for fuel conditioning, and shall not face them.

If it is necessary to deviate from this provision on small craft, the approval of GL is required

### 2. Requirements for fuel conditioning

#### 2.1 Compressors and pressure reduction devices

**2.1.1** It shall be possible to switch off the compressors from a permanently accessible point outside the installation space. In addition, the compressor shall be stopped automatically if the suction pressure is too low. The compressor shall not be restarted automatically before a manual reset has been carried out.

**2.1.2** Positive displacement compressors shall be fitted with relief valves routed into the suction line of the compressors. The relief valves shall be so dimensioned that, with the discharge of the compressor in the closed position, the maximum allowable working pressure is not exceeded by more than 10 %.

**2.1.3** Pressure reduction devices shall be so designed that failure of a pressure reduction valve cannot endanger the downstream components. In particular, the pipes downstream of the pressure reducer shall be protected by safety valves or shall be designed to a pressure rating corresponding to the maximum allowable working pressure that is permissible before the pressure reducer.

#### 2.2 Evaporators

**2.2.1** Heating media for liquefied-gas evaporators or gas preheaters that are routed back into spaces located outside the area of the gas treatment plant shall be passed through degassing containers which are located within the hazardous area.

**2.2.2** A gas detection and alarm system shall be provided within the degassing container.

**2.2.3** The outlet opening of the vent pipe of the degassing container shall be located in a safe area and provided with an approved flame arrester.

#### 2.3 Reformer Systems

##### 2.3.1 General

**2.3.1.1** Reformer systems shall be designed for automatic operation and equipped with all the indicating and control facilities required for assessment and control of the process.

**2.3.1.2** The chemical processes taking place within the unit shall be monitored, see Section 8, C.3.

**2.3.1.3** If limit values determined for the control process are exceeded, the unit must be switched off and interlocked by an independent protective device.

**2.3.1.4** It shall be possible to switch off the reformer unit from a permanently accessible point outside the installation space.

**2.3.1.5** If high surface temperatures may occur, the corresponding insulation or contact protection shall be provided.

#### 2.3.2 Firing equipment

**2.3.2.1** For fuels in terms of these Guidelines, the GL Construction Rules, Main Group I, Part 1, Chapter 2, Section 9 – Oil Firing Equipment shall be applied as appropriate.

**2.3.2.2** Firing equipment in reformer systems shall be designed for automatic operation. Manual operation (even for emergencies) is not permissible.

**2.3.2.3** The firing equipment shall be equipped with a type-tested burner control box and flame monitoring devices. Reliable operation of the flame monitoring devices shall be verified for the corresponding type of fuel and mode of combustion.

**2.3.2.4** After the firing equipment has been switched off, the combustion chamber and the exhaust gas system shall be purged with air or an inerting medium.

**2.3.2.5** Depending on the type of fuel and the burner, GL may define additional requirements for the firing equipment.

**2.3.2.6** The use of gaskets and insulating materials which contain asbestos is not permissible.

#### 2.3.3 Catalytic converters

Catalytic converters in reformer units shall comply with the GL Construction Rules in respect of the environmental conditions to be considered, especially the requirements relating to vibration loading. For seagoing ships, the Rules as per Main Group I, Part 1, Chapter 1, Section 1 – General Rules and Instructions shall apply.

#### 2.3.4 Gas purification

For installations as per Section 1, A.2., the gas purity required for the operation of the fuel cell shall be monitored by suitable methods. If the determined limit values are exceeded, an alarm shall be generated or the system shall be switched off.
If this requirement is not met for installations as per Section 1, A.1., verification shall be provided that no additional hazard can occur through inadmissible impurities.

#### 2.3.5 Exhaust gases

The exhaust gases arising during the reforming process shall be discharged safely to the open air at an adequate distance from openings to accommodation, machinery and service spaces.

#### 2.3.6 Residual gases

The recirculation of fuel (residual gas) from the FC to the reformer is permissible. The recirculation shall be protected by an automatic shut-off valve as per Section 9, D.

## D. Fuel Distribution

### 1. General

**1.1** Fuel pipes shall be independent of other piping systems. Use for other media than fuel has to be prevented. Through their arrangement, it shall be ensured that they are protected against damage.

**1.2** The fuel pipes between the supply tanks, the fuel conditioning system and the machinery space must be as short as possible. Fuel pipes shall be arranged with the greatest possible horizontal distance to the outer shell of the hull.

**1.3** Fuel pipes shall not be routed through safe areas, such as accommodation and service spaces or control rooms. If, in exceptional cases, fuel pipes have to be routed through a safe area, they shall be constructed either as a double-wall piping system or as a pipe within the ventilation duct, see Section 5.

**1.4** Fuel pipes in hazardous areas can be arranged without a double pipe or outside of a ventilation duct, if they are located in a space/area ventilated according to Section 5 or in an enclosed housing which is adequately ventilated and monitored, and if the requirements for explosion protection as per Section 7 are met.

### 2. Pipes for gaseous fuels

#### 2.1 Direct connections of pipes

**2.1.1** Pipes shall be connected by butt welding with full penetration.

**2.1.2** Screw fittings according to standards which are approved by GL for this application can be used for pipes with external diameters of 25 mm or less.

**2.1.3** Flanged joints shall only be used at locations where this is unavoidable. Only flange types approved by GL for that particular application shall be used.

### 2.2 Flanged joints

**2.2.1** If flanged joints cannot be avoided in installation spaces, they are only permissible within ventilated spaces and in areas in which ventilation of the extraction type is provided, see Chapter 5.

**2.2.2** Flanged joints are permissible at the bunkering station.

**2.2.3** With regard to type, make and quality assurance, flanges shall comply with recognized standards.

### 2.3 Inerting

It shall be possible to inert and gas-free the fuel pipes.

# Section 4

# Fuel Cells and Associated Components

## A. Installation

**1.** All parts of fuel cells and the directly associated components containing fuel during normal operation shall be arranged in an enclosed space or suitable enclosure. This space/enclosure shall be ventilated according to Section 5 and equipped with a gas detection system according to Section 8, C.2.

Alternative constructions approved by GL as being equivalent are permissible for submersibles and pleasure craft.

**2.** The installation spaces of fuel cells and their directly associated components shall be separated from the spaces used for fuel storage. Doors between the spaces used for fuel storage and the installation spaces of the fuel cells are not permissible.

**3.** The installation spaces of FC stacks and directly associated components shall be arranged outside of accommodation, service and machinery spaces and control rooms, and shall be separated from such spaces by means of a cofferdam or an A-60 bulkhead. Installation in a conventional machinery space is admissible, on condition that a suitable enclosure is provided.

**4.** Entrances, openings and ventilation openings to accommodation, service and machinery spaces and to control rooms shall be arranged at a distance of at least 3 m from the openings of the installation space of the fuel cells. The openings of the installation space shall not face the entrances, openings and ventilation openings to accommodation, service and machinery spaces and to control rooms.

If it is necessary to deviate from this provision on small craft, the approval of GL is required.

**5.** Openings for exhaust air and residual gases of the FC stack shall be located on the open deck with a horizontal distance of at least 3 m to any sources of ignition and to the openings of accommodation, service and machinery spaces, and to control rooms and other spaces containing sources of ignition.

Alternative constructions approved by GL as being equivalent are permissible for submersibles and pleasure craft.

## B. Fuel Cell Stacks

**1.** For FC stacks which have a total electrical output greater than 1 MW and which contain flammable materials, additional fire protection measures may be required by GL.

**2.** If fuel cells are used for supplying essential consumers, then every fuel cell stack shall be subjected to a performance test at the manufacturer's works. The electrical output and the thermal output of the fuel cells shall be verified by means of a suitable performance test.

**3.** If fuel cell stacks are used for supplying essential consumers, then redundancy shall be ensured.

## C. Inverters Following Fuel Cells

If propulsion units or other essential consumers are supplied with electricity from FC systems, then the inverters shall be so designed that reverse power, such as braking power, cannot pass into the fuel cells.

In general, the requirements set out in the GL Construction Rules, Main Group I, Part 1, Chapter 3 apply.

# Section 5

# Ventilation Systems

## A. General

**1.** Spaces in which there is a risk that an ignitable gas mixture may be formed have to be equipped with mechanical ventilation systems of the extraction type. Depending on the expected type of fuel release, either the entire space or the hazardous areas must be fitted with suction ventilators.

For small installations, a natural ventilation arrangement can be approved by GL.

**2.** It must be possible to control the ventilation systems from a point outside the ventilated spaces. The spaces must be ventilated before access and before taking the equipment into operation. Notices must be provided outside the spaces, with the warning that the ventilation system must be switched on before entering the spaces.

**3.** Ventilation systems must be permanently installed. The ventilation systems are not allowed to be connected to those of other ship spaces.

**4.** The extracted air must be monitored for fuel constituents. The requirements set out in Section 8, C.2. apply.

## B. Spaces with Mechanical Ventilation

**1.** The inlet and outlet openings of the mechanical ventilation system must be arranged in such locations that an adequate flow of air is prevents the accumulation of flammable vapours and ensures a safe working atmosphere throughout the entire room.

**2.** The ventilation system shall be designed for at least 30 air changes per hour with regard to the total geometric volume of the empty space. If the ventilation system fails, an alarm must be generated. Alternative constructions approved by GL as being equivalent are permissible for submersibles and pleasure craft.

**3.** Suitable design of the spaces shall ensure that no gas can accumulate in recesses or pockets.

**4.** Air inlet and outlet openings shall be provided with fire dampers, which must be operable from outside the spaces. Protective screens with a mesh spacing of not more than 13 mm shall be mounted at the outer openings of ventilation ducts.

**5.** Fans shall not form a source of ignition neither within the ventilated space nor within the ventilation system connected to the space. Fans must be of a non-sparking type and must comply with the GL Construction Rules, Main Group I, Part 1, Chapter 2, Section 15, B.5.3.

**6.** Fuel pipes that are routed into the ventilated space must be shut-off automatically by means of a safety shut-off valve as per Section 9, C., if the required air flow is not achieved or cannot be sustained, or if a fuel leak is detected.

## C. Gases and Vapours Heavier than Air

**1.** The spaces shall be ventilated by means of mechanically driven exhaust air fans. The supply air shall be introduced into the upper part of the spaces.

**2.** The exhaust air duct shall be routed as closely as possible to the floor of the space. The space shall be so designed that gases collect at central points from which they are extracted.

## D. Gases Lighter than Air

**1.** The spaces shall be ventilated by means of mechanically driven exhaust air fans. The supply air shall be introduced into the lower part of the spaces.

**2.** The spaces hall be designed in such a way that gases collect at the top at central points from which they are extracted.

**3.** A suction hood or a suction trunk shall be provided for areas containing flanges, valves etc.

**4.** The suction hood or suction trunk shall be arranged in such a way that the air flows around the gas-bearing components, and the air/gas mixture can be extracted at the upper part of the suction hood or trunk.

## E. Ventilation Ducts for Fuel Pipes

**1.** As an alternative to routing the fuel pipe within a double-wall pipe as per F. the fuel pipe can be laid in a tube or tunnel fitted with mechanical ventilation of the extraction type.

**2.** Electrical cables are not permitted to pass through this tube or tunnel.

**3.** The ventilated tunnel intended for the fuel pipe shall be routed until a space is reached which is equipped with a ventilation system.

**4.** The ventilation must be constantly in operation whenever fuel is present in the line. A gas detection unit shall be located in the extracted air stream and be in permanent operation, in order to indicate any leaks and to shut off the fuel supply automatically as per Section 9, C. The safety shut-off valve must close automatically whenever the required air flow is not achieved or cannot be sustained.

**5.** The ventilation system must be capable of maintaining a pressure below atmospheric pressure. The fan motors shall be arranged outside the ventilated tube or tunnel. For the design of the fans, see B.5.

## F. Double-Wall Piping System

**1.** As an alternative to routing the fuel pipe through a ventilation duct as per E. a double-wall pipe can be used. In the case of double-wall pipes, the fuel must be in the inner pipe. The space between the concentric pipes shall be pressurized with inert gas at a pressure between the atmospheric pressure and the fuel pressure. The outer pipe shall be designed for at least the design pressure of the inner pipe.

As an alternative to this design for the outer pipe, a pressure relief arrangement for the outer pipe can be approved by GL, on condition that proof of equivalent safety is provided. The pressure in the jacket pipe and the triggering of the pressure relief device shall be monitored.

**2.** In the event of an inadmissible pressure change in the space between the two pipes, an alarm must be triggered.

## G. Arrangement of the Supply Air and Exhaust Air Openings on Deck

**1.** To prevent dangerous gases or vapours from being drawn in again, the supply air and exhaust air openings of the ventilation systems (to the outside atmosphere) on the open deck shall be arranged as far away from each other as possible. They shall be located with a horizontal distance of at least 3 m to any sources of ignition and to the openings of accommodation, service and machinery spaces, control rooms and other spaces containing sources of ignition.

Alternative constructions approved by GL as being equivalent are permissible for submersibles and pleasure craft.

**2.** Exhaust air openings should be situated as far away as possible from areas in which persons are regularly to be found. These include, for example, embarkation areas, muster stations for life-saving appliances, deck work zones and passenger areas.

**3.** Exhaust air ducts must vent upwards.

# Section 6

# Fire Extinguishing Systems

## A. General

**1.** The area around the manifold for fuel transfer and the installation spaces for systems in which fuels in terms of these Guidelines are used shall be equipped with fire extinguishing systems of a suitable type. For all other spaces containing parts of the fuel cell system, GL may request that a fire extinguishing system be installed.

**2.** The supply facilities of the fire extinguishing system shall always be arranged outside the spaces or areas which are to be protected. It must be possible to set off the fire extinguishing system at a permanently accessible point.

# Section 7

# Explosion Protection

## A. Explosion-Protected Systems

**1.** Electrical equipment is regarded as being explosion-protected if it has been manufactured according to a recognized standard, e.g. the IEC 60079 publications or EN 50014 – 50020, and if it has been inspected and approved by a recognized institution body. Any instructions and restrictions noted in the approval certificates shall be observed.

**2.** With regard to the explosion protection, the requirements set out in IEC 60079-14 shall be observed. The required explosion group and temperature class of the electrical equipment in the Ex zones depend on the type of fuel, and shall be defined for each individual case.

## B. Classification into Zones

### 1. General

Hazardous areas (Ex zones) shall be classified into zones according to the probability of potentially explosive mixtures, in compliance with IEC 60079-10.

Depending on the influence of the ventilation and its availability, an Ex area can be reclassified from its original theoretical zone into an effective zone with a lower hazard level.

### 2. Hazardous area, zone 0

**2.1** Hazardous areas of zone 0 are areas in which an ignitable gas mixture must be expected to be present permanently. These areas include e.g. the inside of tanks or pipes containing flammable liquids with a flash point ≤ 60 °C or with flammable gases.

**2.2** Explosion zone 0 also includes the inside of tanks, containers, heaters, pipes etc. for liquids or fuels with a flashpoint above 60 °C, if these liquids are heated to more than 10° C below their flashpoint.

**2.3** For electrical installations in these areas, only the following may be used:

– intrinsically safe electrical circuits with the degree of protection Ex ia

– equipment specially approved for use in this zone

**2.4** Cables shall have armouring or shielding, or shall be laid in a metallic tube.

### 3. Hazardous area, zone 1

**3.1** Hazardous areas of zone 1 are areas in which an ignitable gas mixture can be expected to be present occasionally. These areas can include e.g. spaces with FC stacks, spaces with fuel tanks and pipes, spaces with fuel conditioning systems, ventilation ducts of pipes, and the monitoring space of double-wall pipes.

**3.2** The extent of zone 1 shall be defined in compliance with IEC 60079-10.

**3.3** For the electrical equipment in this area, only explosion-protected units of a type suitable for shipboard applications shall be used.

**3.4** Cables shall have armouring or shielding, or shall be laid in a metallic tube.

### 4. Extended hazardous area, zone 2

Extended hazardous areas of zone 2 are areas in which an ignitable gas mixture can be expected to be present only very occasionally, and then only for a short period. Areas directly adjacent to zone 1 that are not separated in a gastight manner from zone 1 are assigned to zone 2. The extent of zone 2 shall be defined in compliance with IEC 60079-10.

For electrical equipment in the areas belonging to zone 2, protective measures should be taken depending on the type and application of the equipment. These can comprise the following, for example:

– explosion-protected equipment

– equipment with the degree of protection Ex n

– equipment which generates no sparks in normal operation, and where the surfaces exposed to the outside air cannot reach inadmissible temperatures

– equipment which is contained in a pressurized enclosure in a simplified manner or enclosed in a fume-tight enclosure (minimum protection IP 55), where their surfaces cannot reach inadmissible temperatures. The permissible temperatures depend on the type of fuel, and shall be defined for each individual case.

# Section 8

# Control, Regulating, Monitoring and Alarm Devices

## A. Control and Operating Devices

**1.** If at least two control devices suited for the operation of FC systems are stipulated by the GL Construction Rules, Main Group I, Part 1, Chapter 3, Section 9, B.3., then they shall function independently of each other and shall not affect each other in the event of a failure.

**2.** The effects of the control actions must be indicated at the control panel. If control actions can be taken at several control units (control panels), the following requirements shall be observed:

– conflicting operator actions shall be prevented by means of suitable interlocks

– the control panel which is currently active must be indicated appropriately

**3.** Control devices should be designed in a way that no serious damage or loss of essential functions can occur in the case of faulty operating actions.

**4.** It shall be ensured that the fuel cells can be disconnected from the electrical load at any load condition.

## B. Automatic Control Devices

**1.** For the FC systems, regulating devices shall be provided to keep the process variables within the specified limits under normal operating conditions. The regulating behaviour shall cover the entire range of operation. Parameter changes which can be anticipated must be considered during the design phase. Faults in a regulating circuit shall not affect the proper functioning of other regulating circuits. The power supply to the regulating circuits shall be monitored and an alarm must be generated on failure of the power supply.

**2.** Regulating devices containing computers shall be designed according to the GL Construction Rules, Main Group I, Part 1, Chapter 3, Section 10.

**3.** Regulating devices for fuel cell systems are subject to mandatory type testing.

## C. Monitoring and Alarm Devices

### 1. General

**1.1** Alarm systems shall be provided which indicate unacceptable deviations from normal operating figures by visible and audible alarms.

**1.2** Alarm delays shall be kept within time limits which prevent any risk to the monitored system in the event that a limit value is exceeded.

**1.3** Visible signals shall be individually indicated.

**1.4** In addition, the GL Construction Rules, Main Group I, Part 1, Chapter 3, Section 9, C. shall be observed.

### 2. Gas detection system

**2.1** Spaces in which gas leaks cannot be ruled out shall be monitored by gas detection systems. When a concentration equal to 5 % of the lower explosion limit is reached, a visible and audible alarms must be generated at the control station. When a concentration equal to 10 % of the lower explosion limit is reached, a safety switch-off of the affected system must take place, see also Section 9, A.

**2.2** Gas sensors must be arranged at all locations where an accumulation of gases can be expected.

**2.3** Gas detection systems are subject to approval by GL.

### 3. Monitoring of chemical reactions

Chemical reactions, such as those taking place during fuel conditioning and within the fuel cell, shall be monitored, e.g. by means of temperature, pressure or voltage monitoring.

### 4. Monitoring the performance of the fuel cells

**4.1** If an FC system is used to supply consumers as per Section 1, A.2., then the electrical power provided by the FC system shall be monitored.

**4.2** In the case of load shedding, it shall be ensured that the FC system is automatically transferred into a safe condition from which it can be brought to the normal operating state again.

# Section 9

# Protective Devices and Protective Systems

## A. Protective Devices

**1.** Protective devices shall be as simple as possible, and must be reliable and direct in operation. Where external energy is required for the function of protective devices, the energy supply shall be monitored for possible failure. The suitability and proper function of protective devices must be demonstrated for the given application.

**2.** Protective devices shall be designed in a way that potential faults such as, for example, loss of voltage or a broken wire, cannot create a hazard to human life, ship or machinery. The occurrence of these faults and also the tripping of protective devices shall be indicated by an alarm.

**3.** Protective devices shall be designed to be fail-safe.

**4.** The adjustment facilities for protective devices shall be designed in a way that the last setting can be verified.

**5.** Protective devices, including sensors and actuators, must be independent of control, regulating and monitoring systems. Faults in one protective device shall not affect any other protective device. Protective devices shall be assigned to the systems which are to be protected.

**6.** The monitored open-circuit principle shall be used for protective devices. Alternatively, the closed-circuit principle shall be applied where national regulations demand it. Equivalent monitoring principles are permitted.

**7.** Faults occurring in protective devices must be indicated by an alarm.

**8.** In case of the following events, the affected FC system must be switched off with due consideration to safety, and then locked out:

– emergency shutdown (protective device)

– gas detection: when a concentration equal to 10 % of the lower explosion limit is reached

– fire detection in hazardous areas

– safety switch-off of the system owing to deviations from permissible operating parameters, including chemical reactions

**9.** It shall be ensured that the electric power output can be switched off at any load condition, see Section 8, A.4.

**10.** Protective devices are subject to mandatory type testing.

**11.** The control and regulating devices on the one hand and the protective devices on the other shall be located in separate spaces, so that, in the event of fire or water ingress, both systems are not adversely affected at the same time.

## B. Protective Systems

### 1. General

**1.1** A process-related interlinking of protective devices by the protective system shall not result in an impairment of the safety objectives.

**1.2** When a protective system demands a requirement class of 4 or higher according to the GL Construction Rules, Main Group I, Part 1, Chapter 3, Section 10, the following criteria shall be observed:

– The protective system should be of a fault-tolerant design (multi-module).

– The modules should consist of different hardware.

– If the modules contain software, this should be programmed according to different design criteria and by different persons (redundancy through diversity).

**1.3** Computers in protective systems shall be designed according to the GL Construction Rules, Main Group I, Part 1, Chapter 3, Section 10.

**1.4** Protective systems for FC systems are subject to mandatory type testing.

**1.5** The control and regulating devices on the one hand and the protective system on the other shall be located in separate spaces, so that, in the event of fire or water ingress, both systems are not adversely affected at the same time.

## C. Safety Shut-Off Valves

### 1. Safety shut-off valves

Safety shut-off valves shall be provided at the following points of the fuel system:

- at the outlets from the fuel storage tanks
- at the outlet from the fuel conditioning unit
- at the inlet of fuel pipes in monitored spaces
- Depending on the structure of the system, additional safety shut-off valves may be required.

**2.** It must be possible to close the safety shut-off valves by means of the protective devices and also from a constantly manned position. They must be so constructed that they can only be reset manually.

**3.** In the event of a leak, the fuel supply shall only be taken into operation again when the cause of the leak has been detected and remedied. Instructions on this requirement shall be displayed in a conspicious position in the installation space.

**4.** Safety shut-off valves have to be GL type-approved.

## D. Automatic Shut-Off Valve of Consumers

**1.** Each gas consumer (fuel cells, burners of reformers etc.) must be fitted with a group of valves consisting of three automatically actuated shut-off valves. Two of these shut-off valves must be located in series in the gas pipe leading to the consumer. By means of the third shut-off valve, it shall be possible to relieve the pressure in the section of gas pipe lying between the two shut-off valves. The vent pipe shall lead to the open air. For the outlet of the vent pipe, the requirements set out in Section 3, B.4. apply.

Alternative constructions approved by GL as being equivalent are permissible for submersibles and pleasure craft.

**2.** The shut-off valves must be arranged in a way that actuation or failure of the control circuit of the shut-off valves will cause the two series-connected shut-off valves to close automatically and the vent valve to open automatically. Alternatively, the function of one of the series-connected valves and the vent valve can be incorporated into one valve body so arranged that on actuation the flow to the gas consumer will be blocked and the vent line opened. The three shut-off valves shall be constructed in a way that they can only be reset by hand.

**3.** The shut-off valves must close automatically under the following operating conditions:

- emergency shutdown
- safety shutdown of the system

**4.** It must be possible to actuate the shut-off valves locally and also from any control panel.

# Section 10

# Trials of the System

## A. General

Before the trials commence, a detailed trial programme shall be compiled. The trial programme is subject to approval by GL, see Section 1, F.

## B. Trials of the Entire System

The FC system shall be subjected to the following trials after installation on board:

### 1. Functional trials of components

Safety shut-off valves, automatic shut-off valves, level indicators, temperature measurement devices, pressure gauges, gas detection systems and alarm devices shall be subjected to a functional trial.

### 2. Trials of the protective devices and protective system

During the trial, it shall be verified that, in the event of the following faults, the FC system is automatically transferred into a safe condition:

- alarm of the fire detection devices
- alarm of the gas detection system
- failure of the power supply
- failure of the programmable logic controllers (PLCs)
- triggering of the protective devices
- faults in the protective devices
- faults in the protective system

It shall be verified that the requirements of the safety analysis are met, see Section 1, F.

### 3. Trials of the fire extinguishing system

The functional readiness of the fire extinguishing system shall be verified.

### 4. Functional trials of the FC system

The following operating conditions of the FC system shall be tested (as far as applicable):

- automatic start-up of the FC system
- operational switch-off of the FC system
- load change, load steps
- load shedding
- switch-off during system malfunctions that do not endanger the safety of persons and equipment

### 5. Functional trials of the ship

Within the scope of the functional trials, the interaction of the FC system with the ship systems shall be tested as follows (as far as applicable):

- power generation by the FC system alone
- FC system together with conventional shipboard generation of electrical power
- FC system together with batteries
- change-over to the emergency source of electrical power
- switching the FC system online or offline

If the FC system constitutes the main propulsion system of the ship, it shall be verified that the ship has adequate propulsion power in all manoeuvring situations

**Annex F. METHAPU**

ENERGY
ENVIRONMENT
ECONOMY

# METHAPU


The project "Validation of a Renewable Methanol Based Auxiliary Power System for Commercial Vessels" (METHAPU) is running 2006-2010. Wärtsilä is coordinating an international consortium researching and validating the marine application of a 250 kW Solid Oxide Fuel Cell (SOFC) unit fuelled by methanol. The project is supported by funding within the 6th Framework Programme of the EU.

The objective of the project is to develop and validate marine SOFC technology running on methanol, including fuel bunkering and storage systems. The project will also support the introduction of regulations necessary for allowing the use of methanol as a marine fuel.

High-temperature fuel cells applications such as SOFCs are promising solutions for marine auxiliary power as especially coastal and harbour area emission regulations are becoming more stringent. SOFCs have low emission levels and high overall efficiency which results in a decreased level of emissions. Methanol has a high reforming efficiency and is possible to acquire as a renewable fuel.

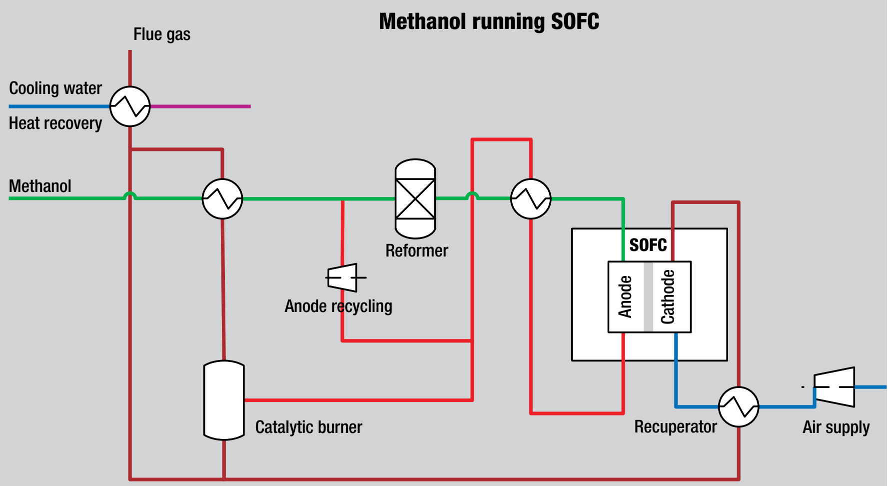
Validation of the SOFC technology will be carried out with a 20 kW SOFC test unit on-board a car carrier involved in international trade. The on-board field tests will address performance and emissions of the whole SOFC application.

WÄRTSILÄ


## SOFC TECHNOLOGY

SOFCs are suitable for use in high-power applications. The electrolyte is a solid, nonporous metal oxide. Fuel cells generally operates in the temperature area 650-900°C. The electrical efficiencies of present fuel cell plants are 30-55%, which is based on the lower heating value (LHV) of the fuel. The fuel cell itself runs on hydrogen meaning the fuel is reformed prior to entering the fuel cell.

The SOFC unit is designed for combined heat and power applications (CHP), giving ~80% of overall efficiency, as the unit generates heat in addition to electricity.




**WWW.METHAPU.EU**

The consortium consists of world-class players in the field of fuel cell system integration, sustainable shipping, classification work and environmental assessment.

- Wärtsilä, Finland
- Lloyd's Register, United Kingdom
- Wallenius Marine, Sweden
- University of Genoa, Italy
- Det Norske Veritas, Norway

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# Annex G. New Developments for Maritime Fuel Cell Systems

# New Developments for Maritime Fuel Cell Systems

F. Vogler, G. Würsig

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# New Developments for Maritime Fuel Cell Systems

**Finn Vogler, Gerd Würsig,** Germanischer Lloyd AG, Germany

## 1 Introduction

As a result of environmental concerns in shipping the international legislation set by the IMO (International Maritime Organisation) requires the reduction of SOx and NOx emissions from shipping (MARPOL Annex VI). To reduce the SOx emissions in environmental sensitive areas so called SECAs (Sulphur Emission Control Areas) are established for example in the Baltic and North Sea. In these areas a maximum sulphur content of 1.5 % in fuel oil is permitted. This value will be decreased in 2010 to 1.0 %. In 2015 this limit shall be again reduced to 0.1 %. For the NOx emissions a reduction in three steps from 2000 to 2016 is planed. For all three types of diesel engines (low, medium and high speed engines) specific limits per g/kWh are defined. Beneath the inner motor measures also emission scrubbers are permitted [1]. According to the high political pressure a $CO_2$ trade for shipping is currently under discussion at the IMO [2].

The European Union introduces additional laws to reduce ship emissions in European waters. The EU limits the sulphur content in fuel oil to 1.5 % since 2006 for all passenger ships sailing between EU ports. According EU-Directive 2005/33/EG it is planned to reduce the sulphur content in the fuel down to 0.1 % for all ships in European ports, alternatively the use of land based power is permitted [1].

Mainly causes by the strong emission regulations in shipping, the demand of more environmental friendly energy converters, better energy efficiency and emission reduction methods is rising continuously. Several methods like exhaust gas treatment, use of gas as ship fuel either as dual fuel engine or gas motor, electrical onshore connections in the ports, energy efficient energy management and improvements of the whole system (e.g. hull design with low resistance) are currently under discussion. Additionally the fuel cell gets more and more in the focus of the maritime industry to be also a good possibility according to the benefits of high efficiency and low emissions.

## 2 Regulatory Background in Shipping

In shipping the legal requirements are based on the conventions and codes of the International Maritime Organisation (IMO) which are mandatory for all ships in the international trade. The most important conventions are the SOLAS (Safety of Life at Sea) and the MARPOL (Maritime Pollution) conventions. In addition to the IMO legislation the unified requirements of the International Association of Classification Societies (IACS) give guidance on interpretation of special topics with the purpose to harmonize the practice of classification societies. In practice the class societies rules classification and construction incorporate the IMO codes and conventions and the unified requirements. Below these rules the technical standards are applied (Fig. 1).


**Figure 1: Rule Framework in Shipping.**

According to the SOLAS convention it is not allowed to use fuel oils with a flashpoint below 60 °C. The only exceptions are Liquid Natural Gas Tankers under the legislation of the International Gas Carrier Code (IGC-Code). All flag states have to follow this requirement. Therefore in practice, any gas applications are principally forbidden on board. Today all ships which are operated with gas as fuel with a flashpoint below 60 °C are operated by special permission of the local authority, but only for national use. According to the good experiences of the Norwegian government and the rethinking in the use of more clean energy, the IMO started on the request of Norway to develop a guideline for the use of natural gas as ship fuel. These so called provisions for gas as ship fuel will come into force on 1$^{st}$ June 2010 [3], but only for natural gas as fuel for internal combustion engines. It is intended to develop a code for gas as ship fuel in parallel, which includes all kind of gases and may be fuels with a flashpoint below 60 °C for all kinds of energy converters, including the fuel cell. This Code may come into force in 2014 with the regularly update of the SOLAS convention.

Germanischer Lloyd was the first classification society worldwide which published already in 2003 a “Guideline for the use of Fuel Cell Systems on Board of Ships and Boats” [4]. These guidelines have been used successfully for a number of applications. In 2008 and 2009 other classification society published rules for fuel cell systems. Further rules from other classification societies are under development to follow the ongoing development in this field.

## 3 Fuel Cell Systems in Shipping

Fuel cell systems are known for their advantages low noise, no or nearly no NOx emissions and a high efficiency already in the low power range. Furthermore they are of modular design, which leads to benefits for their integration. The big disadvantages of fuel cells are their high costs regardless the fuel cell type and the low specific power which feature more or less strongly to all fuel cell types. The lifetime of a fuel cell stack is today also a big issue for most types of fuel cells. In addition the fuel logistic and the fuel price are obstacles to introduce the technology. Pure hydrogen which is the preferred fuel from a technical point of view is not widespread. Only a few filling stations exist, even less for maritime applications. Nevertheless in regional applications with relatively low power demand, like ferry boats or pleasure boats, it may be possible to establish a sufficient fuel supply with one filling station.

In all other cases, especially in applications with a high power demand another logistic fuel than hydrogen is necessary, according to the fact of the low volumetric energy content of hydrogen (Fig. 2). The required volume for the fuel becomes the most limiting factors for gases as alternative fuels in shipping application.

Fuels other than hydrogen require reformer systems to be applied with fuel cells. Several types of reformer systems are present, but most challenging for them is to get rid of the sulphur, especially in typical maritime fuels. Nevertheless ongoing changes in international regulation which will allow the use of natural gas from mid 2010 and the environmental requirements regarding lower sulphur content in bunker fuel will support the use of reformer systems in the future.

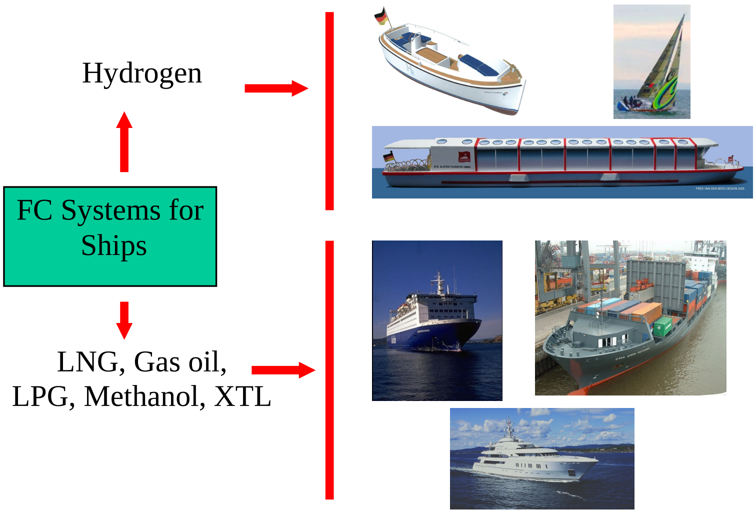


**Figure 2: Which fuel for which application?**

IMO has initiated the development of an international code which will allow the use of different fuel gases and may be also liquid fuels with a flashpoint below 60°C. These developments will also support the use of fuel cell systems in the international shipping.

### 3.1 Suitable FC systems

For the use in shipping low as well as high temperature fuel cells are suitable. In case of use of low temperature fuel cells, the PEMFC (Proton Exchange Membrane Fuel Cell) seems to be the best candidate for the use in naval applications when operated with hydrogen. If the PEMFC is operated with a reformer system it can not compete with conventional internal combustion engines with regard to the efficiency. For the high temperature fuel cells the PAFC (Phosphoric Acid Fuel Cell), MCFC (Molten Carbonate Fuel Cell) and SOFC (Solid Oxide Fuel Cell) is suitable. All three systems normally operate with an upstream reformer system to create a hydrogen rich gas mixture out of hydrocarbons. The PAFC is the mostly deployed fuel cell on commercial bases. Therefore, the PAFC is today an alternative for the use on board of ships. But according to the low efficiency compared to traditional energy converter on board ships, the PAFC is no real opportunity. The MCFC and the SOFC are the most promising fuel cell systems for the use in shipping. The high efficiency and the use of combined heat and power make them suitable for the use in shipping. Today only a few developments of SOFC systems in a reasonable high power range exist. With regard to the status of development the MCFC seem to be the most promising fuel cell system for maritime applications today [5,6,7,8,9].

### 3.2 First applications

In principle fuel cell systems can be used for any maritime application. This starts from pleasure boats, yachts over fishing boats, inland navigational, harbour and supply vessel up to cargo ships and passenger vessel. Even on board of military ships and submarines fuel cells can be used. According to the high power demand of ships (up to 100 MW for main propulsion and 12 MW for auxiliary power for a big container vessel), it has to be mentioned that fuel cell systems at their current status of development are only suitable in niche applications. The main problems are related to the fuel logistics and the fact that fuel cells today can only provide a low power range up to 350 kW. According to the EU funded feasibility study FCShip fuel cell systems with a standardised module size from 500 kW to 1000 kW are needed for shipping applications [10].

In the power range up to 500 kW the fuel cell systems can be used for main propulsion and auxiliary energy. This relates to inland navigational vessel, pleasure boats and yachts, etc. According to the high power demand for propulsion of seagoing ships, the today existing fuel cell system can only be used for auxiliary power. In this area passenger vessel, mega yachts and research vessel will be the first application for fuel cell systems on board. By using 3 to 4 fuel cell systems with a power range up to 500 kW, it is possible to provide the basic load of auxiliary energy for larger seagoing vessel for up to 90 % of the auxiliary energy demand [9].

Fuel cell systems are and will only be used in the areas, where the benefits dominate the costs. The most common example in this respect are the submarines of the German manufacturer HDW used e.g. by the German and Italian navy. Other application areas will be the use of FC-Systems in areas, where the use of internal combustion engines is not permitted (environmental restrictions) and therefore alternative propulsion systems are required.

## 4 Possible Market Potential for Fuel Cell System in Shipping

Germanischer Lloyd has worked on a market analysis for fuel cell systems on seagoing vessels, which was published in the beginning of 2010 [9]. The aim of the study was to identify the possible market and market fields for fuel cell systems on sea going vessels. The study includes beneath the market reflection also the supply logistic and the environmental and economical effects by the use of fuel cell systems in shipping especially for the city of Hamburg.

For the market analysis the world fleet of large commercial vessels (approx. 50.000 vessels) was analysed regarding different reference vessel which represent the most typical ship types. In addition the market for large yachts was included in the evaluation. The analysis based on the use of standardised 500 kW fuel cell modules. For the analysis a partial replacement of auxiliary power on the bases of the standardised modules was assumed. The analysis gives an outlook till 2030.

It can be expected that Mega Yachts, RoRo-Vessel and Cruise Ferries are the first applications for fuel cell systems. These ship types have been analysed more in detail. A market share of fuel cell systems for auxiliary power of 5 % was assumed. The analysis shows that these ship types have a yearly demand for such a technology of about 22 units. This seemed to be a small number, but means a quadrublication of the production capacity of a major MCFC manufacturer in 2008. Additionally it has to be considered that these ship types have only a market share of about 3.5 % of the world fleet!

The outlook over approximately half of the world fleet shows that till 2030 a market volume up to 4250 fuel cell units of 500 kW is possible. The demand for FC systems with a power below 500 kW was not considered in detail but it is obvious that this market is bigger with regard to the number of units. E.g. for small container vessel up to 850 TEU and general cargo vessel there will be an additional market volume for 250 kW fuel cell units up to 600 units till 2030.

These few figures show, that the shipping industry has a very high market potential for fuel cell systems in the future, if the specific maritime requirements can be fulfilled.

Today fuel cell applications in shipping are small scale applications in most cases. Some examples are given below.

## 5 Examples for Successful Fuel Cell Integrations in Shipping

### 5.1 SMART-H2 – Whale watching boat ELDING I

Within the SMART-H2 project (Sustainable Marine & Road Transport on Hydrogen in Iceland) also the marine application of hydrogen will be demonstrated. The main goal of SMART-H2 (2007-2010) will be a demonstration fleet of 20-40 hydrogen vehicles, of different types and using different propulsion technologies and to demonstrate the hydrogen technology onboard a publicly accessible boat. Therefore a 125 ton whale watching boat for 150 passengers was chosen (Fig. 3). The ship's Auxiliary Power Unit (APU) consists of a 10 kW fuel cell operated by compressed hydrogen providing electricity for the ship operation. This enables the boat to switch of the internal combustion engines during whale watching. The ship started its operation in April 2008.


**Figure 3: SMART-H2 – ELDING**

### 5.2 ZEMSHIPS project – FCS ALSTERWASSER

The ZEMSHIPS project (2007-2010), founded by the EU-Life program, has the aim to test practically an emission-free ship operation within an environmental sensitive area and to promote this technology for maritime applications. ZEMSHIPS is the first project in the world to integrate a hydrogen fuelled fuel cells system of this size on a commercial passenger vessel. It combines two fuel cell systems with a peak output of 48 kW each with a 560-V lead gel battery pack (Fig. 4). The prototype FCS ALSTERWASSER has a length of approx. 25.50 metres, a breadth of 5.25 metres and can transport up to 100 passengers. Project partners are ATG Alster Touristik, Germanischer Lloyd, Hamburg University of Applied Science, Hochbahn, hySOLUTIONS, Linde Group, Proton Motor, UJV Nuclear Research Institute. The ship started its operation in 2008-08 [11].

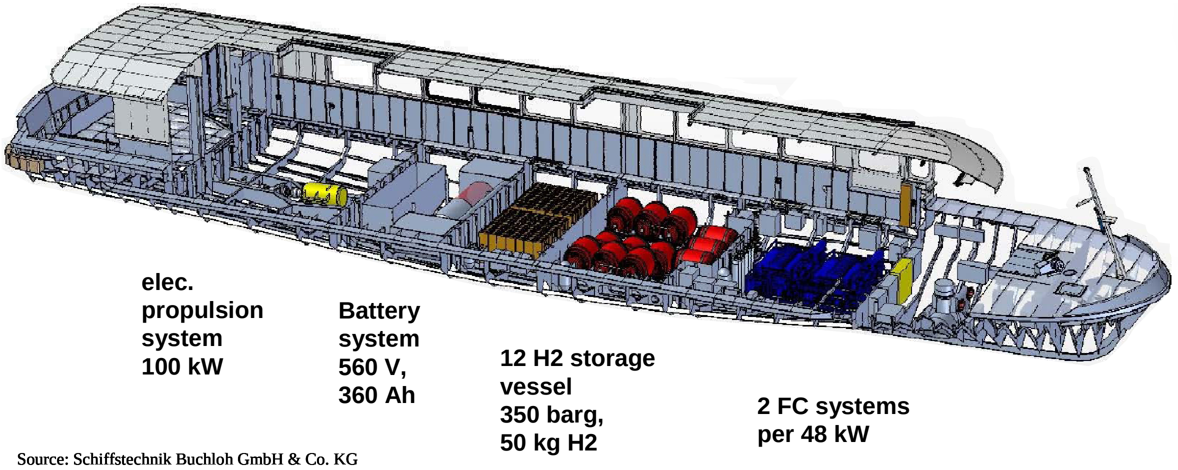


**Figure 4: ZEMSHIPS project – FCS ALSTERWASSER.**

### 5.3 Fuel Cell Boat Amsterdam

The aim of Fuel Cell Boat BV is to realise an inland passenger vessel with a fuel cell system fuelled with hydrogen, including the infrastructure for the refuelling of the vessel. The ship has a length of 22 metres, a breath of 4.25 metres and will be equipped with a fuel cell system of 60-70 kW. The capacity is about 100 passengers. The ship is planned to come in operation summer 2009 [12]. The certification is done by Germanischer Lloyd.

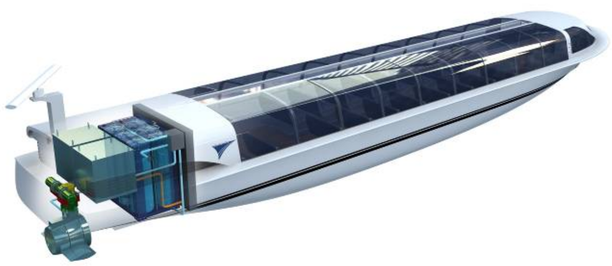

**Figure 5: Fuel Cell Boat Amsterdam.**

### 5.4 Further RUNNING projects

In the following a short overview of some ongoing fuel cell projects is given.

#### 5.4.1 MethAPU

The EU founded MethAPU project (Validation of a Renewable Methanol Based Auxiliary Power System for Commercial Vessels) is running from 2006-2009. The objective of this project is to develop and validate marine SOFC of 250 kW running on methanol. The validation will be carried out with a 20 kW SOFC test unit, which will be operated for one year onboard a car carrier. Partners are Wärtsilä, Lloyd’s Register, Wallenius Marine, The university of Genua and Det Norske Veritas. The costs of the program are some € 1.9 million [13].

#### 5.4.2 FellowSHIP

FellowSHIP (Fuel Cells For Low Emission Ships) is a three phase project. The overall aim of the project is the development, demonstration and qualification of fuel cell hybrid power pack for ships. The first phase (2003-2005) includes a feasibility study and the basic design development. The second step (2005-2009) comprises the building, testing and demonstration of a 320 kWe fuel cell system on an offshore supply vessel, fuelled with LNG. In the third step (2010-…) the testing, qualification and demonstration of power packs from 1 to 4 MWe is planned. Partners of the project are Wärtsilä Ship Power Automation, MTU Onsite Energy, Vik-Sandvik, Eidesvik, Det Norske Veritas. The Budget is about € 18.75 million [14].

## 6 Outlook on Ongoing Projects

### 6.1 e4ships – Lighthouse project for FC systems in shipping

e4ships is a Lighthouse project founded by the National Innovation Programme – NIP of the German government. The purpose of the project, is to demonstrate that fuel cells can function in ship’s power supply systems under everyday conditions. The project starts in 2009 and will end in 2016. The project is divided in a superior project which includes the steering committee and general topics and three demonstration projects for the realisation of suitable fuel cell systems for ships (Fig.6).

The first project SchIBZ includes the development of a 500 kW MCFC system operated on XTL as fuel. The system shall be tested on a commercial paper carrier in northern Europe.

Pa-X-ell, the second demonstration project, is working on the integration of MCFC systems on board of ships, fuelled by LNG. The first system shall be integrated on a cruise ship. The long term aim is to substitute the auxiliary power systems of RoPax Ferries and Cruise ships. The auxiliary power required for these vessels is in the range of 3000 to 10000 kW per vessel.

The project Hy-Ferry works on the integration of a hybrid system with a 240 kW PEMFC operated by hydrogen in inland waterway and costal vessels.

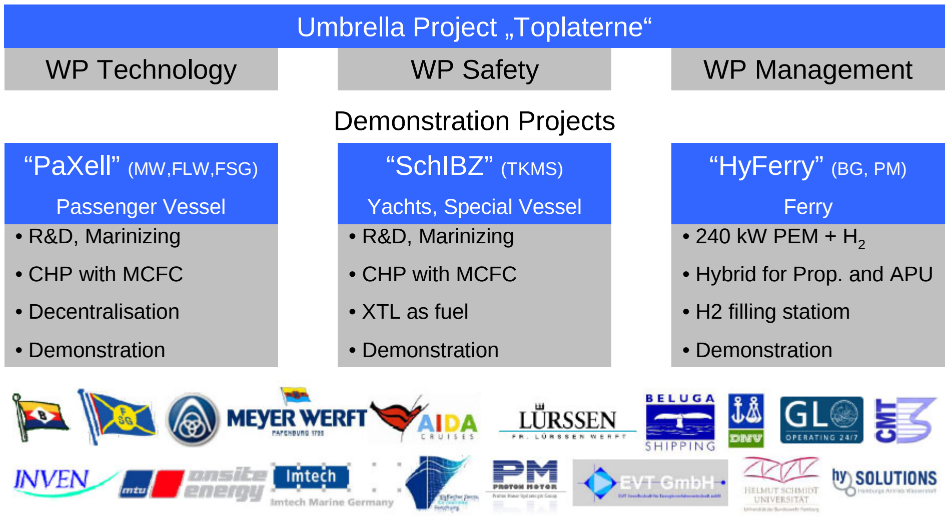


**Figure 6: Structure of e4ships Project.**

## 7 Conclusion

Driven by environmental concerns and the need for sustainable and clean energy in shipping the fuel cell gets in the focus of the maritime industry as a possibility for clean energy conversion on board. Till now fuel cell systems on board of ships are still in the demonstration phase. The only exception is the PEMFC in the submarines from German yard HDW. The PEMFC now starts to come into the market. The high temperature fuel cell, especially the MCFC will probably come into the market during the next 5 to10 years. According to the high power demand in shipping the fuel cell will not replace the existing multi Megawatt main engines of large ships in the foreseeable future. Nevertheless the potential for auxiliary power generation by FC-Systems is much larger than the markets under discussion for large FC-Systems today. In addition this market is less price sensitive than the current target markets of most FC manufacturers. The adoption of fuel cell technology on board will first take place in the replacement of auxiliary power generators. Nevertheless in special markets and applications the fuel cell already today is a good alternative for traditional engines. Especially for pleasure crafts, inland navigational vessel, ferries and also large passenger vessels the fuel cell can be a good alternative. Where a lower power demand or only a regional fuel supply is necessary hydrogen fuelled systems can be applied.

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## Annex H. Característiques Undine

# M/V UNDINE


The PCTC (Pure Car Truck Carrier) m/v UNDINE has a capacity of 7,200 cars or a combination of 3,700 cars and 600 trucks. UNDINE is a sistership to BOHEME, ELEKTRA, MIGNON and MANON. The vessel is built to the highest class of Lloyd's Register of Shipping with the following designations: +100 A1 Vehicle Carrier, movable decks, deck No. 4, 6 and 8 strengthened for Roll on Roll off cargo + LMC, UMS and IWS. Undine was elongated in 2006 by 28 metres, resulting in a 20 per cent increase of car capacity.

## TECHNICAL SPECIFICATIONS

| | |
|---|---|
| Length over all | 227.90 m |
| Beam, moulded | 32.26 m |
| Air draft | 47.92 m |
| Height to upperdeck | 33.48 m |
| Draft, design/max | 9.5/11.02 m |
| Deadweight at maximum draft | 28,183 MT |
| Gross Tonnage | 67,264 GT |
| Net Tonnage | 28,473 NT |
| Stern ramp width | 7.0 m |
| Stern ramp height | 5.0 m |
| Stern ramp capacity | 125 t |
| Number of car decks | 13 (of which 3 are hoistable) |

| | |
|---|---|
| Capacity deck area | 63,124 m$^2$ |
| Capacity of car units* | 7,200 |
| Capacity of cars/trucks | 3,700/600 |
| Engine | KHIC MAN B&W 8S 60MC 14.7 MW |
| Basic complement | 15 |
| Built | 2003, Daewoo Heavy Industry Ltd, Korea |
| Call sign | SHJC |
| IMO Number | 9240160 |
| Flag | Swedish |
| Owner | Wallenius Lines AB, Sweden |
| Operator | Wallenius Wilhelmsen Logistics |

* RT 43 units (one RT43 unit = 7.38975 m$^2$)

WALLENIUS LINES

## Deck and Ramp system

Heavy units are loaded on the strengthened 4th, 6th and 8th decks. Deck No. 5, 7, 9 are divided into hoistable sections. These sections are hoisted/lowered by means of mobile lift-cars.

The 6th deck is the normal entrance deck, but the 7th may also be used for the outside midships ramp if the height of the quay requires it.

The two loading ramps are located on the starboard side. The stern quarter ramp is arranged at a 27 degree angle to the center line to enable loading/discharging of long vehicles. The midship ramp is arranged at a 90 degree angle to the centre line.

## Anchoring/Winches

The deck machinery consists of two combined anchor/mooring winches and six conventional mooring winches, two of which are placed on the forecastle and four on the poop deck. There is a crane on upper deck with a capacity of five tons for bringing supplies and spare parts.

## Cargo Ventilation

Fans evenly distributed throughout the vessel on upper deck creates good ventilation during loading/discharging. In the main holds air is changed at least 25 times an hour and even up to 50 times an hour in the smaller holds.

## Machinery

The main engine is an KHIC B&W, type 8S60MC marine diesel with constant pressure supercharging and a maximum output of 20,000 BHP at 101.3 RPM. The engine is directly reversible and attached to a fixed propeller with remote control from the bridge or engine control room.

For the electrical power supply there are two Wärtsilä diesel engines, type 4R32, each attached to an 3 x 440 V, 60 Hz, 1,400 kW AC-generator installed in a separate room and a shaft generator with a capacity of 950 kW. Power to the new second bowthruster is delivered by one Volvo Penta Genset D34 MS, 3 x 440 V, 60 Hz, 728 kW AC-generator installed in a separate room next to funnel on deck 14.

There is an emergency diesel generator with a capacity of 215 kW. The machinery meets the requirements for Unattended Machinery Space (UMS).

## Navigational Equipment/Bridge

The Bridge is totally enclosed and air-conditioned. The equipment fullfills the requirement for "Sole Look Out" at sea and it is also designed for Pilot/Co-pilot system of working in high traffic areas.

The Navigation System is mainly integrated by means of an INC installation. INC is of the Finnish ASPO "ANTS" (Automated Navigation and Track keeping System) type. The radar equipment has anti-collision computers (ARPA'S) with free selection of picture, synthetical chart picture etc.

The vessel has an ASPO/Wallenius electronic sea chart-system (EC) which gives a range of options to steer the vessel, including among others an automatic one. To calculate the vessel's position there are two DGPS-navigators and when in coastal waters, there is a "fixed radar target" positioning system.

The radio equipment is delivered by Standard Radio of Sweden and the radio station has been fitted with satellite communication (B+C), Maritex, GSM etc and is fulfilling the Global Maritime Distress and Safety Systems rules (GMDSS).

The vessel is equipped with a highly effective Schilling "Mono-Vec" rudder to assist in controlling the lateral movements of the stern. The lateral control of the bow is controlled by two bowthrusters; a 1,500 kW bowthruster by about 23.5 tons thrust and a 665 kW bowthruster by about 10 tons thrust.

## Interior

All accommodation areas are located on upper deck and bridge deck, far away from the engine room and have the same high quality and mainly the same design as the company's other PCTC vessels. The ship also has a mess-room, TV-room/ library, gymnasium, outdoor swimming pool and a sauna.

There is a cabin with its own entrance from the bridge deck for the Canal staff and service personnel. Tally-men have their own office on the entrance deck (deck 6).

## Safety arrangements

For fire extinguishing, the cargo holds, engine room and interior have a permanent installed water fire post system and portable fire extinguishers. Cargo holds and engine room also have CO2-equipment of "total flooding type".

The vessel has a free-falling life boat capable of carrying 30 passengers and a MOB-boat (Man Over Board). In addition to this there are four life rafts with a carrying capacity of 16 passengers each. Each crew member has his/her own survival-suit.

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