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MARITIME

STUDY ON THE USE OF FUEL CELLS IN SHIPPING

EMSA European Maritime Safety Agency

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SAFER, SMARTER, GREENER

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C: SAFETY ASSESSMENT OF GENERIC FUEL CELL APPLICATIONS ON RO-PAX VESSELS AND GAS CARRIERS

EXECUTIVE SUMMARY

This study was initiated to provide the European Maritime Safety Agency (EMSA) with a technical assessment on the use of fuel cells in shipping that, being supported by a technology overview and risk-based analysis, will evaluate their potential and constraints as prime movers and energy sources in shipping.

The study is essentially divided into three main blocks:
A) Technology
B) Regulations
C) Safety

Chapter A, corresponding to the first block, provides a description of the different fuel cell technologies and an overview of major maritime fuel cell projects to date. Consecutively, Chapter B gives an overview of current applicable standards, regulations and guidelines for bunkering, on-board storage and distribution of fuel as well as use of on-board fuel cell installations. Finally, Chapter C provides a safety assessment, with the analysis of the safety challenges for maritime fuel cell applications, exemplified by a RoPax vessel and a Gas Carrier, based on the most promising fuel cell types identified in Chapter A of the study, namely the PEM, HT-PEM and SOFC.

In Chapter A, twelve projects are selected and further described. This includes FellowSHIP, FCShip, METHAPU, Nemo H2, FELICITAS, SF-BREEZE, Pa-X-ell, US SSFC, MC-WAP, ZemShips, SchIBZ and RiverCell. Seven different fuel cell technologies have been evaluated; the alkaline fuel cell (AFC), the proton exchange membrane fuel cell (PEMFC), high temperature PEMFC (HT-PEMFC), direct methanol fuel cell (DMFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC) and the solid oxide fuel cell (SOFC). The choice of these seven fuel cell types was essentially based on their merits, their potential for commercial application, or a combination of both. The nominated technologies were ranked against 11 parameters:

- Relative cost
- Power levels (kW)
- Lifetime
- Tolerance for cycling
- Flexibility towards type of fuel
- Technological maturity
- Physical size
- Sensitivity for fuel impurities
- Emissions
- Safety aspects
- Efficiency (Electrical and total including heat recovery if applicable)

The ranking was weighted for importance, in each of the parameters above, based on specific criteria used in the context of the present study. The three technologies ranked by this exercise to be the most promising for marine use is the solid oxide fuel cell, the PEMFC and the high temperature PEMFC. Short descriptions of these technologies are given below.

Proton Exchange Membrane Fuel Cell (PEMFC)

The PEM fuel cell is a mature technology that has been successfully used both in marine and other high energy applications. The technology is available for a number of applications. The relative maturity of the technology also leads to a relatively low cost. The operation requires pure hydrogen, and the operating temperature is low. The main safety aspects are thus related to the use and storage of hydrogen on a vessel. Energy conversion with a PEM fuel cell, from hydrogen to electricity, would essentially result in water as the only emission and low quality heat, with the low temperature providing however high tolerance for cycling operation. The efficiency is moderate, around 50-60%, and, with the low operating temperature, heat recovery is considered not to be feasible. The modules currently have a size of up to 120kW, and the physical size is small, which is positive for applications in transport, remarkably for marine use.

The major drawback of the PEMFC technology is sensitivity to impurities in the hydrogen as sulphur and CO, a complex water management system (both gas and liquid) and a moderate lifetime. The PEMFC is, in the present study, the technology that has received the highest score in the ranking.

High temperature PEMFC

The HT-PEMFC is a technology that is less mature than conventional low temperature PEM, addressing however some of the problems with the low temperature of the PEM. The higher temperature reduces the sensitivity towards impurities and simplifies the water management since water is only present in gaseous phase. The efficiency is the same as for traditional PEMFCs, possibly somewhat higher due to less parasitic losses, and the higher temperature leads to more excess heat that can be used for ship internal heating purposes. The HT-PEM technology was demonstrated aboard the MS Mariella in Pa-X-ell project with 3 stacks of 30 kW, and in the project MF Vågen, Norway, including a 12kW HT-PEM for small port commuter ferry.

The higher operating temperature allows eliminating the need for a clean-up reactor after the reformer. Such reactors lower the system efficiency, are expensive and space demanding and. Owing to the tolerance for fuel impurities, simpler, lighter and cheaper reformers can be used to produce hydrogen from a broad range of energy-carriers such as LNG, methanol, ethanol or even oil based fuels. The operational temperature of up to 200˚C is assumed moderate enough so that tolerance for cycling is not significantly weakened.

Solid oxide fuel cell

The SOFC is a highly efficient, moderately sized fuel cell. The high operating temperatures means that with heat recovery the total fuel efficiency can reach about 85%, and possibly increasing with further development. There is some experience with use of this particular technology in vessels, including the MS Forester in the SchIBZ project. With further development and experience the price of this technology is expected to be reduced. The fuel cell is flexible towards different fuels, with the reforming from hydrocarbons to hydrogen taking place internally in the cell. The high temperature can be considered a safety concern and, on the environmental perspective, when using hydrocarbon fuels, there will be emissions of CO_2 and some NOx. A promising development for the SOFC technology are hybrid systems combining SOFC, heat recovery and batteries, as it is planned for in the SchibZ project. This leads to the possibility of a more flexible operation of the system and, with less cycling of the SOFC, the problems associated with short cycle life are reduced.

Following the technology descriptions, Chapter B provides an overview of current applicable standards, regulations and guidelines applicable to fuel cell installation in ships. Aspects of particular relevance for the present study, apart from the installation and operation of the fuel, included also fuel-specific provisions in the particular contexts of bunkering, on-board storage, distribution and use. The fuels covered are natural gas (LNG/CNG), ethyl-methyl alcohols, hydrogen, low flashpoint diesel and bio diesel.

Maritime applications of fuel cell systems must satisfy (a) requirements for on-board energy generation systems and (b) fuel-specific requirements regarding the arrangement and design of the fuel handling components, the piping, materials and the storage. In current regulations, these aspects are handled separately.

The International Code of Safety for Ships using Gases or other Low-Flash-Point Fuels, better known as the IGF Code, provides specific requirements for ships using such fuels. Having entered into force on 1 January 2017, the IGF Code is a mandatory instrument applicable to all ships using gases and other low flashpoint fuels, built or converted after the entry into force of the Code. However, presently, it only contains detail requirements for natural gas (LNG or CNG) as fuel, and only for use in internal combustion engines, boilers and gas turbines. A phase 2 development of the IGF Code initiated by IMO and its CCC sub-committee is currently allowing the further development of technical provisions for ethyl/methyl alcohols as fuel and fuel cells. Requirements for fuel cells will constitute a new part E of the IGF Code.

Until these additions and amendments are finally approved and entered into force, applications making use of other gases and low flashpoint fuels, including use of fuel cells, within the frame of the IGF Code Part A, are required to follow the alternative design method in accordance with SOLAS Regulation II-1/55 to be used for demonstration of an equivalent level of safety.

High level Gap Description	Recommendation/Assessment	Gap Category:	Ref. to report
IGF Code:			
- use of fuel cells - use of other low flashpoint fuels than LNG/CNG - bunkering of gaseous H2, other low flashpoint fuels and LH2	Further development of IGF code needed. Detailed safety studies. Use existing standards for non-maritime applications as input.	L, H, K	5.3
Bunkering:			
Rules for bunkering of liquid hydrogen	Review of applicable land based standards. Risk studies and a qualification process to develop rules and bunkering procedures.	L, H, K	5.4.1
Gaseous hydrogen	Review of applicable land based standards. Risk studies and a qualification process to develop bunkering procedures.	L, H, K	5.4.2
Low Flashpoint Liquids	Bunkering procedures for LFL's Safety zones for gas vapour from tanks	L, H, K	5.4.3
On-board storage:			
Storage of compressed hydrogen	Qualification of pressure tanks for maritime use with compressed hydrogen gas. Safety studies considering hydrogen pressure tanks and requirements for safe solutions. Development of provisions for possible high pressure storage technologies in enclosed areas.	L, H, K	5.5.1
Storage of liquid hydrogen	Possible storage related failure modes need to be understood, and land based solutions adjusted if necessary for safe application.	K	5.5.2
Fuel cell System:			
Safe handling of hydrogen releases	Review of and update of fuel cell rules and regulations. Risk studies to improve understanding of possible safety critical scenarios including fire and explosion to recommend risk controlling measures.	L, H, K	5.6.1
Ventilation requirements	The fuel specific properties must be considered. Relevant and realistic hydrogen dispersion simulations needed to evaluate and/or update ventilation requirements.	L, H, K	5.6.2
New arrangement designs	Need for improved understanding of system design issues, new technology challenge existing regulations	L, K	5.6.3
Piping to fuel cell system	Knowledge and safety assessments needed to identify needs to adjust LNG requirements for the use of LH.	L, K	5.6.4
Reforming of primary fuel	Reformer safety issues should be explored and documented	L, K	5.6.5
Ship life phases:			
Best practices/Codes for hydrogen, LFL fuels and fuel cell installations	Procedures should be developed for commissioning, docking, maintenance to reflect the properties of hydrogen and other LFL fuels.	L, H	5.7
Fuel specific:			
Hydrogen	Comprehensive safety studies considering hydrogen specific properties, behaviour and conditions needed for the use of hydrogen in shipping applications	L, K	5.8

Table 1

The major Classification Societies have established, or have under development, Rules covering fuel cells and, to some extent, also low flashpoint fuels. The different Rules' sets provide however a somewhat varying level of detail, unfavourable to harmonization. Onshore fuel cell and fuel standards recognized to be relevant for maritime applications are also provided in the present report.

The ship side of the bunkering operation (from the bunkering flange on the ship side) is covered by the IGF-Code, but not the shore part.. Therefore, other standards for safe bunkering of the relevant fuels are needed to support the implementation of bunkering technology for maritime use. For LNG, the ISO/TS 18683 - Guidelines for systems and installations for supply of LNG as fuel to ships, issued Jan 2015 – provides useful guidance, as does recommended practices and guidelines published by the major classification societies. The standard ISO 20519 "Ships and marine technology – Specification for bunkering of gas fuelled ships" is under preparation for its final publication, but the focus of this standard seems to be limited to LNG.

The last part of the regulatory discussion includes an identification of regulatory and Rule gaps. The table on the left page provides a summary of the findings.

Finally, Chapter C of the report describes the findings of the safety assessment. The purpose of the safety assessment is to analyse possible safety challenges for maritime fuel cell applications to assist further regulatory developments.

For the assessment, generic concepts of fuel cell installations and their integration on a RoPax vessel and a Gas Carrier were developed. These generic concepts are based on the application of the most promising fuel cell types identified in chapter A of the study, namely the PEM, HT-PEM and SOFC. These three fuel cell types are further considered to cover well the technology span of fuel cells today; from low, medium to high temperature cells, respectively. Three fuel types are considered; LNG, methanol and hydrogen.

For the safety assessment study a simplified Formal Safety Assessment (FSA) was followed in the terms of a qualitative Failure Mode and Effect Analysis (FMEA). The FMEA workshop was performed on 19th to 21st of October 2016 at DNV GL premises in Hamburg, Germany. Relevant representatives of the Industry, DNV-GL and EMSA constituted the analysis team.

Altogether 148 failure scenarios related to the usage of the three different types of fuel cells and fuels onboard RoPax vessels and Gas Carrier were investigated. The assessment focused on possible risks to passengers, crew, third party personnel, adjacent systems during normal operation, bunkering and in accidental situation. First, the hazards were identified and ranked as the systems were defined for the analysis. As a result, for some of the failure scenarios, further actions were recommended. For a total of 100 scenarios, additional mitigation actions were recommended. Taking these recommendations into account, it was recognized by the analysis team, that tolerable risk levels (ALARP) could be reached, with respect to operational and human safety.

The most critical events identified during the safety assessment are related to

1. Strong exothermic reaction of reformer material
2. Internal leakage in FC Module
3. High energy collision penetrating liquefied hydrogen (LH_2) tank
4. Rupture of compressed hydrogen (CH_2) tank containment system
5. Leakage of hydrogen rich gases
6. Failure of pressure reduction
7. Failure of electrical power output conditioning system
8. Thermal runaway of onboard energy buffer
9. Loss of active purging system
10. Leakage during bunkering of hydrogen
11. Vehicle crash penetrating Fuel Cell Power

System Installations

The safety assessment has shown that some specific items related to the use of Fuel Cell Power Systems on board ships shall be further studied, including, in particular:

- The Influence of different fuel behaviour on the definition of hazardous zones and safety distances
- The storage of hydrogen as fuel with respect to collision and potential storage under accommodations

A

FUEL CELLS IN SHIPPING

INTRODUCTION

The present study on the use of fuel cells in shipping was commissioned by the European Maritime Safety Agency (EMSA), as part of this agency's role in supporting EU Member States and the European Commission with regards to solutions for sustainable shipping, namely in the development of knowledge and information regarding alternative fuels and clean power technologies. In this context, and as the main motivation for this study, it can be highlighted that fuel cells in particular have been receiving increased interest as an alternative power supply for ships.

This is owing to the merits of the technology, resulting not only in reduced air emissions and improved fuel efficiency, but also increasing the available options to ship owners for complying with increasingly stringent environmental regulations.

Favouring compliance to current environmental regulations, in line with a more sustainable development in the shipping industry, fuel cell power production is indeed a technology that can eliminate NO_X, SO_X and particle (PM) emissions, and reduce CO_2 emissions, especially when compared with emissions from diesel engines. Fuel cells powered by low carbon fuels (e.g. natural gas) will have local and regional benefits as both emissions and noise are reduced. In the longer term, hydrogen fuel generated from renewables could lead to ships with zero carbon emissions.

A fuel cell power pack consists of a fuel and gas processing system and a stack of fuel cells that convert the chemical energy of the fuel to electric power through electrochemical reactions. The process can be described similar to that of a battery, with electrochemical reactions occurring at the interface between the anode or cathode and the electrolyte membrane, but with continuous fuel and air supplies, Different fuel cell types are available, and can be characterized by the materials used in the membrane.

The use of the fuel cell as an electricity generator was invented by William Grove in 1842 (Vie stich et al., 2001). Due to the success and efficiency of combustion engines, fuel cells have not been widely considered for general use, and, until recently, fuel cells have been applied only for special purposes, such as space exploration and submarines. However, rising and fluctuating fuel prices and a strong focus on reduction of global and local emissions have led to an increasing focus on the development of fuel cells for application in other areas as well. Market studies (Fuel Cell Today, 2013) have revealed that fuel cells should no longer be considered as a technology for the future; they are already commercially available today for a diverse range of applications (e.g. portable electronics, power plants for residential use, and uninterruptible power supply). During 2014 and 2015 the stationary fuel cell sector became overall substantially more sustainable, with a broader range of fuel cell system suppliers, increasing growth capital flowing to the sector, price drops across the board and an increase in the number of companies with overall annual revenue above $100 million . When looking at the maritime industry in particular, as this current report discloses; a wide range of maritime fuel cell projects are ongoing, and the application of the fuel cell in commercial shipping projects is increasing. To this end, recent press releases announce that cruise line operator Royal Caribbean Cruises Ltd. and Meyer Turku shipyard will develop next generation of LNG powered cruise ships with a number of innovations such as an application of fuel cells for power generation.

However, on a global scale, it is recognised that fuel cell technology is still a diminutive business. In order to become a viable and realistic alternative for future energy solutions, including ships, several hurdles must be overcome. One of the most important is the ability to leverage a technology into a market, thereby creating the mass production that will provide economy of scale which again will lead to cost reductions. A technological and societal move that underpins this development is the trend that companies are switching from selling technology to selling services. An example is new car manufacturers emerging; making cars that will not be sold but will be leased on per mile used, with the price to include the fuel . This may ease concern over the technology, and may also distribute the extra cost of the fuel cell among several users. Another example is the project financing facility between fuel cell manufacturers and venture funds. This facility provides long term

financing for projects that the fuel cell manufacturer is developing under power purchase agreements.

Another hurdle that possibly slowly is starting to find its solution is the problem of how to make hydrogen and other novel fuels such as methanol available as long as the demand is waiting for the infrastructure. Policy shifts observed in many countries, is slowly helping to solve this problem. For example in Korea and Japan focusing on adoption of hydrogen solutions in urban transport applications and in society at large. In Norway, the governmental office for coastal ferry infrastructure is requesting emission free solutions for several new route licenses. Also, emission free cars including hydrogen cars are offered several courtesies such as reduced taxes, admission to the highways' commuting lanes, free toll and parking etc.

As to what fuel cell technology have the best future prospects, the question is best answered by considering the application. Smaller and medium applications may favor low and medium temperature technology, such as proton exchange membrane (PEM) and high temperature PEM. Larger application which can more easily accommodate waste heat solutions, such as industrial and large maritime, are better for the high temperature solutions such as molten carbonate or solid oxide fuel cells.

The total shipment of fuel cells in 2015 amounts to 335 MW, with transport sector standing for 178 MW and stationary sector 157 MW. The largest manufacturers are South Korea and USA, with Japan following. Europe is behind on fuel cell manufacturing, but is leading in terms of experience and number of maritime application projects.

In fact, as this report documents, a rather large number of maritime fuel cell projects have been run in Europe the last 10-15 years. Which provide the background for - and motivation behind - the request for carrying out the work encapsulated in this report. With so doing, EMSA is forming a dedicated activity to prepare and spur further interest in maritime fuel cell projects, an initiative well timed considering the coming environmental regulations and the continuing maturation of fuel cell and hydrogen technology.

In this report, an overview of different fuel cell technologies is provided, in all cases with a clear reference to possible applications in shipping, or for a wider marine use, and the projects where experience and knowledge of marine use of fuel cells have been gained are further elaborated. This is followed by a regulatory mapping, including an overview of standards/regulations and guidelines applicable for fuel cells in shipping, as well as for bunkering of novel fuels such as hydrogen. Regulatory gaps are identified and listed. Finally, the report provides the results from an individual risk assessment of integrated maritime FC applications, performed within the frames of the project. The risk study was limited to three selected

technologies. The report reproduces the results from the nomination process, whereby the chosen three technologies are selected based on a scrutiny of their potentials. This scrutiny covers a predefined list of 11 attributes including criteria on:

Technology:	6 criteria	power levels, lifetime, tolerance for cyclic operation, efficiency, maturity, sensitivity to fuel impurities
Cost:	1 criteria	relative cost between different FC types
Safety:	1 criteria	special safety aspects relevant for each FC type
Environment:	1 criteria	emissions
Ship application:	2 criteria	physical size of FC, relevant fuels

The ranking and scores provided during the nomination and selection is qualitative in nature, and serves as a comparison between the technologies. This reflects the difficulty of establishing concrete figures on new technology, which is still under development. In defining the list of decision criteria, emphasis has been to use benchmarks that will be decisive as to whether a project will include fuel cell technology or not. Less focus has been put on engineering aspects and other issues not judged to be business critical. An example of the latter will be ventilation system issues necessitated by the different fuel cell types.

The three different fuel cell types was then considered for two ship types; a RoPax vessel and a chemical carrier; forming a total of six alternative vessel/fuel cell configurations. The vessel categories were predefined by EMSA in their call. The risk assessment covers all six configurations.

1 – FUEL CELL PROJECTS IN SHIPPING

A total of 23 fuel cell project in the maritime sector was identified, the list is given in Table A.1. The projects vary from assessments of potential for fuel cell use, rule development and feasibility studies and concept design to testing of fuel cells in various vessels. Chapter A.5 describes more in detail 12 selected projects; that is FCShip, METAHPU, FellowSHIP, SF-BREEZE, US SSFC, Felicitas subproject II, MC-WAP, ZEMShips, Nemo H2, Pa-X-ell, SchIBZ and RiverCell.

Project	Concept	Main partners	Year	Fuel Cell	Capacity	Fuel
FellowSHIP	320 kW MCFC system for auxiliary power of Offshore Supply Vessel	Eidesvik Offshore, Wärtsilä, DNV	2003-2011	MCFC	320 kW	LNG
Viking Lady METHAPU Undine	20 kW SOFC tested for the evaluation of 250 kW SOFC solution for marine APU.	Wallenius Maritime, Wärtsilä, DNV	2006-2010	SOFC	20 kW	Methanol
E4Ships – Pa-X-ell MS MARI-ELLA	60 kW modularized HT-PEM fuel cell system developed and tested for the decentralized auxiliary power supply onboard passenger vessel MS MARIELLA.	Meyer Werft, DNVGL, Lürssen Werft, etc	Phase 1: 2009-2017 Phase 2: 2017-2022	HTPEM	60 kW (each stack is 30 kW)	Methanol
E4Ships - SchIBZ MS Forester	100 kW containerized SOFC system developed and tested for the auxiliary power supply of comercial ships. Scalable up to 500 kW units.	Thyssen Krupp Marine Systems, DNVGL, Leibniz University Hannover, OWI, Reederei Rörd Braren, Sunfire	Phase 1: 2009-2017 Phase 2: 2017-2022	SOFC	100 kW	Diesel
E4Ships - Toplanterne	Support of IGF Code development to include a FC chapter and set the regulatory baseline for the use of maritime FC systems	DNV GL, Meyer Werft, Thyssen Krupp Marine Systems, Lürssen Werft, Flensburger Schiffbaugesellschaft, VSM	Phase 1: 2009-2017 Phase 2: 2017-2022	-	-	-
RiverCell	250 kW modularized HT-PEM fuel cell system developed and to be tested as a part of a hybrid power supply for river cruice vessles	Meyer Werft, DNVGL, Neptun Werft, Viking Cruises	Phase 1: 2015-2017 Phase 2: 2017-2022	HTPEM	250 kW	Methanol
RiverCell – Elektra	Feasibility study for a fuel cell as part of a hybrid power supply for a towboat	TU Berlin, BEHALA, DNVGL, etc	2015-2016	HTPEM	-	Hydrogen
ZemShip - Alsterwasser	100 kW PEMFC system developed and tested onboard of a small passenger ship in the area of Alster in Hamburg, Germany	Proton Motors, GL, Alster Touristik GmbH, Linde Group etc.	2006-2013	PEM	96 kW	Hydrogen
FCSHIP	Assess the potential for maritime use of FC and develops a Roadmap for future R&D on FC application on ships	DNV, GL, LR, RINA, EU GROWTH progam	2002-2004	MCFC SOFC PEM	-	Various
New-H-Ship	Research project on the use of hydrogen in marine applications	INE (Icelandic New Energy), GL, DNV, etc	2004-2006	-	-	-
Nemo H2	Small passenger ship in the canals of Amsterdam	Rederij Lovers etc	2012-present	PEM	60 kW	Hydrogen
Hornblower Hybrid	Hybrid ferry with diesel generator, batteries, PV, wind and fuel cell	Hornblower	2012-present	PEM	32 kW	Hydrogen
Hydrogenesis	Small passenger ship which operates in Bristol	Bristol Boat Trips etc.	2012 - present	PEM	12 kW	Hydrogen

Figure A.1: Viking Lady

Project	Concept	Main partners	Year	Fuel Cell	Capacity	Fuel
MF Vågen	Small passenger ship in the harbour of Bergen	CMR Prototech, ARENA-Project	2010	HTPEM	12 kW	Hydrogen
Class 212A/214 Submarines	Hybrid propulsion using a fuel cell and a diesel engine	CMR Prototech, ARENA-Project, ThyssenKrupp Marine Systems, Siemens	2003 - present	PEM	306 kW, 30-50 kW per module (212A) 120 kW per module (214)	Hydrogen
US SSFC	The program addresses technology gaps to enable fuel cell power systems that will meet the electrical power needs of naval platforms and systems	U.S. Department of Defens, Office of Naval Research	2000 - 2011	PEM MCFC	500 kW (PEM) 625 kW (MCFC)	Diesel
SF-BREEZE	Feasibility study of a high-speed hydrogen fuel cell passenger ferry and hydrogen refueling station in San Francisco bay area	Sandia National Lab., Red and White Fleet	2015 - present	PEM	120 kW per module. Total power 2.5MW	Hydrogen
MC-WAP	MC-WAP is aiming at the application of the molten carbonate fuel cell technology onboard large vessels, such as RoPax, RoRo and cruise ships for auxiliary power generation purposes	FINCATIERI, Cetana, OWI, TÜBITAK, RINA, NTUA, Techip KTI, etc	2005-2010	MCFC	Concept design of 500 kW, final design of 150 kW	Diesel
FELICITAS – subproject 1	Application requirements and system design for FC in heavy duty transport systems	Lürssen, FhG IVI, AVL, HAW, Rolls-Royce, INRETS, VUZ	2005-2008	-	-	-
FELICITAS – subproject 2	Mobile hybrid marine version of the Rolls-Royce Fuel Cell SOFC system	Rolls-Royce, Uni Genoa, Lürssen, HAW, Uni Eindhoven	2005-2008	SOFC	250 kW (60 kW sub system)	LNG, other fuel also evaluated
FELICITAS – subproject 3	PEFC-Cluster - improving PEFC reliability and power level by clustering	NuCellSys, FhG IVI, CCM	2005-2008	PEM	Cluster system (80 kW basis component)	Hydrocarbon fuels and hydrogen
FELICITAS – subproject 4	Power management – concerns general technical problems of FC-based propulsion	FhG IVI, Lürssen, NTUA, NuCellSys, CCM, Uni Belfort, AVL, CDL	2005-2008	PEM	-	-
Cobalt 233 Zet	Sports boat employing hybrid propulsion system using batteries for peak power	Zebotec, Brunnert-Grimm	2007 - present	PEM	50 kW	Hydrogen

Table A.1: Fuel cell projects in shipping

2 – PROJECT DESCRIPTIONS OF SELECTED PROJECTS

As the project list in table A.1 shows there have been several projects on the use of fuel cells in shipping, below 12 selected projects are described in more detail. In this chapter we cover the background and objective of the projects, technical details (fuel cell type, fuel, reforming technology and power) where applicable and results from the project. Information that is specific to the fuel cell type (catalyst, electrolyte, temperature, cell efficiency and emissions) will be covered in chapter 6.

FELLOWSHIP

Background and objectives

The goal of the FellowSHIP project at large was to develop, design, build, test and qualify integrated system solutions that would enable the fuel cell technology to meet industrial requirements, including grids with frequent dynamics such as in ships, trains and offshore applications. The project met this by developing a fuel cell installation compatible with maritime requirements and with power electronic solutions that allow the use of existing fuel cell technology in merchant ships.

The FellowSHIP project phase II started in 2007 and ended 31st July 2010. The project was managed by DNV Research & Innovation, and received the main part of its external funding from the MAROFF programme within the Research Council of Norway. Parts of the project were also funded by Innovation Norway and German Federal Ministry of Economics and Technology. Partners in the project were DNV AS, Eidesvik AS, Wärtsilä Norway AS (WNO), Wärtsilä Ship Design Norway AS (WSDNO) and MTU Onsite Energy GmbH. Total budget for phase 1 and 2 amounted to more than 120 MNOK (ca. 14 MEUR).

The project included a thorough development and testing regime, with complete development and testing of the 320 kW prototype power pack on land with all subsystems before lifting aboard. Thereafter followed the testing and qualification program onboard the newly delivered offshore supply vessel Viking Lady (Figure A.1). The vessel Viking Lady was selected for the project by the shipowner Eidesvik, and is a modern offshore supply vessel designed with the superstructure aft as opposed to conventional OSV's, partly for which reason the vessel design received the European Ship of the Year price in 2004. The vessel is all electric, powered by LNG by use of dual fuel engines. This made it an attractive test platform since the "infrastructure" of fuel and robust electrical plant was in place.

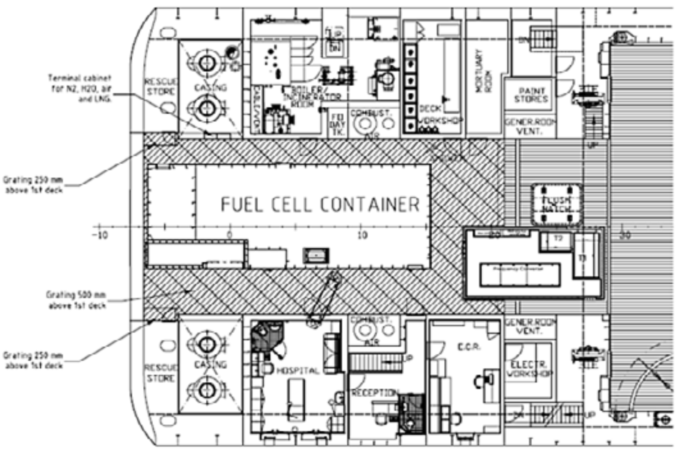


Figure A.2: Fuel cell container on Viking Lady

Technical details

The FellowSHIP project used a molten carbonate fuel cell (MCFC) of 320 kW with LNG as the fuel. The fuel was internally reformed in the fuel cell, removing the need for external reforming technology. The stack efficiency at 100% load was measured to 52.1% and total fuel cell efficiency including internal power consumption losses 44.1%. The internal consumption of electric power is high due to the R&D nature of the installation (involving redundant systems and extra safety margins), and will be lower in a commercial installation. A heat recovery system was used to harvest excess energy. The energy recovery system was not optimised, thus the total efficiency of the system did not reach its full potential.

Results

The following will highlight some of the main results of the work.

Development of hardware: fuel cell and support systems

The basis for the marinised fuel cell was MTU's "Hot Module" (HM400) design. The HM400 was at that time a newly developed design with a stack of 500 fuel cells. The existing mechanical design and process supply were adapted to marine operation.

To provide the air, gas and water quality required, the "media supply" (MS) unit was developed and built by MTU with input on marine specifications from the project partners. Some changes from previous installations were needed to meet the requirements for onboard operation and class approval; e.g. an Ex zone (gas safety) for parts of the equipment had to be established and compensators had to be eliminated from the pipe work.

Figure A.3: The media module containing support systems for the fuel cell

A safe and efficient integration of the power produced from the fuel cell in Viking Lady's electrical propulsion system was an essential goal for the technology development. The Fuel Cell delivers a direct current voltage varying between 380VDC – 520VDC depending of its load condition and age. Due to material limitations requiring slow load changes, the electrical system had to be designed to keep stable conditions for the Fuel Cell. The electrical equipment were developed and built by WNO and mounted into a dedicated container. Operational experience showed that the system worked as intended and protected the fuel cell against harmful dynamic load changes.

Onshore test program

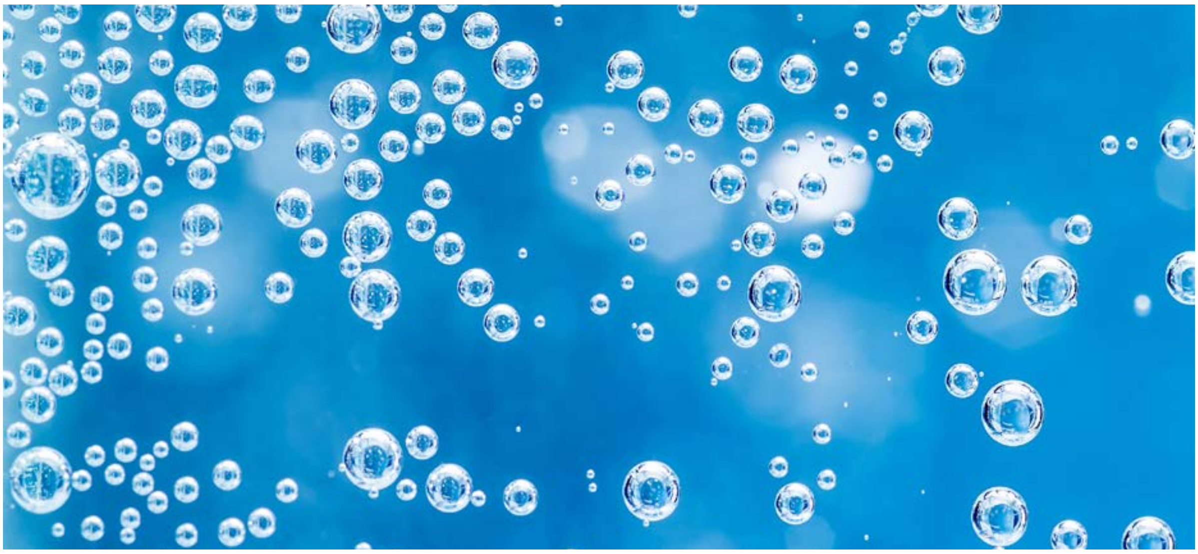
Since the installation was to be mounted on a vessel in operation, an onshore test period for the plant was planned to minimize the time needed for hook-up and modifications onboard. The onshore test period started 1st July 2009. WNO and MTU solved a number of issues related to interface and integration between their systems, the test were therefore of high value to the project.

Demonstration onboard; design and implementation of vessel modifications and hardware installation

To assure successful implementation and testing of the power pack onboard, close integration in the overall ship design was necessary. Interface to the existing LNG fuel system, additional electrical cable routing, hull modifications to support extra weight and safety measures towards gas leaks and fire was designed by WSDNO and integrated in the new build. Due to the temporary nature of the installation and the need for onshore testing it was decided to build two custom made containers as separate machine rooms on deck. The largest container accommodates the HotModule and the Media Supply including all support gases. This design was also performed by WSDNO in close contact with Eidesvik, and with input from the other partners.

Class approval

Rules were developed based on existing fuel cell standards that were adapted for a ship environment. The DNV rules "Fuel cell installations" was issued in July 2008, and Viking Lady with the FellowSHIP installation was the first vessel to obtain a certificate with the "FC-Safety" notation. The prime role of DNV in the project was to assure that the installation was



compatible with marine safety requirements. The approval process had focus on gas safety and the electrical interface to the vessels existing power system. Onshore and onboard testing of the installation was done to verify compliance with class rules.
The approval process generated valuable experience and feedback on the new rules.

Modelling and simulation
DNV started in the fall of 2007 work toward simulating fuel cells. The work done under the FellowSHIP project resulted in a model of a fuel cell that exhibits the expected physical behaviour. The fuel cell models can be combined into a model of a fuel cell stack. Simulations included both steady state and dynamic calculations, where the goal was to shed light on the fuel cell's performance under load changes and other external influences. Data for verifying the models were available towards the end of the project.

Operational experience
In February 2012, the total operation time had reached 18500 hours, with maximum expected operational time estimated to 24000 hours. The fuel cell stack has been running at constant loads, between 30mA/cm2 and 120mA/cm2 (full load). A few tests challenging the dynamic response of the system has also been performed. The onboard test program measured a maximum electrical efficiency of 52,1% from the fuel cell stack at full load (330 kW), corresponding power to net was 44,1%. The internal consumption of electric power is high due to the R&D nature of the installation (involving redundant systems and extra safety margins), and will be lower in a commercial installation. Exhaust gas testing was preformed confirming predicted low emission levels of NO_x, SO_x and CO_2.

Impact of results and project follow-up

Being a pilot installation the project has revealed a number of areas for further development. For example, future installations will have a different solution when it comes to nitrogen purging, and pure hydrogen for start-up sequence will be likely not be necessary. No major showstoppers have been revealed, but the required investment cost is considered high. The project partners brought the vessel Viking Lady to Copenhagen during the UN Climate Change Conference "COP 15", putting focus on the LNG fuelled vessels and fuel cell technology as two promising technologies to reduce global and local pollution from shipping.

Overall the project has been a technical success as the first large scale installation of a fuel cell in a merchant vessel. It has generated a massive international attention promoting the companies and countries involved as initiators of new environmental technology.

Fellowship summary

FC type	Power	Fuel	Type of project
Molten carbonate	320 kW	LNG	Concept study and marine operation of fuel cell on vessel

FCSHIP

Background and objectives

The project "Fuel Cell technology for SHIPs" (FCSHIP) was formed with the aim to enable EU fuel cell technology providers to be more competitive in the perspective future market for maritime applications, enable EU ship-owners to utilize fuel cell new technology and to assist EU in meeting sustainable development, energy saving and air pollution reduction objectives.

The short and medium term objectives of the work were to:

- Define the end users' demand for the application of fuel cells on board ships for both main propulsion and auxiliary applications;
- Evaluate safety and operational demands for ships equipped with fuel cells
- Assess both economically and environmentally, the potentials of fuel cells application for waterborne transport.
- Provide a "roadmap" for further R&D on FC application on ships

The project was an EU shared-cost RTD project in the GROWTH Program, intended as a start for marine related fuel cell research & development within EU. The program was of two years duration (July 2002 - June 2004), with 21 partners from six countries (NO, NL,D,UK,I, FIN). The financial budget was EUR 2.5 million with EUR 1.4 million EU contributions.

The project was organised with 5 main workpackages:

1. Synthesis of previous experience and demonstration projects
2. Basic safety and operational requirements for future use of FC systems onboard ships
3. Conceptual design and case ship analysis
4. Assessment of infrastructure, energy efficiency, environmental and life cycle costs
5. Synthesis & Recommendations

Results

Two case ships were considered theoretically for fuel cell installations; a RoPax vessel and a harbour commuting ferry.

Basic safety requirements were developed by the participating class societies and industrial partners.

The following general statements were given:

- Safe FC-Systems for ships are possible. No major obstacles have been detected.
- International consensus with respect to safety requirements is important due to the internationality of shipping. As a first step the consensus among the participating class societies demonstrate that this international common understanding is possible.
- International cooperation of class societies in R&D is important to ensure equal knowledge and international accepted safety requirements
- A number of further RTD is needed to solve the problems and to guaranty the necessary level of safety (comp Gaps and Needs). Experience and R&D is needed for reliability, availability records of FC-Systems
- A general list of recommendations for rule development was made

The environmental study analyzed the energy requirements, emissions of greenhouse gases (GHG) and air pollutants as well as the costs for the supply of conventional and alternative fuels to the two case ships considered in the FCSHIP project (Well-to-Tank energy, emissions and costs).

The main conclusions were:

- Pilot- und Demonstration Projects with systems of some hundred kW power are urgently needed for the development of commercial products
- Hydrogen and PEMs are usable for small systems with some hundred kW for local operation
- Liquid fuels based on hydrocarbons must be used for first MCFC and SOFC FC-Systems in the low MW range
- The development of commercial FC-Systems is a precondition for the use of synthetic liquid fuels with high volumetric power density in future FC-Systems for ships.
- No fundamental obstacles for the integration of FC-systems into a commercial ships exist
- No fundamental obstacles with respect to safety exist.

FCship summary

FC type	Power	Fuel	Type of project
Molten carbonate Solid oxide PEM	NA	Hydrogen for PEM Hydrocarbons for MCFC and SOFC	Roadmap for future R&D on FC in marine use.

METHAPU

Background and objectives

The Methapu project (Methanol Auxiliary Power Unit) was formed after the initial feasibility phase 1 of FellowSHIP, which included a feasibility study of fuel cells for auxiliary power production for a RoRo Car Carrier.

The project was a European Commission (EC) funded research project (6FP) with strategic objectives to:

1. Assess the maturity of methanol using technology on board a commercial vessel.
2. Validate marine compatible methanol running solid oxide fuel cell technology.
3. Innovate necessary technical justifications for the use of methanol on board cargo vessels involved in international trade in order to support the introduction of necessary regulations to allowing the use of methanol as a marine fuel.
4. Assess short-term and long-term environmental impacts of the application.
5. Enable future research activities on larger marine compatible solid oxide fuel cell units and methanol based economy.

METHAPU included Wärtsilä Corporation, Lloyd's Register, Wallenius Marine, University of Genoa and Det Norske Veritas (DNV).

Technical details

The METAPHU project have evaluated a 250 kW SOFC unit using methanol and have operational experience from a 20 kW SOFC unit with a methanol reformer.

Results

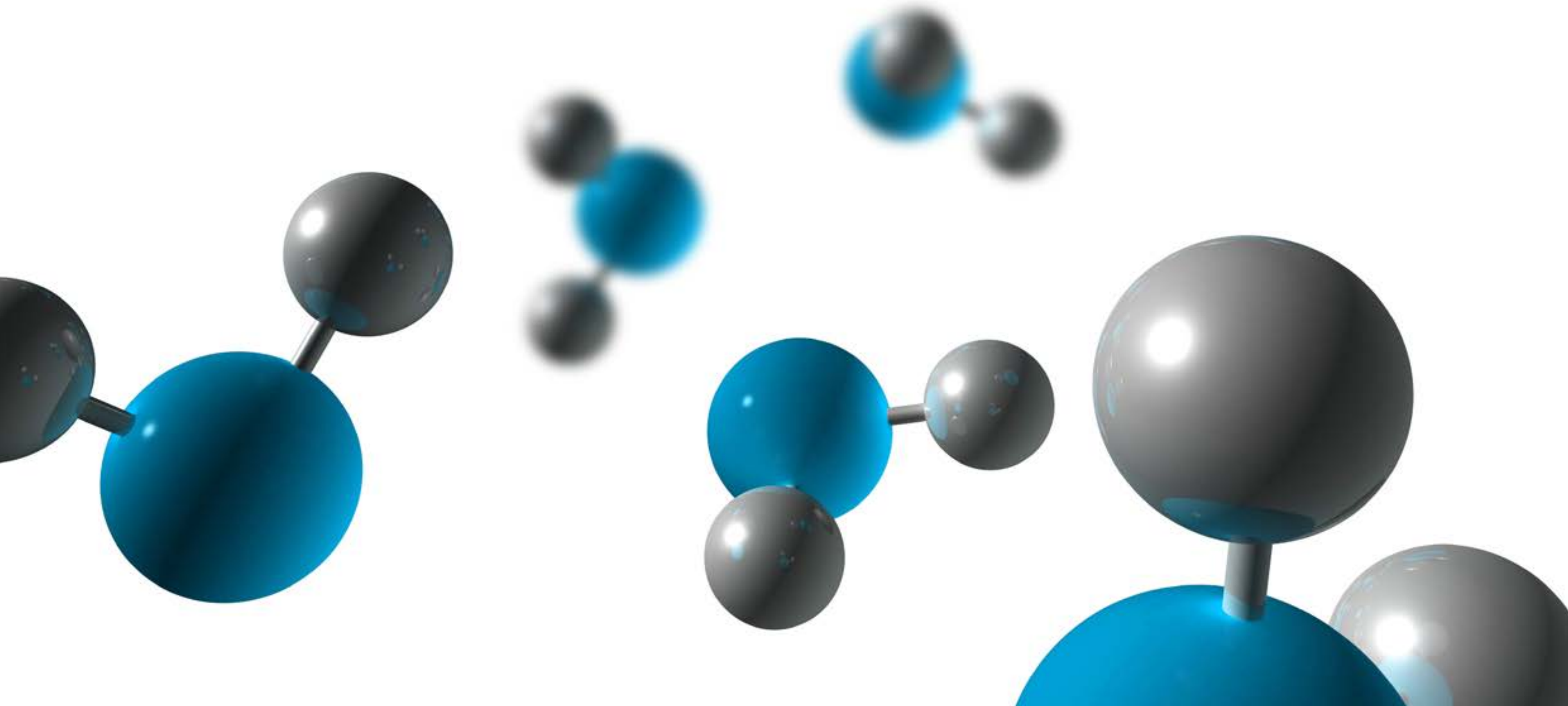
The project consisted of 11 technical workpackages, including among others:

- Marine modification of the 250 kW SOFC unit,
- Safety & reliability study of 250 kW unit,
- LCA of the marine vessel using methanol based fuel cells.
- Design, build and test methanol reformer and marine compatible 20 kW unit.
- Modifications of the commercial vessel for methanol use, install, integrate and commission the 20 kW unit into the vessel, operational safety assessment, and finally field study and emission evaluation of the 20 kW unit.

The METHAPU project started November 2006 and was finished in October 2010. The METHAPU project was the first to use methanol as a marine fuel and developed operational safety rules applicable for other installations and projects using methanol as a marine fuel. The SOFC unit were placed on open deck including the methanol tank and fuel system to make the safety arrangements easier. The project was technically successful and The METHAPU project succeeded in running the fuel cell on methanol for about 700 hours.

METHAPU summary

FC type	Power	Fuel	Type of project
SOFC	250 kW (concept study) 20 kW (Marine operation	Methanol	Concept study and marine operation of fuel cell on vessel



NEMO H2

Background for the project and objectives

By early 2006, 5 companies (Alewijnse Marine Systems, shipping company Lovers, Linde Gas, Marine Service North and Integral) concurred to set up a project aimed at the development, construction and exploitation of a hydrogen boat, Nemo H2 (Figure A.4). The hydrogen boat was intended for transport of passengers in the city center of Amsterdam.

Figure A.4: Launching of Fuel Cell Boat "Nemo H2"

Technical details

The implementation of a fuel cell on a passenger boat was planned for 100 persons with a 65 kW PEM fuel cell that sails on hydrogen, a 30 to 50 kW battery system and 40 kg onboard hydrogen storage in 8 cylinders at 350 bar. Also part of the project was the realisation of a hydrogen filling station at the waterside with a capacity of 60 Nm³/h.

Figure A.5: Installation of Fuel Cell Module at Nemo H2

Class approval

The GL "Guidelines for the Use of Fuel Cell Systems on Board of Ships and Boats" were applied to obtain a certificate with the FC class notation for the passenger vessel with hydrogen fuelled fuel cell system. A risk assessment of the developed design was carried out to evaluate the risks and elaborate the respective safety procedures for operation of the integrated hybrid system.

Results

The Fuel Cell installation including fuel cell system, batteries and hydrogen storage were successfully approved and integrated in the ship. The risk assessment, approval, onshore and onboard testing showed that a safe operation of the vessel is possible.

NEMO H2 summary

FC type	Power	Fuel	Type of project
PEM	60 kW	Hydrogen	Hybrid system of PEM fuel cell and batteries on a passenger vessel

SF-BREEZE

Background and objectives

SF-BREEZE (San Francisco Bay Renewable Energy Electric vessel with Zero Emissions) is a collaboration project between Sandia National Laboratories, The red and White Fleet, the American Bureau of Shipping, the U.S. Coast Guard and naval architect Elliott Bay Design Group. The project started in 2015 and is a feasibility study to examine the technical, regulatory and economic aspects of building and operating a high-speed hydrogen fuel cell passenger ferry and hydrogen refueling station in San Francisco bay area. The project aims to design, build and operate a 150 passenger high-speed hydrogen fuel cell passenger ferry using (Figure A.6) a PEM fuel cells and liquid hydrogen as fuel. The outcome of the feasibility study will be a "Go/No-Go" recommendation to proceed with the actual design and build of the ferry and hydrogen station.

Results and technical details

The concept as it is planned now is an aluminium ferry with two electro motors of 2.5 MW driven by 41 fuel cell units of 120 kW each. The fuel cells and fuel storage system are above deck due to safety and regulatory considerations, and takes up a substantial part of the ferries area that would normally be used for passengers. The fuel is liquid hydrogen and the project also includes a hydrogen fuelling station on shore.

SF-Breeze summary

FC type	Power	Fuel	Type of project
PEM	120 kW per module. Total power 2.5 MW	Liquid hydro-gen	Concept study of high speed fuel cell ferry

Figure A.6: Illustration design of SF-BREEZE

PA-X-ELL

Background for the project and objectives

Pa-X-ell is part of the lighthouse project "e4ships" by the National Innovation Programme for Hydrogen and Fuel Cell Technology (NIP). The goal is to reduce emissions on cruise ships, yachts and RoPax-ferries through the integration of a fuel cell-based decentralized energy grid. Another aspect of the project is the verification of safety concepts for the use of fuel cells onboard passenger vessels and the review of economy. To allow a decentralized and secure system the project focus on modular high temperature PEM fuel cells integrated into standardized racks.

The main partners of the project are MEYER WERFT, Fr. Lürssen Werft, Flensburger Schiffbau-Gesellschaft, DNV GL, DLR and SerEnergy. The project has been launched in April 2009 and is finishing the first phase until December 2016.

Results

Development of hardware: Modularized Fuel cell system

The modular HT-PEM fuel cell is developed and designed by SerEnergy and Fischer eco solutions and provides 5 kW. Eight of these fuel cells will be

Figure A.7: Containment of onshore test container

Figure A.8: FC demonstrator onboard MS Mariella [source: Meyer Werft]

set together to one rack (30 kW). Through a modular and standardized system setup it is possible to adapt to any situation for maritime utilization. The required hydrogen is produced internally by reforming of methanol. Methanol is particularly suitable, since it is liquid at ambient conditions, easy to reform to H2, and is readily available. However, since methanol is toxic, in phase II of the project the use of natural gas (NG) will be investigated. Furthermore the use of thermal energy was investigated for a further use for heating and cooling by the use of an absorption chiller unit (ACU).

Onshore test programme

In summer 2014 the first research plant with FC-modules of the first generation was put into operation for a first land test program at Meyer premises. For four months the plant was in the endurance test. The data collected during this period were then used to develop the fuel cells of the second generation. Operating experience and the new FC-modules also required an adjustment of the internal structure of the racks.

Since March 2015 the plant is working with new racks and an adapted control of the ACU.
Demonstration onboard

An identical ACU is already being used successfully on board the German research vessel “Sonne”. Currently one module provides an electrical power output of 5 kW this will be increased to 20 kW in phase II. The ACU of the research plant (8 x FC-modules, 30 kW) has a power input of 20 kW and provides a cooling capacity of 17 kW.

Aboard the ferry MS Mariella a second research fuel cell was installed in autumn 2016 supporting the ship with electrical and thermal energy. The onboard test will be extended in a second phase of the project.

Regulatory approval

The main safety hazard from fuel cells on-board seagoing vessels are fuels with a low flashpoint, such as methanol or hydrogen; to manage the risk, requirements for sufficient ventilation, alarm systems, fire protection and other measures to limit likelihood and consequences of a gas leakage are formulated.
For fuel cell installations, in particular on passenger vessel, the regulatory regime consists at present of three main sets of rules and regulations: SOLAS, including Safe Return To Port (SRTP) requirements, International Gas Fuel (IGF) Interim Guideline and Class Rules.

Impact of results and project follow-up

The project demonstrated the successful use of a HT-PEM fuel cell on a ship as support for the onboard electrical and heat systems, with a significantly lower noise and exhaust emissions.

Further it is shown that a decentralized energy concept offers many advantages like small energy flows within the system, low material and energy demand, high redundancy and a high safety.

All current project consortia plan to continue their activities. This includes the further development of the fuel cell and racks as far as the increase of performance up to 20 kW per Module and the increase of service life up to more than 20,000 operational hours, as well as the installation of a complete decentralized power grid on a ship

The plan further provides to contribute to the development of new regulations and guidelines especially the alignment of SOLAS requirements for Central electrical power generation and Main Switch Board and SOLAS requirements for Emergency generator

PA-X-ELL summary

FC type	Power	Fuel	Type of project
HT-PEM	60 kW	Methanol	Concept study and marine operation of fuel cell on vessel

US SSFC

Background and objectives

The US Ship Service Fuel Cell (US SSFC) project was run by the Office of Naval Research (ONR, U.S. Department of Defence) from 2000-2011 focusing on basic and applied research to address the gaps between the existing fuel cells and the requirements for fuel cells used in naval applications. Improving power generation capabilities within the critical weight and volume constraints and at the same time assuring safe and flexible operations was the key goal for the project. NAVSEA (Naval Sea System Command), Penn Engineering, FuelCell Energy and SOFCo are major partners in this project.

Technical details

The US SSFC includes evaluation and development of a 625 kW MCFC and a 500 kW PEM fuel cell both using diesel as fuel. Both systems are complete with supporting systems including diesel reforming, purification of the fuel prior to the fuel cell and a complex heat and energy recovery systems and systems for regeneration of catalyst. MCFC system has an efficiency of 53 % and the PEM FC has an efficiency of 35 %. A lesson from the project is that further scale-up is limited by the volume and complexity of the systems.

Results

The US SSFC program focuses on two modular 2.5 MW fuel cell systems, a FuelCell Energy MCFC system and a McDermott Technology PEM system:

FuelCell Energy - MCFC 2.5 MW
- Phase 1: Conceptual design of 2.5 MW fuel cell – four 625 kW MCFC modules
- Phase 2: Detailed design, construction and land based testing of 625 kW MCFC module
- Phase 3: Demonstration at sea

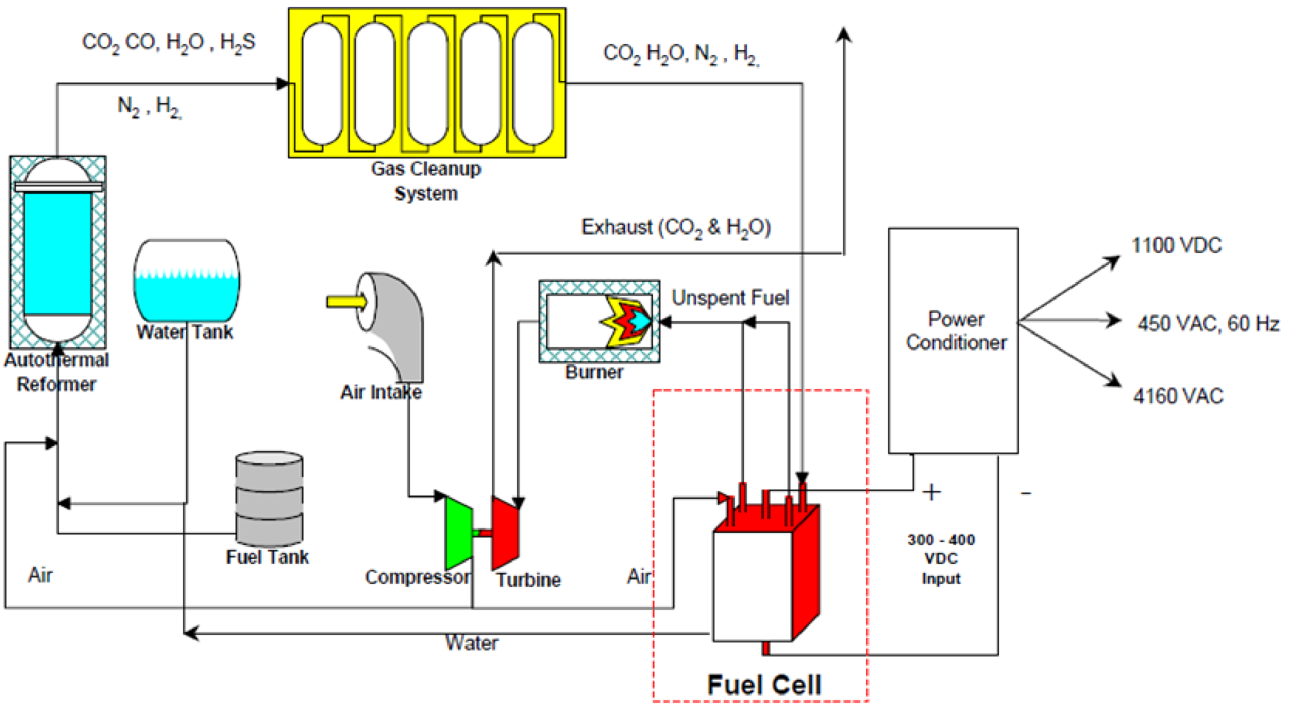


Figure A.9: Fuel cell and fuel processing system for a 625 kW MCFC module

Fuel processing is the key to the efficient operation of the fuel cell. This is shown in Figure A.9 and includes reforming of fuel, purification (desulfurization and CO converting to CO_2), a burner for unspent fuel and a gas turbine. The burner and gas turbine is crucial for the energy efficiency of the system

PEM 2.5 MW system

- Phase 1: Conceptual design of 2.5 MW fuel cell – five 500 kW PEM FC
- Phase 2: Design and construction of McDermott Technology integrated fuel processor

As for the MCFC module, integrated fuel processing is important for the performance of the cell. The McDermott Technology 500 kW SSFC Integrated Fuel Processor (IFP) (Figure A.10) is used to reform and purify the fuel prior to the PEM fuel cell and also include systems for burning of hydrogen and a turbo compressor.

US SSFC summary

FC type	Power	Fuel	Type of project
MCFC	2.5 MW, four 625 kW modules	Diesel	Concept design, testing on land and sea of one moduel
PEM	2.5 MW, five 500 kW modules	Diesel	Concept design, testing on land of fuel processing unit

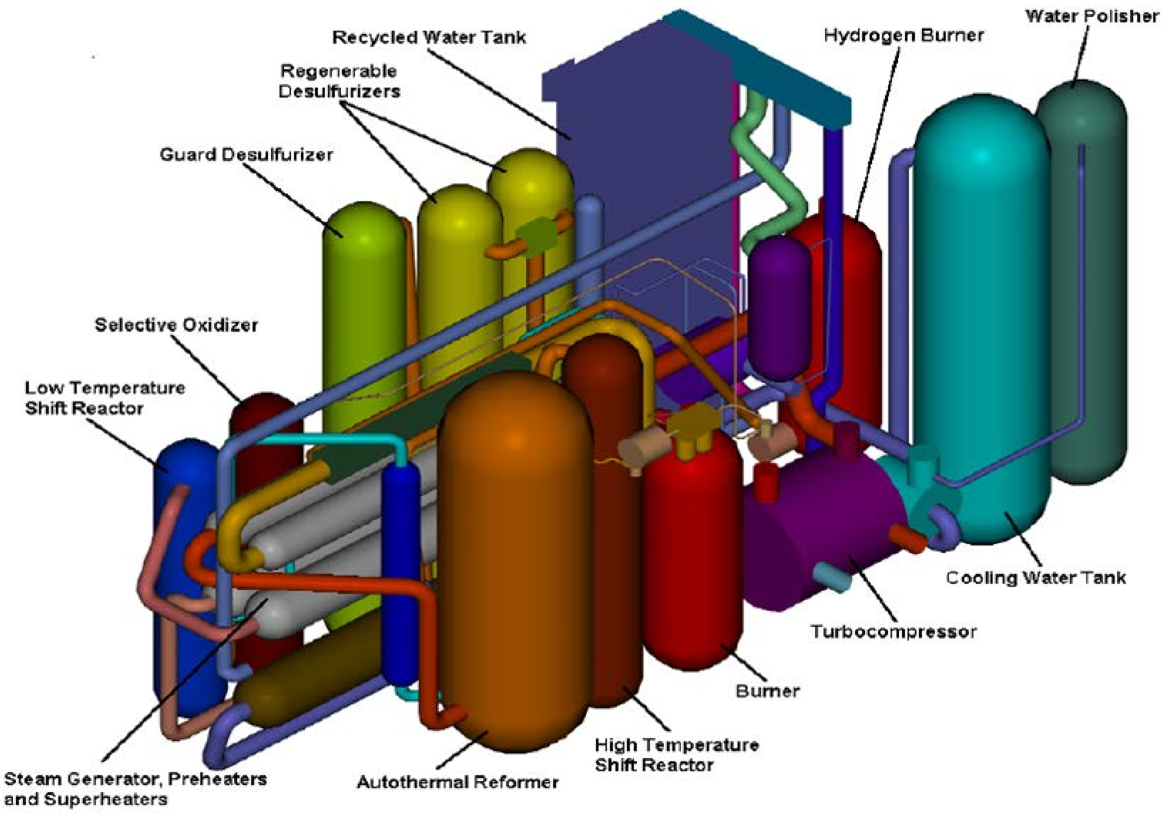
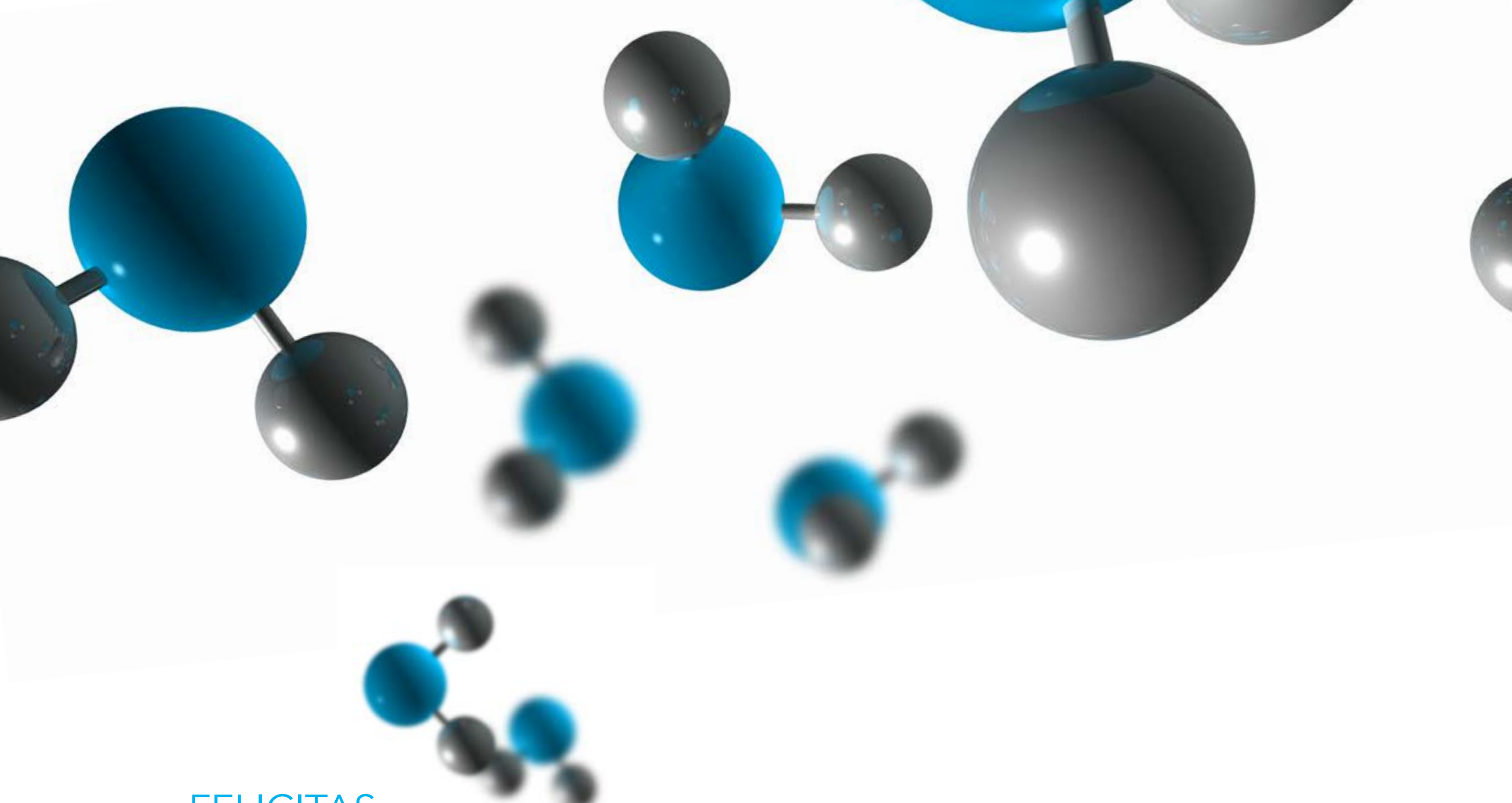


Figure A.10: McDermott Technology 500 kW SSFC Integrated Fuel Processor (IFP)



FELICITAS

Background for the project and objectives

The project was led by Rolls-Royce Marine Electrical Systems working with Lürssen as shipbuilder, and three Universities; Genoa, Eindhoven and Hamburg. The FELICITAS Subproject II focused on a version of the Rolls-Royce Fuel Cell Systems Ltd for marine use. The projects starting point is the Rolls-Royce Fuel Cell Systems 1 MW Pressurised SOFC, and this will be the basis for the design of a 250 kW APU. The goal was to minimise design changes to system architecture and thus additional development and product cost for a marine version of the existing stationary Fuel Cell System.

In addition to this, the use of different hydrocarbon based fuels instead of hydrogen and harvesting of surplus heat from the fuel cell was the main research topics.

The FELICITAS Project focused on key aspects of adapting of the Rolls-Royce SOFC design to marine use:

- Impact of the marine environment on the operation of the fuel cell, e.g. humidity and salt air, and fuel contaminants as they affect electro-chemical performance;
- Issues associated with vessel motion on the fuel cell system, e.g. shock loads, as well as vibration effects from other propulsion units in a vessel e.g. diesel engines;
- Effect of the power demands of a marine application on a fuel cell unit, especially the varying 'hotel' loads;
- Fuel availability and choices for fuelling fuel cells in a marine application.

Part of the FELICITAS subproject II carried an investigation of the integration challenges of a fuel cell system into a yacht. Lürssen undertook a detailed study of the specific interfaces between the yacht including:

- Water supply by means of a two stage system to meet the water requirements of an SOFC system;
- Fuel supply and fuel storage;
- Energy storage system for load following;
- Fuel and exhaust piping;
- Power management system.

And the necessary indirect interfaces to:
- Safety equipment (sensors, firefighting equipment, explosion safe equipment);
- Ventilation and cooling rooms.

Results

The FELICITAS Project achieved the following outcomes:

- Development and marinization of a 250 kW SOFC unit
- Testing of 60 kW sub-system for marine use and stationary power 250 kW generator module
- A much improved and detailed understanding of the impact of the marine environment, operation and application on a Rolls-Royce SOFC technology, notably a yacht, was achieved.
- Testing of Rolls-Royce SOFC materials and components in marine relevant conditions was successfully undertaken, and the results show that there are challenges connected to using fuel cells in marine environments.

Figure A.11: Stationary Power 1 MW hybrid SOFC system and 250 kW Generator module of Rolls-Royce Fuel Cell Systems

- The Rolls-Royce stack concept and system showed a high mechanical integrity in marine motion conditions.
- High system efficiency (> 60 %) of hybrid SOFC configurations was verified by detailed simulations and partly by experiments.

Heat management and recovery systems

The key to the high efficiency was heat management and recovery systems. This is related to

- Heat recuperation for preheating of inlet mass flow,
- Management of heat sinks like internal fuel processing and
- Using heat by-product by gas and in some cases steam turbines.

In particular, the introduction of gas turbines offered a remarkable increase of electrical efficiency but on the other hand increased the complexity of the system and required careful system design and management.

Fuel options

The use of fuels other than LNG (the preferred fuel for stationary power fuel cell systems) required fuel pre-processing and fuel options was studied in detailed for a marine SOFC. In developing a fuel processing concept for a marine application, aspects of the challenge included:

- Fuel preferences and requirements of the commercial customer;
- Physical and technical constraints of the vessel;
- Technical requirements of the SOFC system, and
- Available fuel processing technologies.

This investigation led to the conclusion that the preferred fuel for a Rolls-Royce marine SOFC is LNG.

SOFC – PEMFC coupling

FELICITAS also looked into coupling of a SOFC and PEMFC system. The coupling could combine the advantages of each technology and lead to a better overall efficiency of the system compared to a single technology. The SOFC is used both as a generator of electricity and a contribution of the remaining carbon monoxide in the reformation of diesel.

Several results were achieved from this investigation

- An efficient diesel reformer with a relevant method for heavy-duty transport application was developed.
- Development of a micro-reactor for the purification of the SOFC downstream to supply the PEMFC.
- Tests of the components in operating conditions as closed as possible to real conditions from the ones in the system.
- Simulation of the SOFC-PEMFC system to quantify its performances.

FELICITAS summery

FC type	Power	Fuel	Type of project
SOFC	250 kW	LNG	Concept study

MC-WAP

Background for the project and objectives

Molten-Carbonate fuel cells for Waterborne Application (MC-WAP) was coordinated by CETENA (Italian ship research center) from 2005-2010. It was supported by EU (EURO 9.9 million) with 17 partners from 7 countries including universities, technology providers, research centres, class society (RINA) and shipyard (FINCANTIERI). The total budget for the project was Euro 17.2 million. The project includes a concept design and onshore testing of a 500 kW MCFC system and installation and testing of a 150 kW MCFC on a vessel.

The main goal of MC-WAP project was to develop, construct and install a MCFC system on a ship and to give the maritime industry a benchmarking based on real-life and real-size tests. The MC-WAP system consist of a fuel processing unit and a fuel cell unit and the project work includes:

- Optimisation of fuel processing and fuel cell unit for marine operation
- Optimizing the integration of the two units
- Onboard design, installation and testing of the total system

Technical details

The MC-WAP system is a 150 kW system using a molten carbonate fuel cell (MCFC) with diesel as the fuel. The system is comprised of two units; a fuel processing module and the fuel cell module. The fuel processor module is a reforming unit, converting diesel to syngas that can be used in the molten carbonate fuel cell. The excess heat from the fuel cell is used in a steam generator. The steam is used for energy and heat production that can be used in the fuel processor module and in other ship systems.

Results

The MC-WAP project developed a fuel cell and fuel processing unit for marine operation and tested these systems in the onshore Marmara research centre (Turkey) and onboard a vessel. One major output of the project is the integration of the two units, the basic process flow for the integrated system is shown in Figure A.12.

The major outcomes of this projects are:

- Concept design of a 500 kW MCFC system for marine use.
- Improved design and integration of fuel cell and fuel processing units
- Onshore and onboard testing of a 150 kW MCFC unit and fuel processing unit

MC-WAP summary

FC type	Power	Fuel	Type of project
MCFC	150 kW in operation 500 kW concept	Diesel	Concept study and marine operation of fuel cell and fuel processing unit.

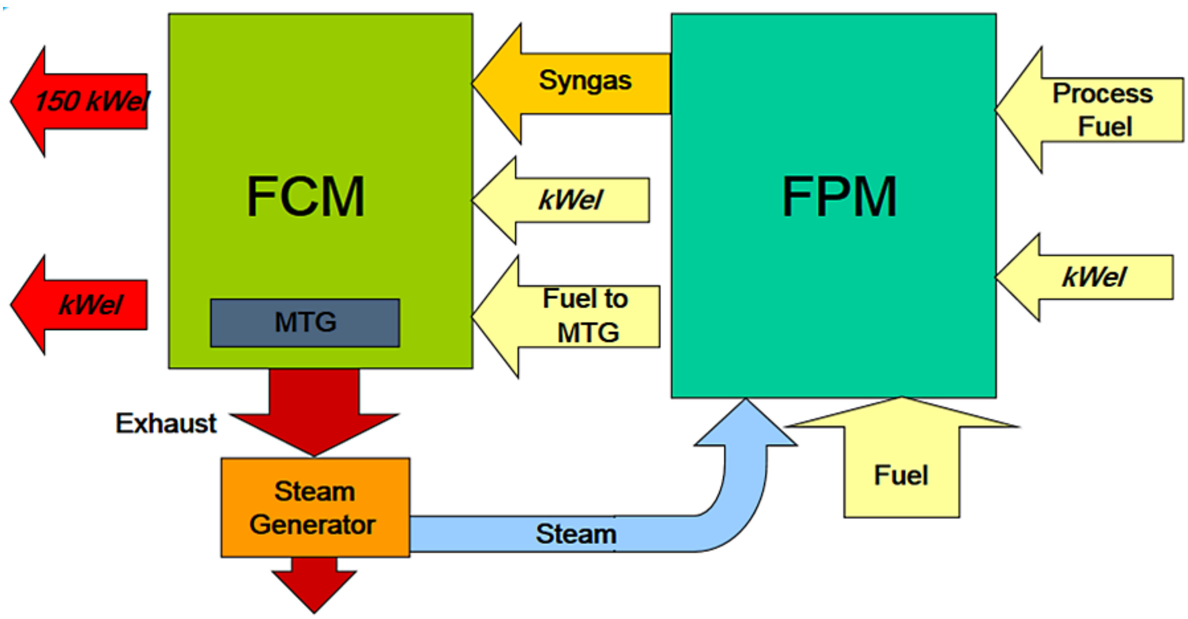


Figure A.12: Process flow in the MC-WAP system with fuel cell module (FCM) and fuel processing module (FPM)

Figure 13: FCS Alsterwasser laying at the H2 refuelling station in Hamburg

ZEMSHIPS

Background for the project and objectives

To comply with new and future emission requirements the ZemShip project aim to design, build and test an emission-free inland passenger vessel for commercial use in the urban area of Hamburg. This is made possible by integrating a hybrid fuel cell and battery based propulsion system, instead of using a diesel electric system. One of the main tasks is to test the efficiency and practical performance of the fuel cell driven ship and the corresponding infrastructure required for providing and bunkering hydrogen as fuel.

The funded project was launched in November 2006 and ended in April 2010. The Hamburg Ministry of Urban Development and Environment (BSU) were the initiator and coordinator with the support of eight other partners like Alster Touristik GmbH (ATG), Hamburger Hochbahn AG, Germanischer Lloyd, Proton Motor Fuel Cell GmbH, Linde Group, hySOLUTIONS, UJV Nuclear Research Institute and The Hamburg University of Applied Sciences. In August 2008 the prototype ship FCS Alsterwasser was delivered and started its regular service for ATG. In 2010 the battery system and parts of the vessel were damaged by a fire onboard. The repair was used to upgrade the FC installation for further operation. In 2013 the hydrogen fuel supply was terminated by the supplier Linde due to economic reasons. Up to there the Alsterwasser transported more than 43,000 passengers with an FC-system operation of over 2,500h. The FCS Alsterwasser is still able to be operated on Fuel Cells or battery mode.

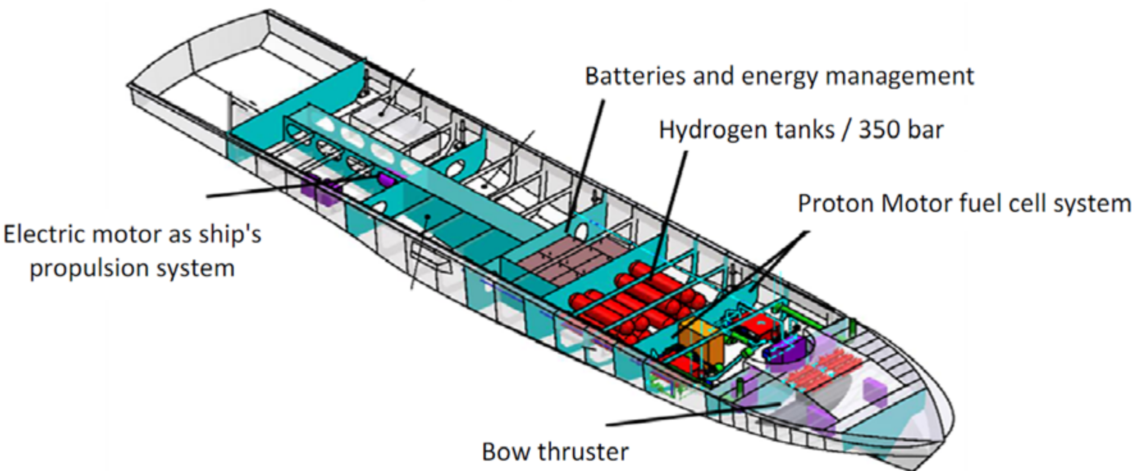


Figure 14: FC system concept of FCS Alsterwasser

Figure A.15: H2 compression and storage station


Figure A.16: Onshore test plant

Results

The following will highlight some of the main results of the work.

**Development of hardware:
Fuel cells and battery system**
Basis of the new developed hybrid system were the two PEM A 50 maritime fuel cell systems (48 kW peak power each) and seven lead gel battery pack with a total capacity of 560V and 360Ah delivered by Proton Motor.

The liquid cooled PEM fuel cell is adapted to the typical installation situation in ships. The fuel cell stacks are installed optimally together, with all the important peripheral systems such as cooling and air supply incorporated in a single compact assembly. That means the system can be integrated in other ship types as well, without the need for special adaptation. The electrochemical process in the fuel cell takes place without emissions.

The energy delivered by the fuel cell is buffered in a battery array to supply the electric motor on demand. The energy management system provides the energy needed for sailing or manoeuvring for the electrical propulsion engines or the electrical bow thruster and thus extend the life cycle considerably.

**Development of hardware:
Hydrogen refuelling station**
Important for operation of the ship was an easy operation of the refueling system. The refueling system designed allows a refueling of the FCS Alsterwasser in 30 minutes with up to 50 kg compressed hydrogen in twelve 350-bar pressure tanks. This amount of hydrogen ensures enough energy for approx. three days in operation. To refuel the Linde Group designed an innovative fuelling station and developed an entirely new process for storing hydrogen, known as ionic compression. This new method compresses the gaseous hydrogen up to 450 bar without the use of mechanical pistons. Apart from its extraordinary efficient process its most outstanding feature is the pureness of the hydrogen gas. Unwanted contaminations by using metal pistons are avoided. Another advantage is the short time of 12 minutes needed to fill up to 50kg of compressed hydrogen.

Demonstration on board; vessel modifications
The design of the ship's hull faced the builder with new challenges. The installation height of the fuel cell, including hydrogen tanks and batteries, required more height than in a normal ship, so the only way for the boat to pass under low bridges was a lowering and raising system for the ship's roof, i.e. a roof lifting design.

Class approval
The existing GL"Guidelines for the Use of Fuel Cell Systems on Board of Ships and Boats" were applied to obtain a certificate with the FC class notation for the biggest passenger vessel with hydrogen fuelled fuel cell system. The prime role of GL in the project was to assure that the installation was compatible with marine safety requirements, as the most important suppliers were from the landbased industry. The

Figure A.17: Illustration of FC demonstrator onboard MS Forester

storage of high pressurized hydrogen as fuel onboard of a passenger vessel was under special consideration during class approval. A risk assessment of the developed design showed that under consideration of the safety measures as defined in the GL FC guidelines additional risks in comparison to a conventional diesel system could be decreased to a minimum. Onshore and onboard testing of the installation was done to verify compliance with class rules.

Modelling and Simulation

For the vent mast location CFD simulation were carried out to show, that the release of hydrogen doesn’t affect the ship operation taking into account the behavior of hydrogen.

Operational Experience

During a test run the on board installed lead-gel batteries overheated. This resulted in a fire that damaged the ship. Because of the separation of systems for energy conversion, energy storage and fuel storage and a properly functioning safety system both the fuel cell and the hydrogen storage remained undamaged.

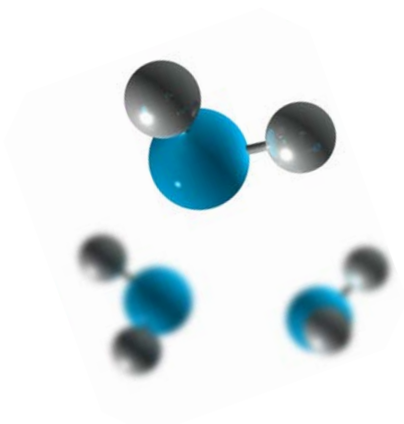
Impact of results and project follow-up

The most important finding of the project is that it is possible to operate a passenger ship with zero emissions. The response from passengers and crew has been entirely positive. Particularly positive points were the absence of exhaust fumes and the way the ship glides silently through the water.

The ZEMSHIPS project can be directly transferred to all areas where passenger ships of this size are operated.

The technical safety requirements and concepts for the hydrogen and fuel cell technology on board were elaborated by Germanischer Lloyd as the ship certifier. A large number of administrative obstacles had to be dealt with in order to get the project going. The path prepared now serves as the basis for future ships.

Scientific issues in connection with the project have been examined by two universities. The Hamburg University of Applied Sciences has addressed energy efficiency. It was not possible to collect the measurement data on the Alsterwasser in such a way as to get a clear separation of the consumers, and thus clear analysis of the energy transmission path. But data capture was sufficiently reliable and delivered consistent data, in good quality and quantity. Only 30 % of the energy of the hydrogen used in fact reached the drive shaft. Technical improvements were incorporated in April 2010, but they have not yet been scientifically evaluated.



SCHIBZ

Background for the project and objectives

SchiBz is also part of the lighthouse project "e4ships" by the German National Innovation Programme for Hydrogen and Fuel Cell Technology (NIP) (part of NOW) and puts the focus on development, design and testing of a modular and compact fuel cell for merchant ships. The APU system, based on a SOFC and a Li-Ion battery, is intended to provide 50 to 500 kW with low-sulphur diesel (10 ppm sulphur) and achieve an electrical efficiency of at least 50 %. In addition, an exhaust gas recovery system should be implemented to increase the overall efficiency.

In order to collect results, a research plant with an output of 100 kW will be operated on land at first and then be put on the MS Forester for 12 months. To achieve this goal the project was extended to December 2018.

The project is managed by ThyssenKrupp Marine Systems. Partners are M&P, OWI, DNV GL, Leibniz Universität Hannover, Reederei Rörd Braren and sunfire.

Results

Development of hardware: Fuel cell system
In 2013 Sunfire joined the SchiBz project as main developer and supplier of high temperature solid oxide fuel cells (SOFC). After two years Sunfire delivered a prototype fuel cell system with an integrated reformer and an output of 50 kW. The newly developed SOFC module runs on low-sulphur diesel using a ceramic solid electrolyte to convert fuel into electric power and heat at an operating temperature of around 800 degrees Celsius.

The recirculating of exhaust gases and the integrated reforming process developed by the Öl-Wärme-Institut (OWI) makes it possible to achieve electrical efficiency of over 50 % and overall efficiency in excess of 90 %. This prototype is prepared for extensive testing. Until summer 2016 the reforming process has been tested for over 3200h. A 10 kW test plant also has been tested for over 1000h.

Class approval
The prime concern was to assure that the installation was compatible with marine safety requirements, as the most important suppliers were from the landbased industry. The development of a new high temperature fuel cell system, external diesel reformer and containerized installation was under special consideration during class approval.

Impact of results and project follow-up

Currently, this project has resulted in a new designed for a high-temperature solid oxide fuel cell for the use as an auxiliary power unit on land and ships.

By the end of 2016 it is planned to install a test system on the MS Forester which provides 25 to 50 percent of the electricity demand.

On a long view cost reduction, enhancements of the exhaust gas recovery, the automation of the composite network of a ship and the development of a DC power supply is planned. Furthermore a battery system that compensates for the differences in power supply of the fuel cell and the load of the board network is also planned.

SchiBz summary

FC type	Power	Fuel	Type of project
SOFC	100 kW	Diesel	Marine operation of fuel cell

RIVERCELL

Background for the project and objectives

At the moment RiverCell is a feasibility study for an inland passenger ship with a decentralized power grid and part of the lighthouse project "e4ships". Within this project different fuels for a modular power grid similar to the project Pa-X-ell (page 20) are examined. After the selection of the best concept an inland passenger ship will be designed in detail and build for long-term testing. Attention is paid mainly to the conditions of the use of an inland waterway vessel, such as changeable driving profiles and high environmental demands.

Partners of this project are Flensburger Schiffbau Gesellschaft, DNV GL, Serenergy, Viking Technical, MEYER WERFT, NEPTUN WERFT, hySolutions, fischer eco solutions and HADAG.

The planned period is from 2015 to 2022.

Results

Concept development: Fuel cell installation
The HT-PEM fuel cells will be part of a distributed hybrid system consisting of three diesel generators, two fuel cell racks and two buffering batteries. One part of the system is located in the rear and the other part is located in the bow. In all concepts the fuel is bunkered at the middle of the ship. The propulsion system consists of four Rudder propeller and two bow thruster.

Depending on the load the diesel generators can be switched on to allow a nearly noiseless electrical drive in the harbour or when manoeuvring. The batteries serve as a buffer against power spikes. This system provides high system stability, efficient operation and a reduced emission level.

Class and safety requirements
As part of the project an existing ship was considered and theoretically remodeled to investigate the storage method for three different kinds of fuels.

First LNG, LPG and H2 at cryogen temperatures were compared to normal diesel fuel. These fuels needed three to ten times more storage volume and reduced the effective volume by five percent. After that NG was compared. For gaseous NG the effective volume reduced by 20 percent. Both methods showed a weight problem and on the LNG storage in addition a trim problem occurred.

The final concept considered the storage of methanol which would need 2.5 more storage volume than diesel. Neither a trim nor a weight problem occurred. Challenging for the project is the use of methanol as fuel which is not regulated, yet. Special requirements of the CCNR are to be observed as the vessel will be an inland vessel operating in EU inland waters.

Impact of results and project follow-up

The hybrid concept as a total energy supply is promising especially in urban and sensitive environmental zones. Methanol as fuel is advantageous for volume-critical vessels but there are more regulations needed.

By 2018 the design and approval of the test vessel is scheduled. Furthermore the ship is to be built by 2020 and all tests to be completed by the end of 2022.

Rivercell summary

FC type	Power	Fuel	Type of project
HT-PEM	250 kW	Methanol	Concept study

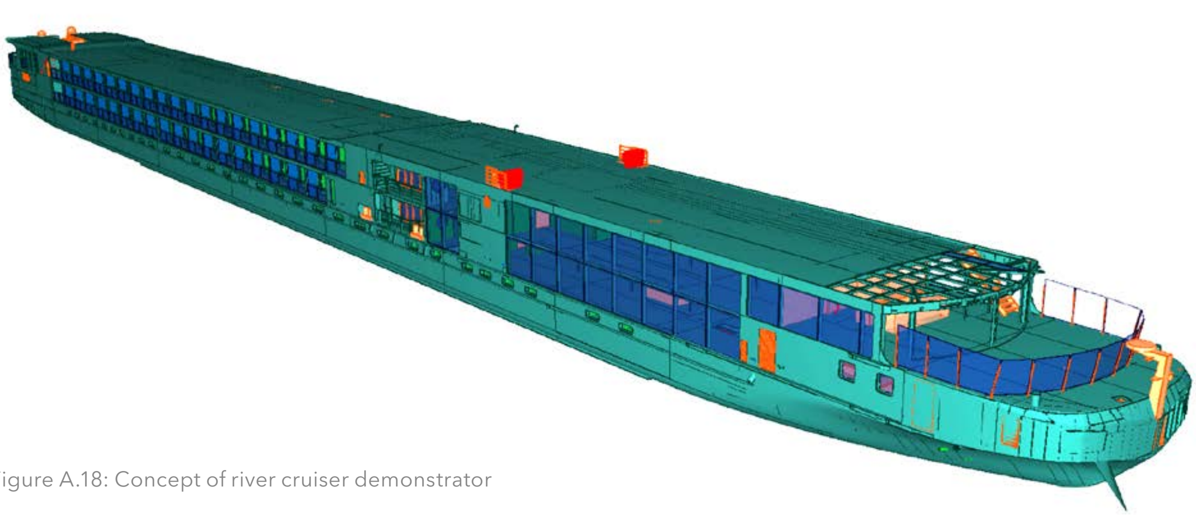


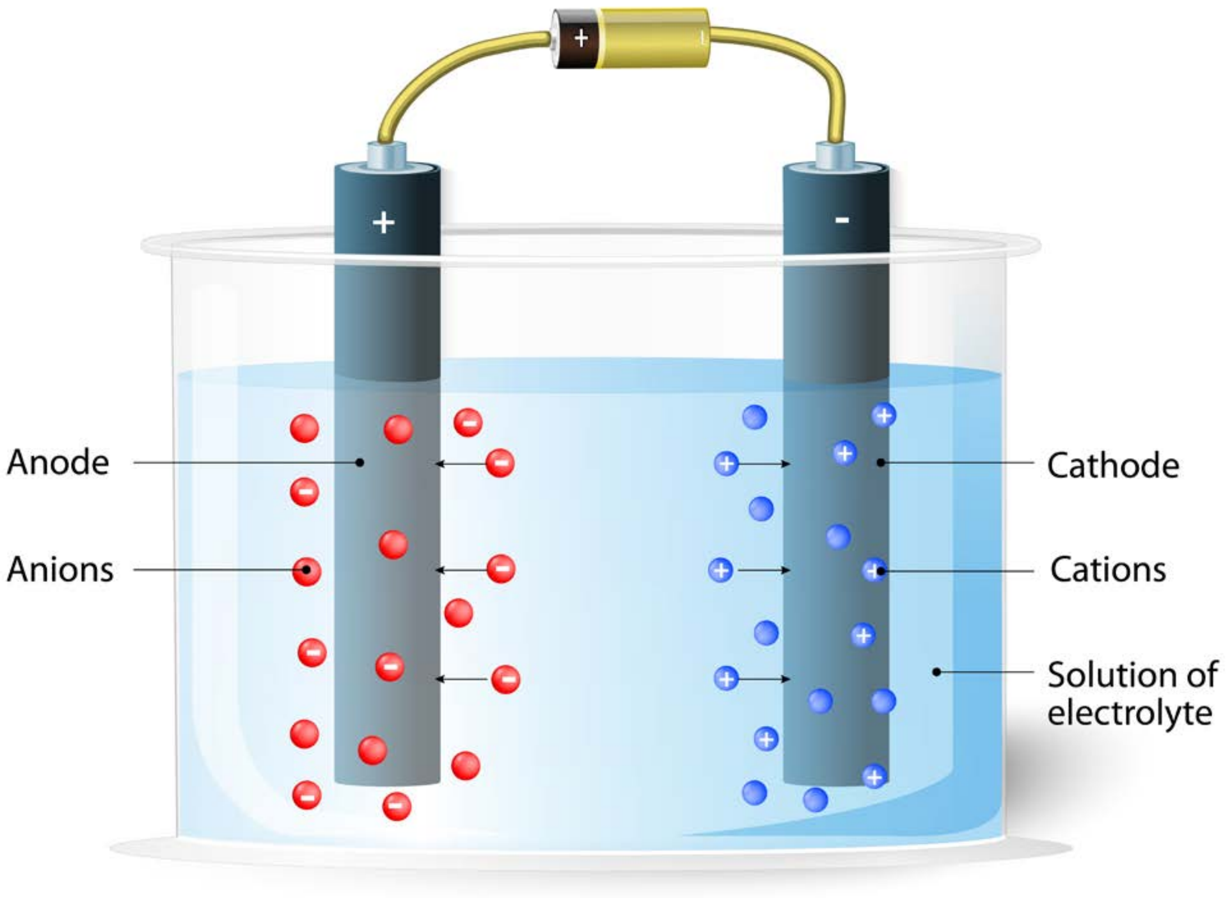
Figure A.18: Concept of river cruiser demonstrator

PROJECT PARTNERS DETAILS FOR THE SELECTED PROJECTS

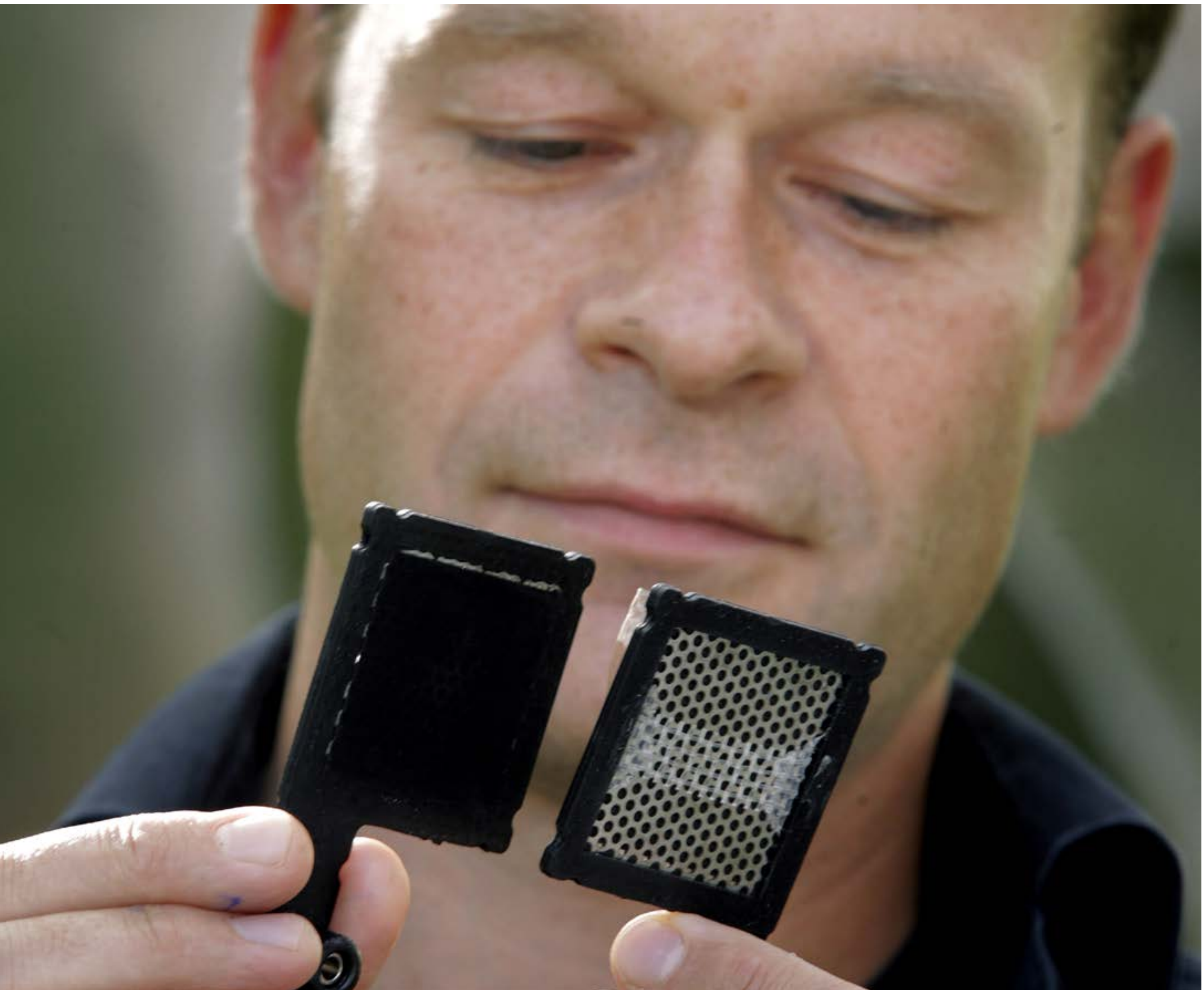
Project	Partners	Role	Contact person
FCShip	21 partners from 6 nations (NO, NED, GER, UK, ITA, FIN)	Collaborative efforts describing technology, hurdles, opportunities, regulatory issues, safety, environmental studies.	Coordinator: Norwegian Shipowner Association
METHAPU	Wallenius Marine AB, DNVGL, Lloyds Register, University of Genova, Wartsila	Wallenius Marine: Ship Owner DNVGL: Operational studies Lloyds Register: Class and safety assessments University of Genova: Life cycle studies Wartsila: Project mgmt, Equipment supplier fuel cell	Ed Fort (LR) Tho Pan (Wartsila)
FellowSHIP	DNV, Wärtsilä Norway, Eidesvik, Vik-Sandvik, MTU Onsite Energy	DNV: Project mgmt, Risk, Rule development, Environmental Studies Wartsila: Equipment supplier power electronics and electro system parts Eidesvik: Ship Owner Vik-Sandvik: Ship and machinery systems design MTU: Equipment supplier fuel cell	Tomas Tronstad (DNVGL), Ingve Sørfonn (Wartsila), Jan Fredrik Meling (Eidesvik)
SF-BREEZE	Sandia National Lab., Red and White Fleet, American Bureau of Shipping, U.S. Coast Guard, Maritime Administration, Elliott Bay Design Group	Sandia: Project mgmt, technical, economic and regulatory evaluation Red and White Fleet: Ship owner/operator	Joseph W. Pratt (Sandia) Thomas C. Escher (Red and White Fleet)
US SSFC	U.S. Department of Defens, Office of Naval Research	-	-
FELICITAS –subproject 2	Rolls-Royce, Uni Genoa, Lürssen, HAW, Uni Eindhoven	Rolls-Royce: Project mgmt, testing, SOFC power mgmt., control and simulation Lürssen: Fuel processing, SOFC power mgmt. Uni Genoa: SOFC power mgmt, control and simulation Uni Eidhoven and HAW: Fuel processing	Mike Addis (Rolls-Royce) Duetruch Kirchner (Lürssen)
MC-WAP	FINCATIERI, Cetana, OWI, TÜBITAK, RINA, NTUA, Techip KTI, etc	Cetana: Project mgmt FINCATIERI: Ship owner	Schembri Marco (Cetena)
ZemShips	Hamburg Ministry of Urban Development and Environment (BSU), Alster Touristik GmbH (ATG), Hamburger Hochbahn AG, Germanischer Lloyd, Proton Motor Fuel Cell GmbH, Linde Group, hySOLUTIONS, UJV Nuclear Research Institute and The Hamburg University of Applied Sciences	BSU: Project mgmt Proton motor: Technology provider	Müller-Remer (ATG) Langfeldt (DNV GL)
Nemo H2	Alewijnse Marine Systems, shipping company Lovers, Linde Gas, Marine Service North and Integral	Integral: Project mgmt Lovers: Ship owner Alewijnse marine systems: Ship electonic systems Marine Service North: Mechanical engineering Linde gas: Production, storage and distribution of hydrogen	Hauke Sie info@fuelcellboat.nl

Project	Partners	Role	Contact person
Pa-X-ell	Meyer Werft, DNV GL, Lürssen Werft, etc	Meyer Werft: Project mgmt, Technical development Lürssen Werft: Technical development DNV GL: Safety analysis and certification	Untiedt (MW) Tellkamp (DNV GL)
SchiBz	Thyssen Krupp Marine Systems, DNV GL, Leibniz University Hannover, OWI, Reederei Rörd Braren, Sunfire	TKMS: Project mgmt, System integration DNV GL: Safety analysis and certification Leibniz University Hanover: Modelling and Simulation Reederei Rörd Braren: Provisioning Trial Vessel OWI: Fuel Reforming Sunfire: Fuel cell modules	Leites (TKMS) Langfeldt (DNV GL)
RiverCell	Meyer Werft, DNV GL, Neptun Werft, Viking Cruises		Christenson (MW) Langfeldt (DNV GL)

Table A.2



3 – FUEL CELL TECHNOLOGIES



ALKALINE FUEL CELL (AFC)

The alkaline fuel cell (AFC) is one of the earliest types of fuel cells, most famous for being used on NASA space shuttles. Also the first fuel cell driven passenger ship, The Hydra, was driven by a 5 kW AFC. The typical power output of an AFC is 1-5 kW, but
recently report of test with 200 kW power output from stationary AFCs have been reported.

The AFC consist normally of a nickel anode, a silver cathode and an alkaline electrolyte. The electrolyte an alkaline solution (eg. potassium hydroxide, KOH) which can be either mobilized or immobilized in a matrix. The fuel is hydrogen (H2) and oxygen (O2) and hydroxyl ions (OH-) are transported through the electrolyte from the cathode to the anode. The hydrogen and oxygen needs to be pure to avoid degradation of the AFC. See Figure A.19 below for a schematic of an AFC, and Figure A.20 for a flow chart for the AFC process.

The AFC consumes hydrogen and oxygen and produces energy and water. In the NASA space shuttle, the AFC was also used as a source of water and heat. The main reactions that are occurring are the following:

Anode reaction:
$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$

Cathode reaction:
$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$

Total reaction:
$2H_2 + O_2 \rightarrow 2H_2O$

Benefits and Challenges

AFC is a low cost fuel cell, with low-cost catalysts and readily available electrolytes. It can operate at room temperature, which is beneficial from a safety perspective, but also ensures that the requirements for the material used are less stringent (and less expensive). The operation of the AFC is flexible, and cold start is possible. Water is the only by-product of the AFC, no other emissions. The AFC have a moderate efficiency, 50-60 %, and no need for reforming of fuels or heat recovery systems.

The major concern for the AFC is CO_2 poisoning. CO_2 in the fuel will react with the alkaline electrolyte, reducing the efficiency and eventually reading to precipitation and blocking of the cell by potassium carbonate.

$2KOH + CO_2 \rightarrow K_2CO_3 + H_2O$

Because of this the AFC requires pure oxygen and pure hydrogen to function in an optimal range over a prolonged time. If air is to be used, removing CO_2 is necessary and other fuels than hydrogen are not recommended as long as substantial purification is performed before injection to the AFC.

Further development

Direct borohydride and metal-hydride fuel cells are subclasses of the AFC that are under development and do not have the same problems with CO_2 poisoning as the traditional AFC. These technologies are still too immature to be relevant for use in ships, but might be a future option.

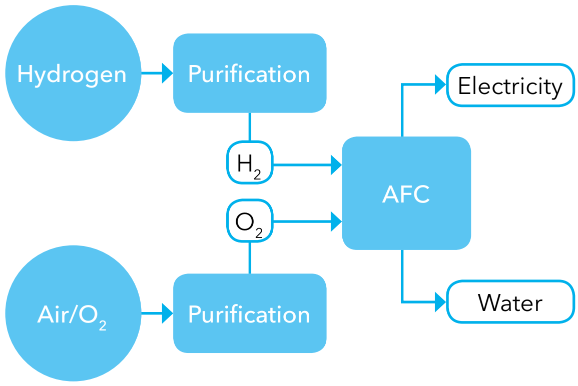


Figure A.20: Flow chart for an alkaline fuel cell system

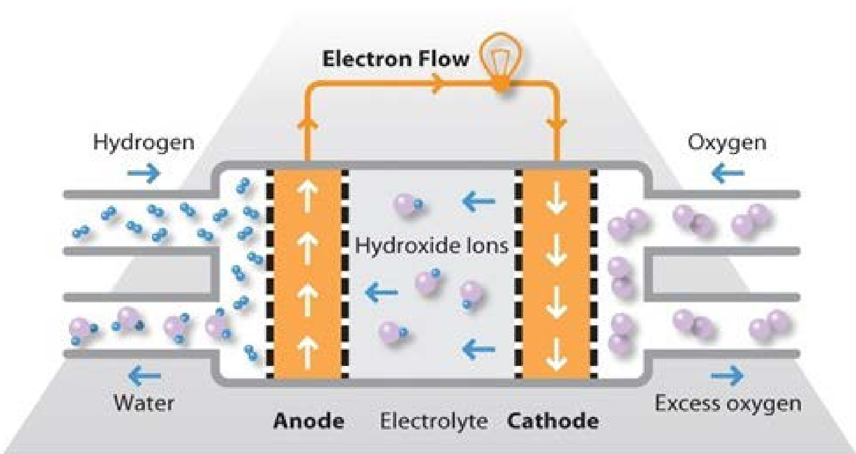


Figure A.19: Schematic of an alkaline fuel cell (AFC)

PROTON EXCHANGE MEMBRANE FUEL CELL (PEMFC)

Proton exchange membrane fuel cells have been used extensively in many applications, it is used in several cars and the Alsterwasser passenger ship with a power output of 96 kW and in German Type 212A class submarines with modules from 30-50 kW each. It has also been used in other ships with power levels ranging from 12-60 kW.

The proton exchange membrane fuel cell (PEMFC) uses platinum-based electrodes and the electrolyte is a humidified polymer membrane that is an electric insulator, but permeates hydrogen ions (H+). The operating temperature is 50-100°C, temperatures above 100°C is not feasible as the membrane needs to stay humid. A schematic of the PEMFC is given in Figure A.21 below.

The PEMFC uses hydrogen and oxygen, and produces water in addition to electricity and heat. If other fuel sources than hydrogen is to be used it needs to be converted to hydrogen prior to injection to the PEMFC. For hydrocarbons this means steam-reforming and water-gas-shift. In the PEMFC, the main reactions that are occurring are the following:

Anode reaction:
$2H_2 \rightarrow 4H^+ + 4e^-$

Cathode reaction:
$O_2 + 4H^+ + 4e^- \rightarrow 4H_2O$

Total reaction:
$2H_2 + O_2 \rightarrow 2H_2O$

A flowchart for a PEMFC using hydrogen is given in Figure A.22.

Benefits and Challenges

The PEMFC has ha high power-to-weight ratio (100-1000W/kg), a low operation temperature that allows for flexible operation and less stringent material requirements that makes it a suitable fuel cell for transportation. The efficiency of the PEMFC system is moderate, 50 -60 %, and excess heat is of such a quality that heat recovery is not feasible. Also, the low temperature leads to a complex system for water management to obtain efficient operation of the PEMFC.

The platinum catalyst leads to a higher cost, and it can be poisoned by carbon monoxide (CO) and sulphur (S). A pure hydrogen source is needed, but the PEMFC is not as sensitive to poisoning as the AFC. Hydrocarbons can be used as a fuel for PEMFC, but a separate steam reforming and subsequent water-gas-shift system is required to make hydrogen of the necessary purity. If hydrogen is used as a fuel, the PEMFC emits only water. CO_2 and low levels of NO_x are emitted if hydrocarbons are used as fuel.
Further development

There is continuous development of the PEMFC to improve operation flexibility and durability, and reduce cost. New membrane materials as Metal-Organic frameworks and reducing catalyst loading are part of this development. High temperature PEMFC (HTPEM) and Direct methanol PEMFC (DMFC) are subcategories of PEMFCs that are further described below.

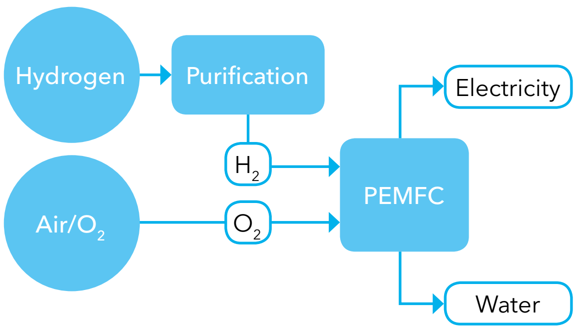


Figure A.22: Flow chart for PEM fuel cell system.

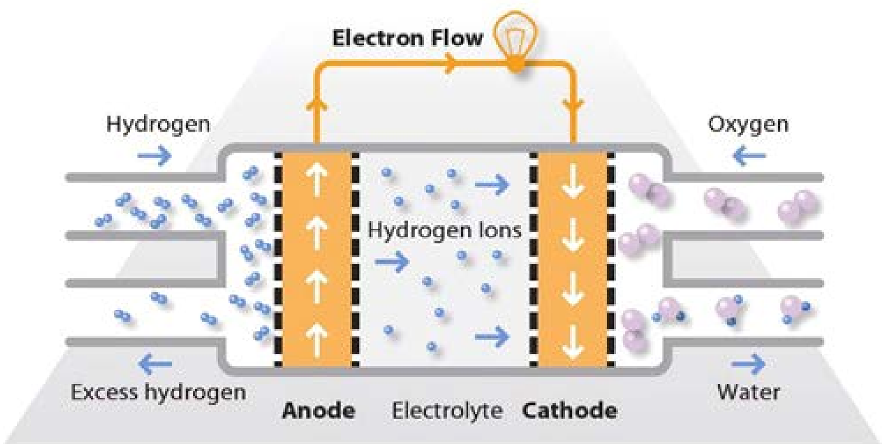


Figure A.21: Schematic of a proton exchange membrane fuel cell (PEMFC) .

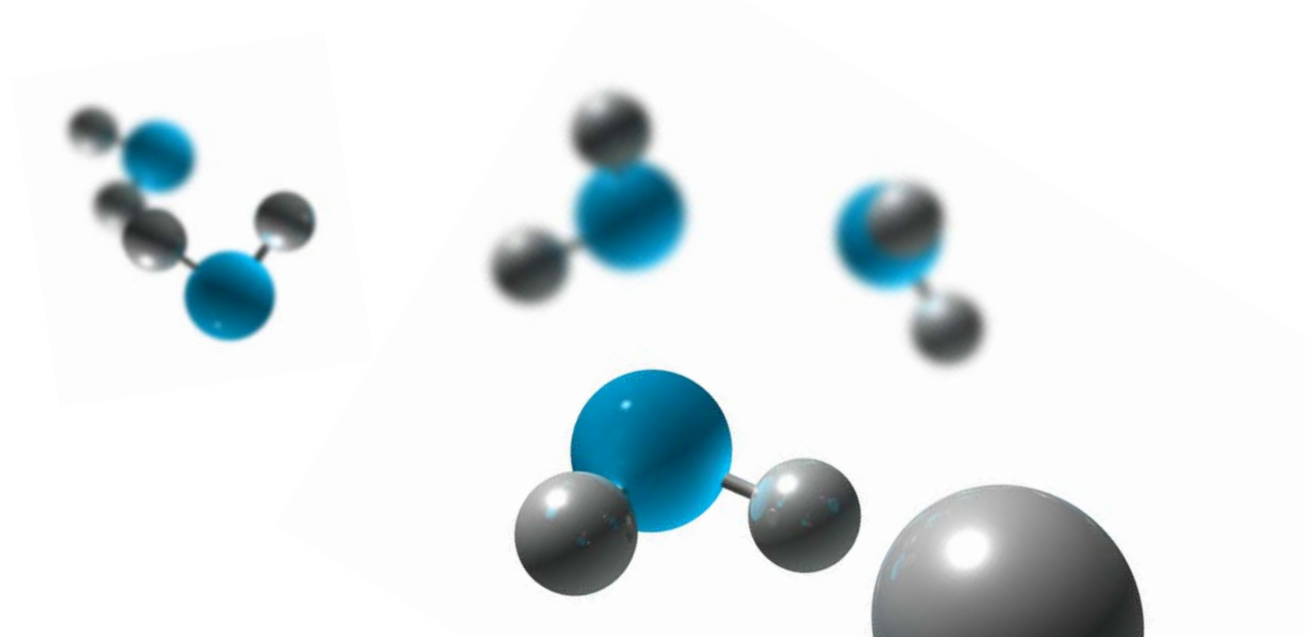
HIGH TEMPERATURE PEM

The main difference between a High temperature PEMFC (HT-PEMFC) and a PEMFC is the operating temperature. The HTPEMFC can operate at temperatures up to 200°C by using a mineral acid electrolyte instead of a water based one. The reaction and fuel are the same as in the PEMFC. A 12 kW HTPEMFC have been in use in the passenger ferry MF Vågen using metal hydride as the source of hydrogen.

Benefits and Challenges

Compared with the PEMFC, the High temperature PEMFC is less sensitive to poisoning by CO and sulphur and has no need for a water management system. It is also possible to harness the excess heat from the fuel cell in a heat recovery system. A HTPEMFC has a lower power density, and it is not possible to cold start it. The electrical efficiency of a HT-PEM fuel cell is similar or slightly better than PEM fuel cells, 50-60 %, but there is a potential to harvest more energy from heat recovery with can increase the overall efficiency of a HT-PEM fuel cell system.

Source: Prototech



DIRECT METHANOL FUEL CELL (DMFC)

As the name says, the Direct methanol fuel cell (DCFC) uses methanol directly without prior reforming to hydrogen. As the PEMFC, the DMFC has a polymer membrane electrolyte. The electrodes have a platinum-ruthenium catalyst able to directly utilise the hydrogen in methanol (CH_3OH) to generate electricity. A schematic of the DMFC is given below (Figure 23).

DMFC is generally good for delivering a small amount of electricity over a prolonged time, and power outputs of up to 5 kW is the norm. The DMFC normally operates between 50-120°C. Higher temperature and pressure can increase cell efficiency, but will lead to higher overall losses in the system, and the benefit is lost.

The DMFC uses a weak methanol in water solution (3 %) as fuel. As methanol is the fuel, the oxidation at the anode leads to CO_2 emission. The main reactions in the DMFC are:

Anode reaction:
$CH_3OH + 2H_2O$ -> $6H^+ + CO_2 + 6e^-$

Cathode reaction:
$3/2\ O_2 + 6H^+ + 6e^-$ -> $3H_2O$

Total reaction:
$CH_3OH + 3/2\ O_2$ -> $CO_2 + 2H_2O$

A flowchart for a DMFC using hydrogen is given in Figure A.24.

Benefits and Challenges

The DMFC uses methanol directly without any need for reforming. This is a fuel with high energy density, that is easy to handle and store compared with hydrogen. Using methanol also leads to CO_2 emissions, but the DMFC has no NO_x emissions.

The efficiency of a DMFC is low, around 20 %. Also, the major challenge with DMFC is methanol crossover, which is that methanol crosses over the membrane to the cathode where it reacts directly with oxygen. This leads to reduction of cell efficiency.

Further development

Improvement of membranes may reduce methanol crossover.

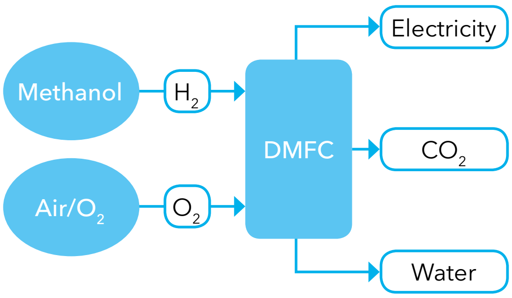


Figure A.24: Flow chart for a direct methanol fuel cell system.

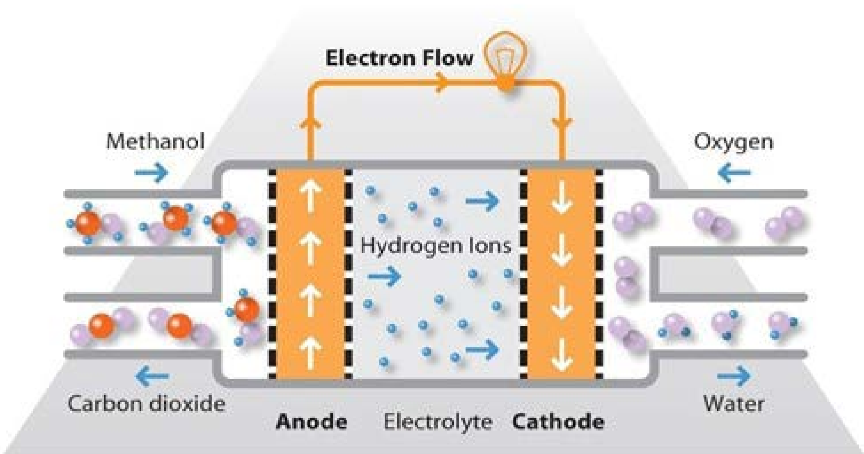


Figure A.23: Schematic of a direct methanol fuel cell (DMFC)

PHOSPHORIC ACID FUEL CELL (PAFC)

Phosphoric acid fuel cell (PAFC) was the first fuel cell with higher temperature, operating at temperatures up to 200°C. The increased temperature means that the excess heat from the fuel cell is of such a quality that it can be utilised, increasing the overall efficiency of the fuel cell from around 40 % (electrical efficiency) up to 80 %.

PAFC has an electrolyte of phosphoric acid in a silicon carbide structure and electrodes made of platinum dispersed on carbon, a schematic presentation of this is given in Figure A.25.

The PAFC uses hydrogen as fuel under acidic conditions, the reactions that occur is therefore the same as in PEM fuel cells: purification

Anode reaction:
$\mathbf{2H_2 \ -> \ 4H^+ + 4e^-}$

Cathode reaction:
$\mathbf{O_2 + 4H^+ + 4e^- \ -> \ 4H_2O}$

Total reaction:
$\mathbf{2H_2 + O_2 \ -> \ 2H_2 O}$

Due to the higher temperatures, other fuel sources than pure hydrogen can be used. This includes hydrocarbons like LNG and methanol. The hydrocarbons need to be reformed in a separate stage before the PAFC. A PAFC system for the use of LNG, methanol or other hydrocarbons would include both a reformer and a heat recovery system, see Figure A.26.

In a PAFC the heat recovery system will typically be a steam turbine. The reforming will be a steam reforming converting LNG (mainly methane, CH_4) to carbon monoxide and hydrogen. A subsequent water-gas-shift can also be used for further converting to CO_2 and more hydrogen. The steam reforming is a process that requires energy.

Steam reforming:
$\mathbf{CH_4 + H_2O \ -> \ CO + 3H_2}$

Water-gas-shift:
$\mathbf{CO + H_2O \ -> \ CO_2 + H_2}$

Benefits and Challenges

The efficiency of the PAFC itself is relatively low, around 40 %, but including heat recovery the efficiency can be as high as 80 %. The higher temperature in the PAFC also makes it less sensitive to CO poisoning and other contaminants than other fuel cells using platinum catalyst.

The system has a low power density, and will thus be large and heavy. The moderate temperature makes start up slower than for low temperature fuel cell, but the PAFC is less prone to negative effects of cycling than the higher temperature fuel cells.

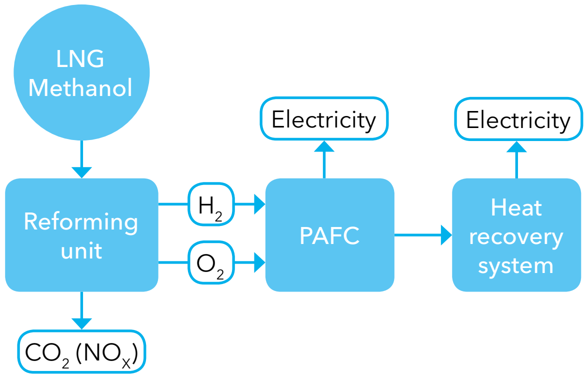


Figure A.26: Flow chart for a phosphoric acid fuel cell system.

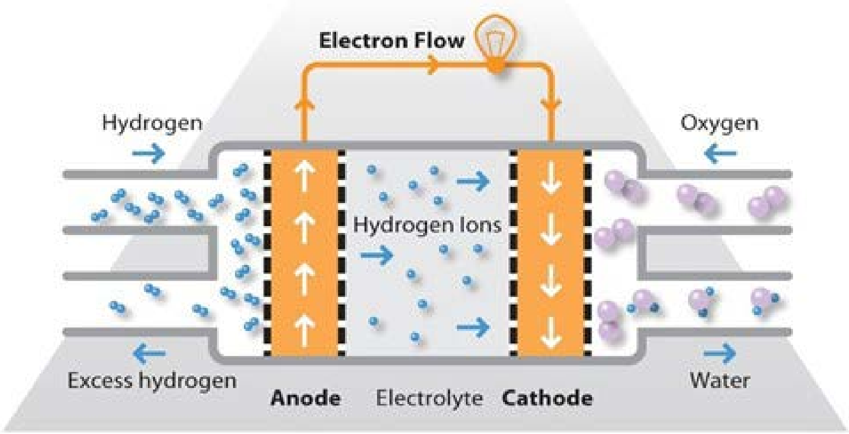


Figure A.25: Schematic of a phosphoric acid fuel cell (PAFC)

MOLTEN CARBONATE FUEL CELL (MCFC)

The molten carbonate fuel cell (MCFC, Figure A.27) is a high temperature fuel cell operating at temperatures between 600-700°C. The electrolyte is a molten carbonate salt, and there is no need for noble-metal catalyst. The anode is normally a nickel alloy and the cathode is normally nickel oxide with lithium incorporated in the structure.

The MCFC have been used in the FellowSHIP project (320 kW fuel cell using LNG on Viking Lady), in the US SSFC (625 kW fuel cell concept development) and in the MC-WAP project (150 kW fuel cell using diesel).

The high temperature makes the MCFC flexible towards the choice of fuel, both LNG, flue gases from coal and hydrogen can be used. A reforming unit is not needed, as the reforming occurs in the fuel cell itself. Using hydrocarbons leads to CO_2 emissions. As no air is present where the reforming takes place at the anode, the reforming is not a source for NO_x emissions, but the subsequent heat and energy recovery systems have the potential for some NO_x emissions.

Internal reforming of LNG:

Steam reforming:
$$CH_4 + H_2O \rightarrow CO + 3H_2$$

Water-gas-shift:
$$CO + H_2O \rightarrow CO_2 + H_2$$

Total reaction from reforming:
$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

Fuel cell reactions

Anode reaction:
$$2H_2 + 2CO_3^{2-} \rightarrow 2H_2O + 2CO_2 + 4e^-$$

Cathode reaction:
$$O_2 + 2CO_2 + 4e^- \rightarrow 2CO_3^{2-}$$

Total reaction for fuel cell:
$$2H_2 + O_2 \rightarrow 2H_2O$$

As with the PAFC, the MCFC is suitable for a heat recovery system. The flue gases can be used in a after burner or a gas turbine, and more energy can be extracted in an steam turbine. The electrical efficiency is around 50 %, but the total efficiency for a MCFC can be as high as 85 %. A flowchart for a MCFC using LNG, methanol or other hydrocarbons is given in Figure A.28. If hydrogen is used as the fuel, there will be no CO_2 emissions from the cell, only CO_2 in circulation to regenerate carbonate in the electrolyte.

Benefits and Challenges

The MCFC is a highly efficient fuel cell, with low cost catalyst and electrolytes, and high flexibility towards fuels and contaminants. The high temperature makes it suitable for energy recovery systems, but also makes it vulnerable to negative cycling effects like corrosion and cracking of components. The MCFC has a slow start-up, and is less flexible towards changing power demands than low temperature fuel cells.

Further development

Combining MCFCs with batteries to allow for a more stable operation of the fuel cell may significantly reduce the thermal strain from cycling. This will also allow for more flexible operations with faster start-up and ability to cater to changing power demands.

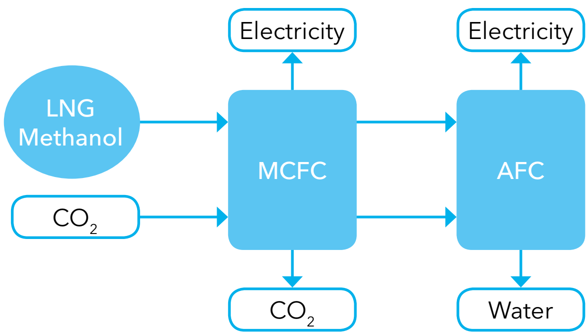


Figure A.28: Flow chart for a molten carbonate fuel cell system.

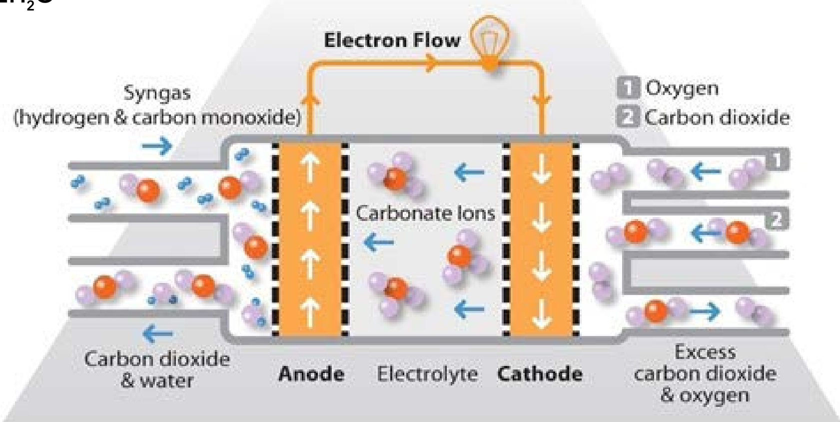


Figure A.27: Schematic of a molten carbonate fuel cell (MCFC) .

SOLID OXIDE FUEL CELL (SOFC)

Solid oxide fuel cells (SOFC) is another high temperature fuel cell. The SOFC operates at temperatures between 500-1000°C. The electrolyte is a porous ceramic material, yttrium stabilized zirconia is common. As the MCFC, the SOFC uses a nickel alloy as the anode, but the cathode is a normally made of lanthanum strontium manganite, a material that has the required porosity and is compatible with the electrolyte. A schematic representation of a SOFC is given in Figure A.29.

SOFCs are generally used in large scale power production on shore up, with capacities up to 10 MW. Several projects have been looking into SOFCs for maritime use, including the Methapu, Felicitas and SchIBZ projects.

The SOFC shows the same flexibility towards fuels as the MCFC, being able to use hydrogen, LNG, methanol and hydrocarbons as diesel. The reforming to syngas (hydrogen and carbon monoxide) occurs within the fuel cell. Unlike the MCFC the SOFC does not require CO_2 to be added at the cathode. The emission from the SOFC is CO_2, but this is eliminated if hydrogen is used as the fuel. This is the reactions that happen in the SOFC:

Internal reforming of LNG:

Steam reforming:
$CH_4 + H_2O \rightarrow CO + 3H_2$

Water-gas-shift:
$CO + H_2O \rightarrow CO_2 + H_2$

Total reaction from reforming:
$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$

Fuel cell reactions

Anode reaction:
$2H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^-$

Cathode reaction:
$O_2 + 4e^- \rightarrow 2O^{2-}$

Total reaction for fuel cell:
$2H_2 + O_2 \rightarrow 2H_2O$

A flowchart for a SOFC using LNG, methanol or other hydrocarbons is given in Figure A.24. The electrical efficiency of a SOFC is high, about 60 %, but can be increase to as high at 85 % or higher if a heat recovery system is applied

There are two possible geometries for SOFCs; planar and tubular . In a planer SFOC (Figure 31B) each cell is a flat plate, each component of the cell laid upon each other. The tubular SOFC (Figure 31A) is formed as a tube, one electrode being the inner tube, and the outer tube being the other electrode, and the electrolyte between them. Even though the tubular SOFC is more stable towards thermal cycling, the planar SOFC is considered the more favourable design due to a higher energy density and that it is easier to produce. As for the MCFC, combing SOFCs with a battery will reduce thermal strain and ensure a more flexible operation.

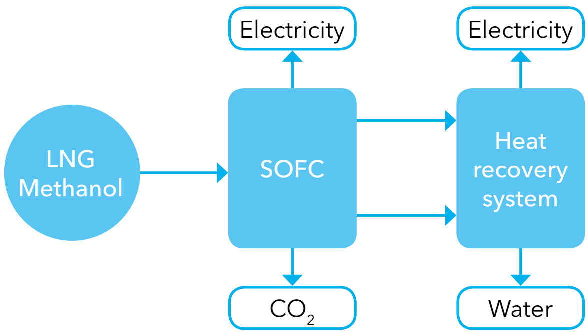


Figure A.30: Flow chart for a solid oxide fuel cell system.

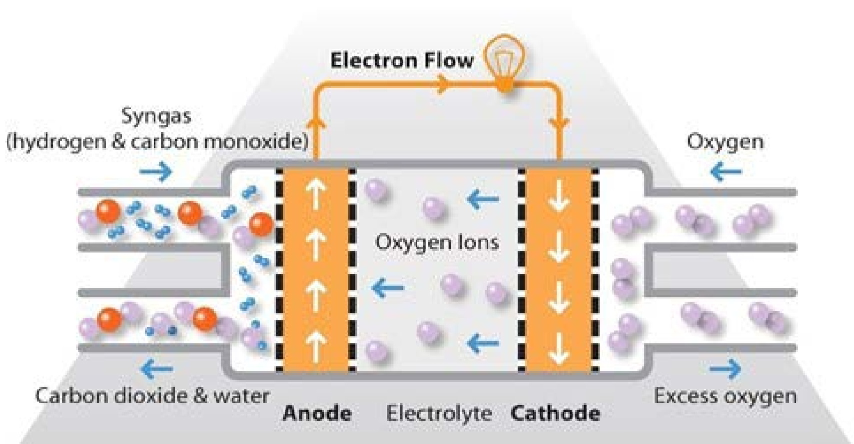


Figure A.29: Schematic of a solid oxide fuel cell (SOFC) .

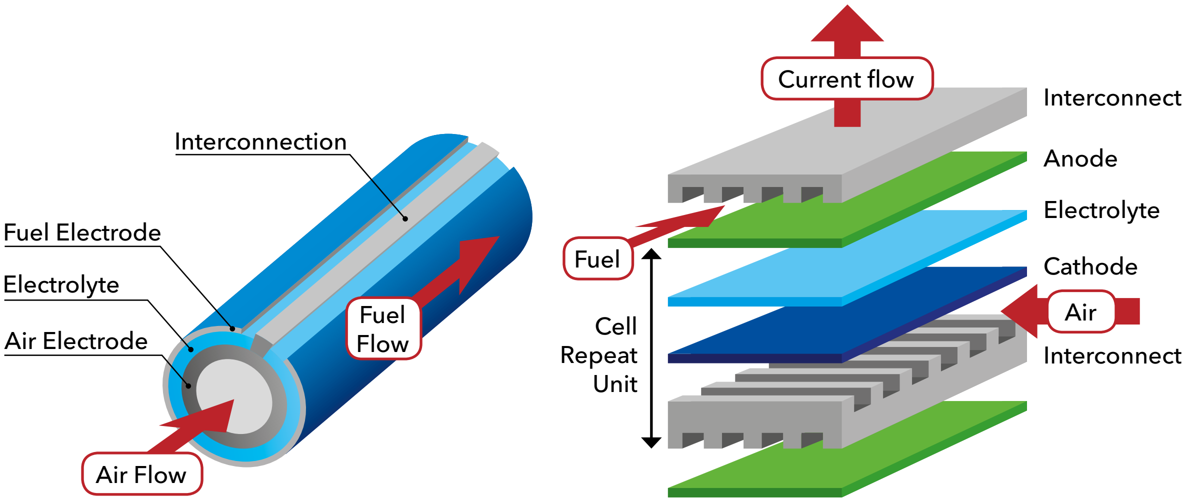


Figure A.31: Cell structure of tubular (A) and planar (B) solid oxide fuel cell

SYSTEM EFFICIENCIES OF FUEL CELLS

Recapturing the system efficiency of the various projects described in this report proved to be challenging. In order to give any credible figure, one would need the correct system architecture for all projects in addition to the component efficiencies of the particular piece of technology applied, such as power electronics /electro components. Then comes the problem of defining the interfaces and frames of the system boundaries.

In general, the difference between system efficiencies of fuel cell systems power systems will mostly depend on the difference between core fuel cell types, since the remaining components in theory can be more or less identical (and is project specific). The efficiency difference between core fuel cell types is defined by the efficiency of the electrochemical reaction taking place in the cell and the parasitic losses required for the balance of plant. The total efficiency figure thus achieved is normally believed to be representative and comparable for the various fuel cell types, as quoted in this report.

In addition comes the efficiency gain that can be tapped from the usable waste heat. The fuel cell types described in this report varies hugely in this respect, from the low temperature PEMFC with "waste" heat below 100°C to the MCFC with waste heat above 650°C.

Common for almost all of the projects described herein is that the focus of the work accomplished has been on demonstrating successful integration and operation of the fuel cell. Less focus has been paid to optimizing the installation in all aspects, including fuel efficiencies. This holds especially for integration of waste heat arrangements. The FellowSHIP project included - after the initial operation was completed - a specially designed cogen arrangement. However, due to external issues, some design parameters were changed that reduced a bit of the optimization effects since a huge portion of the exhaust had to be bypassed the cogen plant. Total system efficiency reported was above 71%.

4 – PROMISING FUEL CELL TECHNOLOGIES FOR MARINE USE

For the purpose of performing a dedicated risk assessment of fuel cells, a selection of the most promising technologies was requested. To to this , a list of the most relevant parameters were developed.

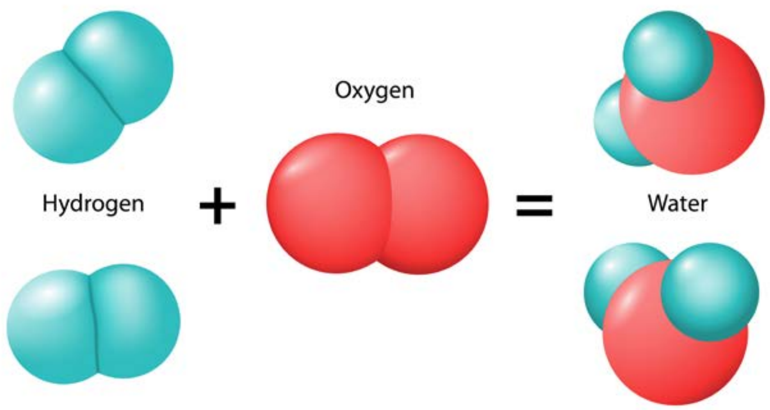
These parameters are:

- Relative cost to other fuel cells
- Power levels (kW) for largest available module (which then can be grouped to larger systems)
- Lifetime
- Tolerance for cycling
- Flexibility towards type of fuel
- Technological maturity
- Physical size
- Sensitivity for fuel impurities
- Emissions
- Safety aspects
- Efficiency (Electrical and total including heat recovery if applicable)

An evaluation of these criteria is given in the table A.3 on the following page for the fuel cell technologies described in this report (AFC, PAFC, MCFC, SOFC, PEMFC, HT-PEMFC and DMF).

These above criteria was chosen because they are considered to be vital for evaluating if a fuel cell technology is suitable for marine use in the near future, and for comparing different technology. In defining the list of decision criteria, emphasis has been to use benchmarks that will be decisive as to whether a project will actually choose to include fuel cell technology. Less focus has been put on engineering aspects and other issues not judged to be business critical for the project. An example of the latter will be ventilation system issues necessitated by the different fuel cell types.

Safety is one of the major issues when it comes to marine use of technology, and safety aspects will be fully treated in chapter C of the assignment and hence not covered in any depth in task 1. The rationale behind this is that the three chosen technologies will be taken further to a safety assessment.

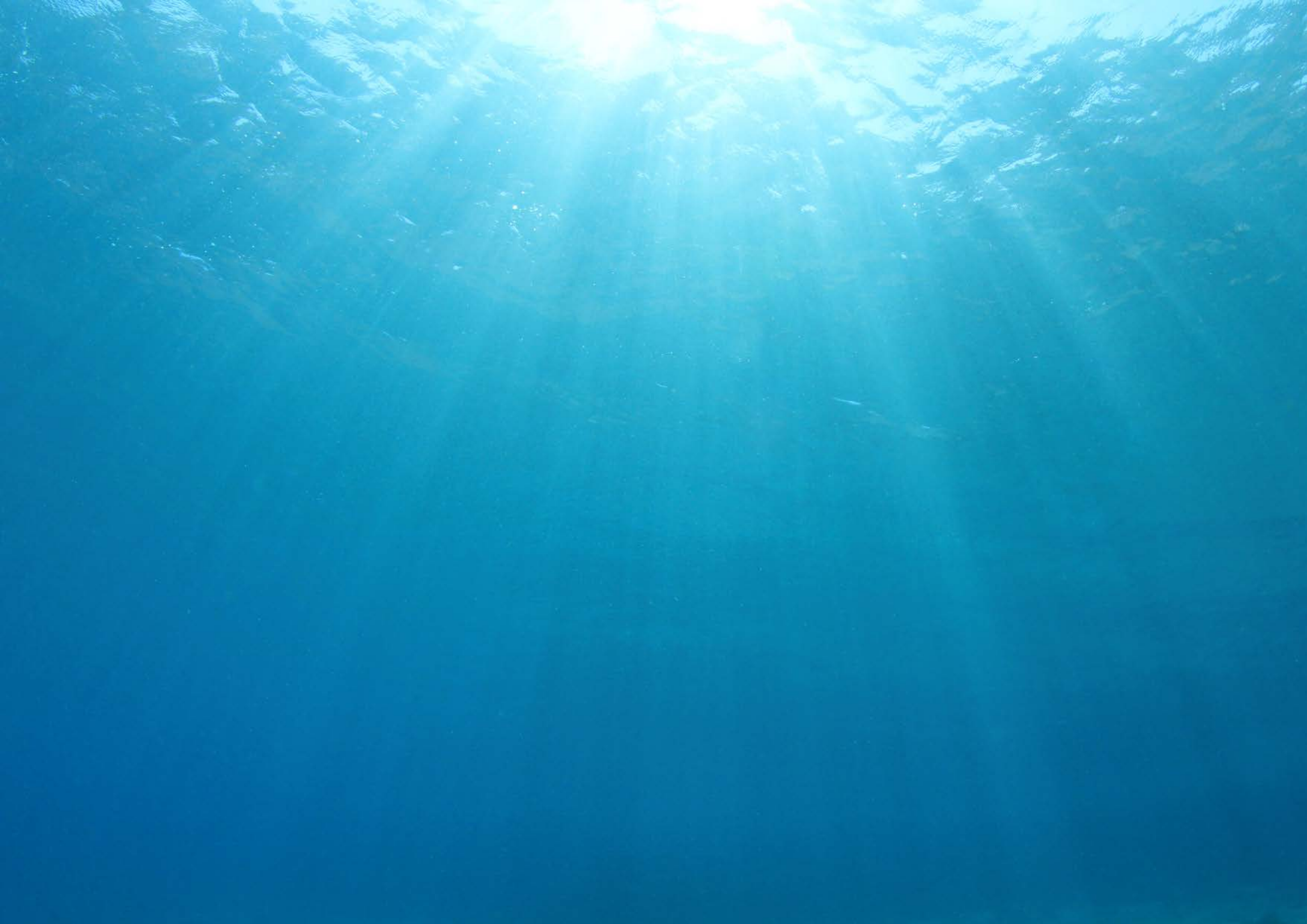


$$2H_2 + O_2 = 2H_2O$$

SUMMARY OF FUEL CELL TECHNOLOGIES

Technology	Relative cost	Module Power levels (kW)	Lifetime	Tolerance for cycling	Fuel	Maturity	Size	Sensitivity to fuel impurities	Emissions	Safety Aspects	Efficiency
Alkaline fuel cell (AFC)	Low	Up to 500 kW	Moderate	Good	High purity hydrogen	High, experience from several applications including one ship	Small	High	No	Hydrogen	50-60 % (electrical)
Phosphoric acid fuel cell (PAFC)	Moderate	100-400 kW	Excellent	Moderate	LNG, Methanol, Diesel, Hydrogen	High, extensive experi-ence from several appli-cations	Large	Medium	CO_2 and low levels of NO_x if carbon fuel is used.	High temperature (up to 200 C). Hydrogen and CO in reforming unit	40 %(electrical) 80 % (with heat recovery)
Molten carbonate fuel cell (MCFC)	High	Up to 500 kW	Good	Low	LNG, Methanol, Diesel, Hydrogen	High, extensive experi-ence from several applica-tions including ships	Large	Low	CO_2 and low levels of NO_x if carbon fuel is used.	High temperature (600-700 C), Hydrogen and CO in cell from internal reforming	50 %(electrical) 85 % (with heat recovery)
Solid oxide fuel cell (SOFC)	High	20-60 kW	Moderate	Low	LNG, Methanol, Diesel, Hydrogen	Moderate, experience from several applications including ships	Medium	Low	CO_2 and low levels of NO_x if carbon fuel is used.	High temperature (600-700 C),Hydrogen and CO in cell from internal reforming	60 %(electrical) 85 % (with heat recovery)
Proton Exchange Membrane fuel cell (PEMFC)	Low	Up to 120 kW	Moderate	Good	Hydrogen	High, extensive experi-ence from several applica-tions including ships	Small	Medium	No	Hydrogen	50-60 % (electrical)
High Temperature PEM fuel cell (HT-PEMFC)	Moderate	Up to 30 kW	Unknown	Good	LNG, Methanol, Diesel, Hydrogen	Low, experience some ap-plications including ships	Small	Low	CO_2 and low levels of NO_x if carbon fuel is used.	High temperature (up to 200 C). Hydrogen and CO in reforming unit	50-60 % (electrical)
Direct methanol fuel cell (DMFC)	Moderate	Up to 5 kW	Moderate	Good	Methanol	Under development	Small	Low	CO_2	Methanol	20 % (electrical)

Table A.3



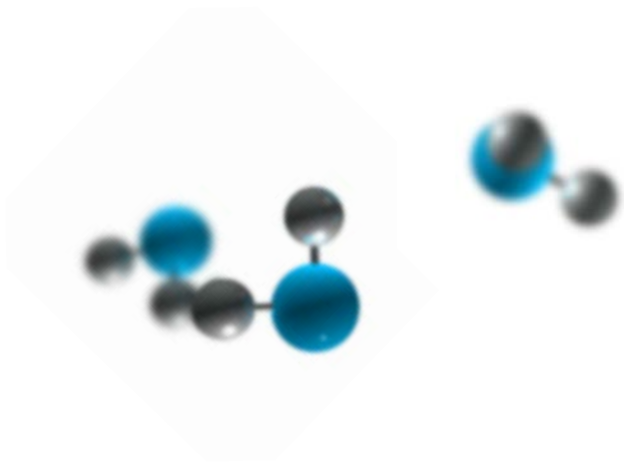
THE 3 MOST PROMISING FC TECHNOLOGIES

For the purpose of performing a dedicated risk assessment of fuel cells, a selection of the most promising technologies was requested. The risk study was limited to three selected technologies. The following reproduces the results from the nomination process, whereby the chosen three technologies are selected based on a scrutiny of their potentials. This scrutiny covers a predefined list of 11 attributes including criteria, listed in the table below.

A high total score is indicating high attractiveness. The scoring uses a weighting (scale 1 to 3, with 3 indicating highest in importance) and ranking (scale 1 to 3, with 3 indicating the highest character).

Parameter group	Attribute	Description
Technology	Module Power levels	The reported maximum power level (kW) of the module units. The modules are the building blocks of larger systems thus enabling construction of applications ranging from kW to MW size. The parameter is given the weighting 2 in order not to punish smaller unit systems. Such systems can easily be modularized similar to batteries.
Technology	Lifetime	The parameter considers the calendar and operational lifetime, however not taking into account to the cyclic life of the application. The parameter is given the weighting 3 to reflect the importance of meeting industrial requirements.
Technology	Tolerance for cyclic operation	Cyclic operation includes endurance against start/stops as well as transients during operation caused by load changes. The parameter is given the weighting 2 as it is considered that any fuel cell installation is most likely integrated with batteries for peak shaving and improving overall fuel efficiency.
Technology	Efficiency	The efficiency parameter considers the totality of stand-alone electric efficiency and the potential for heat recovery. The parameter is given the weighting 3 to reflect the expected importance of fuel saving when choosing fuel cell in favour for incumbent technology.
Technology	Maturity	The maturity parameter considers the totality of actual maturity of the core technology and the maturity for maritime use. The parameter is given the weighting 3 to reflect the importance that this issue represent for a conservative shipping industry.
Technology	Sensitivity to impurities in the fuel	Cover the issue that some require high degree purity H2, to the extent that aboard reforming of e.g. LNG will still require post-purification, while other cell types are more flexible. Issues such as contamination of the air, relevant e.g. for alkaline fuel cells, is also covered by this parameter.
Cost	Relative cost	This is the relative cost between different FC types. The parameter is given the weighting 3 considering the ever present importance of budgets.
Environment	Emissions	The emission of harmful substances to air, that could be NO_x, SO_x, CO_2, PM or other. Since the emissions are mostly dictated by the choice of fuels, the parameter is given the weighting 2 in order to reflect that all fuel cell types have the options of running on hydrogen. The issue that some require high degree purity H2 while other cell types are more flexible is covered in the sensitivity parameter.
Safety	Special safety aspects	The rating is given so that the combination of high temperature combined with hydrogen as fuel is discredited. MCFC and SOFC is given credit that H2 is only present internally in the cell and BOP, eliminating separate H2 tanks and distribution systems. The parameter is given the weighting 3 to reflect the importance of safety of new technology.
Ship application	Physical size	The parameter is a balance of the energy density of the core cell as well as the needed space requirements of the total installation including all ancillary systems. The parameter is given the weighting 3 indicating that ship uptake of FC technology is likely biased towards compact systems.
Ship application	Fuels	The parameter is a balance of the flexibility provided by the fuel cell in fuel selection, but also sensored against the usability of the fuels for maritime applications. The parameter is given the weighting 3 to reflect the importance for ship application

Table A.4



The ranking and scores provided during the nomination and selection is qualitative in nature, and serves as a comparison between the technologies. This reflects the difficulty of establishing concrete figures on new technology, still under development.

The result of the ranking exercise is shown in the table below.

The PEMFC and the High Temperature PEMFC were the two technologies receiving the highest score in the ranking. While there are many similarities between these two technologies, they also differ in important aspects such as complexity of installation, fuel options, tolerance for fuel impurity and total efficiency including waste heat recovery. For this reason, it was decided to select both technologies for use in the subsequent risk assessment. The third and last technology selected for the risk assessments was a high temperature fuel cell, namely the SOFC. With this, the project has designated one low temperature fuel cell and one medium temperature and one high temperature technology to continue to the risk assessment.

Proton Exchange Membrane Fuel Cell (PEMFC)

The PEM fuel cell is a mature technology that has been successfully used both in marine and other high energy applications. The technology is available for a number of applications. The maturity of the technology is the main reason why this is one of the most promising fuel cell technologies for marine use, this also leads to a relatively low cost.

The operating temperature is low, and operation requires pure hydrogen. The safety aspects are thus related to the use and storage of hydrogen on a vessel. Using hydrogen as fuel, the only emission is water and low quality heat. The low temperature provides high tolerance for cycling operation.

The efficiency is moderate, 50-60 %, and with the low temperature, heat recovery is not feasible. The modules currently have a size of up to 120 kW, and the physical size is small, which is positive for marine use.

The major drawback of the PEMFC technology is sensitivity to impurities in the hydrogen as sulphur and CO, a complex water management system (both gas and liquid) and a moderate lifetime. The PEMFC was the technology receiving the highest score in the ranking.

High temperature PEMFC

The HT-PEMFC is a technology that is less mature than conventional low temperature PEM, but is addressing some of the problems with a low temperature PEM. The higher temperature reduces the sensitivity towards impurities and simplifies the water management since water is only present as gas phase. The efficiency is the same as for traditional PEMFCs, possibly somewhat lower due to less parasitic losses, and the higher temperature leads to more excess heat that might be used for ship internal heating purposes. The HT-PEM technology was demonstrated aboard the MS Mariella in Pa-X-ell project with 3 stacks of 30 kW, and in the project MF Vågen, Norway, including a 12 kW HTPEM for small port commuter ferry.

The higher operating temperature allows eliminating the need for a clean-up reactor after the reformer. Such reactors are expensive, space demanding and lower the system efficiency. Owing to the tolerance for fuel impurities (HTPEM cell can tolerate up to 3 % (30,000ppm) CO and up to 20ppm of sulphur without permanent degradation, as opposed to less than 30ppm CO and less than 1 ppm of sulphur for LTPEM), simpler, lightweight and cheaper reformers can be used to produce hydrogen from a broad range of energy-carriers such as LNG, methanol, ethanol, diesels,

The operational temperature of up to 200°C is assumed moderate enough so that tolerance for cycling is not significantly weakened.

Solid oxide fuel cell

The SOFC is a highly efficient, moderately sized fuel cell. The high operating temperatures means that with heat recovery the fuel efficiency can reach about 85 %, and possibly increasing with further development. There is some experience with use of the technology in vessels, including the MS Forester in the SchIBZ project. With further development and experience the price of this technology is expected to be reduced.

The fuel cell is flexible towards fuels, and the reforming from hydrocarbons to hydrogen take place internally in the cell. The high temperature is a safety concern, and when using hydrocarbon fuel there will be emissions of CO_2 and NO_x.

A promising development for the SOFC technology is hybrid systems that combine SOFC, heat recovery and batteries, as it is planned for in the SchibZ project. This leads to the possibility of a more flexible operation of the system, and with less cycling of the SOFC, the problems associated with cycling is reduced.

Technology / Attributes	Relative cost	Module kW levels	Lifetime	Tolerance for cycling	Fuel	Maturity	Size	Sensitivity fuel im-purities	Emissions	Safety Aspects	Efficiency	Total
Weighting	3	2	3	2	3	3	3	3	2	3	3	
Alkaline fuel cell	3	3	2	3	1	2	2	1	3	3	2	
	9	6	6	6	3	6	6	3	6	9	6	66
Phosphoric acid fuel cell	2	3	3	2	2	2	1	2	3	2	2	
	6	6	9	4	6	6	3	6	6	6	6	64
Molten carbonate fuel cell	1	3	3	1	3	3	1	3	1	2	3	
	3	6	9	2	9	9	3	9	2	6	9	67
Solid oxide fuel cell	1	3	2	1	3	3	2	3	2	2	3	
	3	6	6	2	9	9	6	9	4	6	9	69
Proton Exchange Mem-brane	3	3	2	3	1	3	3	2	3	3	2	
	9	6	6	6	3	9	9	6	6	9	6	75
High Temperature PEM	2	2	2	3	2	2	3	3	3	2	3	
	6	4	6	6	6	6	9	9	6	6	9	73
Direct methanol fuel cell	2	1	2	3	3	1	2	3	1	3	1	
	6	2	6	6	9	3	6	9	2	9	3	61

Weighting use the scale 1 to 3, with 3 indicating the highest in importance
Ranking use the scale 1 to 3, with 3 indicating the highest character
A high total score is indicating high attractiveness

Table A.5

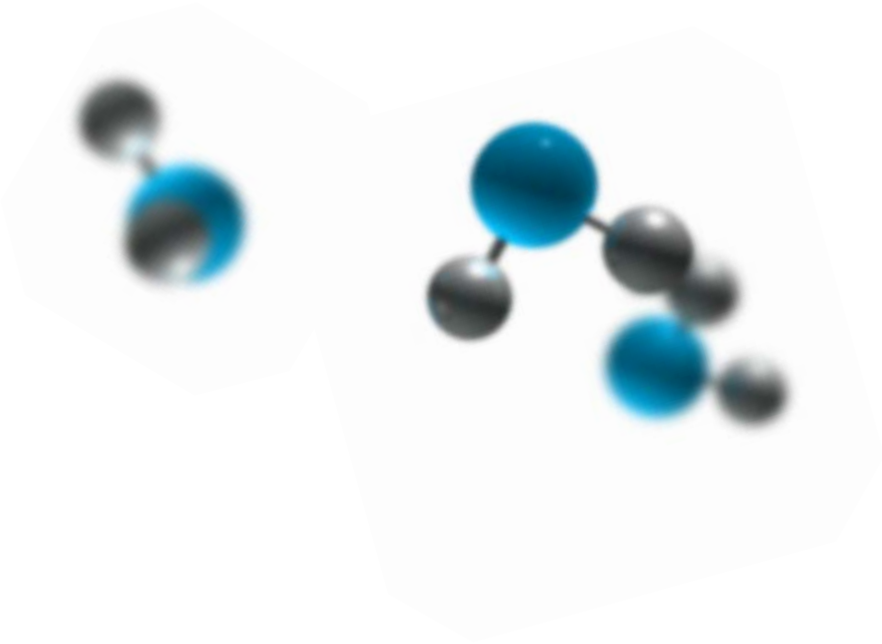
Fuel cells that were not chosen

The fuel cells under this study show a broad spectre of attributes. The selection of the three most promising technologies should not be interpreted as the one and only truth. Different ship type circumstances will lead to different rating of the technologies, not to mention different weighting of the parameters. As an example; the alkaline fuel cell (AFC) requires very clean hydrogen. Waste product hydrogen from industrial process facilities may for example provide fuel for AFC's in local nearby ferry installations, thus providing niche opportunities instead of drawbacks. A comparison of attributes will always include some trade-offs, and when for example in this report it was decided to assign weighting 2 for the parameter "flexibility for cycling", this is meant to reflect that it is highly likely that a fuel cell installation will be integrated with a battery, but we have not included the extra cost that batteries will introduce.

The PAFC and MCFC may be considered less promising for most marine use due to their large size. The FellowSHIP project utilised MCFC predominantly because of the high power achievable combined with relatively moderate costs. The high power allowed for testing and development of new power electronics and ancillary systems scalable to incumbent power systems. MCFC's are very proven in use, and for ship applications where size is less critical, and where total power needs are not too high, such as for some cargo vessels or special purpose vessels MCFC's may become an interesting option.

The AFC drawback is the high sensitivity for impurities, requiring high purity hydrogen and oxygen supplies that are adding complexity in commercial marine use, and also cost. If the purification of hydrogen can be solved in a less expensive way, the alkaline fuel cell may be viewed as a future candidate, as it offers zero emissions, fairly large modules, good tolerance for cycling, low cost of the core technology and few special safety issues.

The DMFC have a low efficiency, 20 %, and is thus not considered attractive for the large energy demands of marine use.



B

STANDARDS/REGULATIONS/
GUIDELINES FOR FUEL CELL
INSTALLATIONS IN SHIPPING

INTRODUCTION

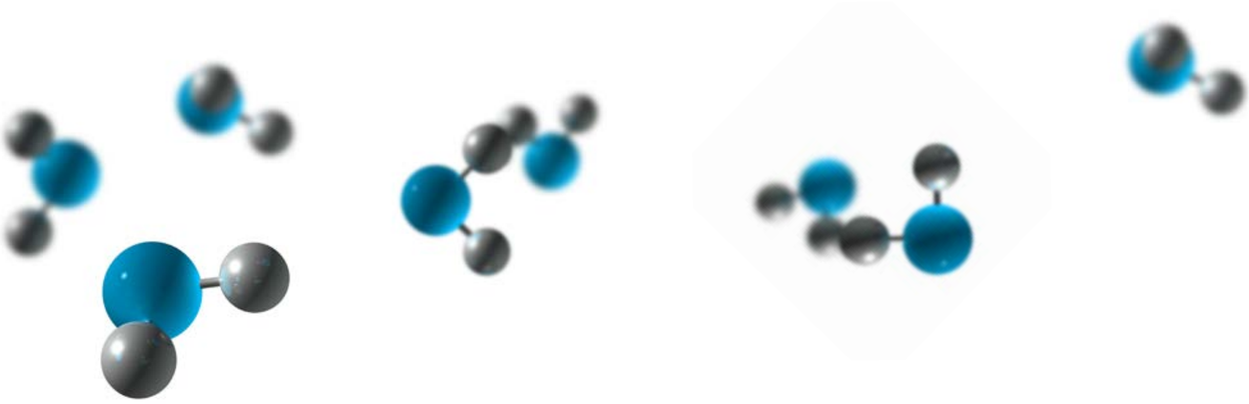
The current chapter gives an overview of current applicable standards, regulations and guidelines for bunkering of fuel, on-board storage and distribution and on-board use of fuel cell installations in shipping. Regulatory information has been reviewed both on a national and international level. The current regulatory development and existing gaps towards safe and efficient use of fuel cells in maritime applications are reviewed.

Considering the current rate of environmental regulations coming into force, it should be safe to say the industry is amid a turning point. Fuel cells powered by low carbon fuels (e.g. natural gas and other low flashpoint fuels) will have local and regional benefits as both emissions and noise are reduced.

Low flashpoint fuels (methanol, ethanol, low flashpoint diesel and bio diesel) including hydrogen have huge potential to contribute to future sustainable low-carbon economy. There is large expectation and ambition towards wider application of such fuels including hydrogen made from carbon free resources. It is anticipated that future hydrogen trade will be encouraged by wider utilization and higher demand. To achieve this, new solutions will be needed both for supply side and demand side. It will be needed to scale up the distribution/transportation which bridges between supply and demand. As preparation for the full-fledged commercialization of fuel cell vehicles, huge effort has been put on the coordination of Regulation, Codes and Standards for fuel cell vehicles and their infrastructures.

For wider application of low flashpoint fuels and hydrogen, further pre-normative work will be needed to close the gaps within current regulations, codes and standards.

The first chapter of the study on the use of fuel cells in shipping mapped current and past maritime fuel cell projects. A presentation to the most relevant fuel cell technology types were done, with selection of the three most promising for marine use, from a list of seven. The three types selected was the solid oxide fuel cell (SOFC), the PEMFC and the high temperature PEMFC. These are different fuel cells, normally using different types of fuels. Whereas the PEM is only capable of running on pure hydrogen, the high temperature PEM and the SOFC allow fuels such as LNG, methanol/ethanol or even low sulphur diesels. These fuels will be reformed in a lesser or greater degree prior to entering the fuel cell. Ultimately however, even for the latter fuel cells hydrogen will be an active substance in the cell, meaning that the issue of hydrogen safety is present also there in form of possible leakages from piping, fixture and the cell itself.



1 – STANDARDS/REGULATION FOR FUEL CELLS IN SHIPPIN

The present chapter provides an overview of current applicable standards, regulations and guidelines for bunkering of fuel, on-board storage and distribution and on-board use of fuel cell installations in shipping. Regulatory information has been reviewed both on a national and international level. The current regulatory development and existing gaps towards safe and efficient use of fuel cells in maritime applications are reviewed. The overview provides a snapshot of the regulatory environment for fuel cell installations aboard ships at the date of publication. Relevant work is currently ongoing at international level, one example being rules for fuel cell installations currently in development in IMO.

Fuel cell installations in ships are today in discussion within a complex regulatory context development. On one hand, environmental regulations come into force at an increased pace driving the industry towards a turning point. On the other hand, safety rules for fuel cell installations onboard ships are increasingly drawing the necessary regulatory certainty for practical implementation of this technology. Favouring compliance to current environmental regulations, in line with a more sustainable development in the shipping industry, fuel cell power production is a technology that can eliminate NO_X, SO_X and particle (PM) emissions, and reduce CO_2 emissions, especially when compared with emissions from diesel engines. Fuel cells powered by low carbon fuels (e.g. natural gas and other low flashpoint fuels) will have local and regional benefits as both emissions and noise are reduced. In the longer term, hydrogen fuel generated from a growing number of renewable energy resources could lead to ships with near-zero carbon emissions.

In parallel with the regulatory context developments, fuel cells are, on the technology frame, an important solution that may largely benefit from adoption of low flashpoint fuels (methanol, ethanol, low flashpoint diesel and bio diesel) including hydrogen. All these fuels, as mentioned above, have huge potential to contribute to future sustainable low-carbon economy. There are large expectations and ambitions towards wider application of such fuels including hydrogen made from carbon free resources. Hydrogen trade will be encouraged by wider utilization and higher demand. To achieve this, new solutions will be needed both for supply side and demand side. It will be needed to scale up the distribution/transportation which bridges between supply and demand. As preparation for the full-fledged commercialization of FC vehicles, huge effort has been put on the coordination of Regulation, Codes and Standards for fuel cell vehicles and their infrastructures.

The large potential benefits of low flashpoint fuels come with a large set of concerns regarding their use and storage onboard ships. Typically, with a 60°C minimum threshold for marine oil fuels (exemption only for fuels for emergency generators or lifeboats), shipping is today faced with the need to widen the basket of fuels for onboard use. Environmental compliance drives the change but the adoption of lower flashpoints fuels onboard needs the regulatory structure that is today being offered at international level by the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code). With an entry into force in January 2017, the IGF Code establishes, on its current text, the requirements for construction and operation of ships by liquefied natural gas (LNG). Following its first revision, scheduled in 2020, fuel cells and other low-flashpoint fuels will also be included in the scope of the Code.

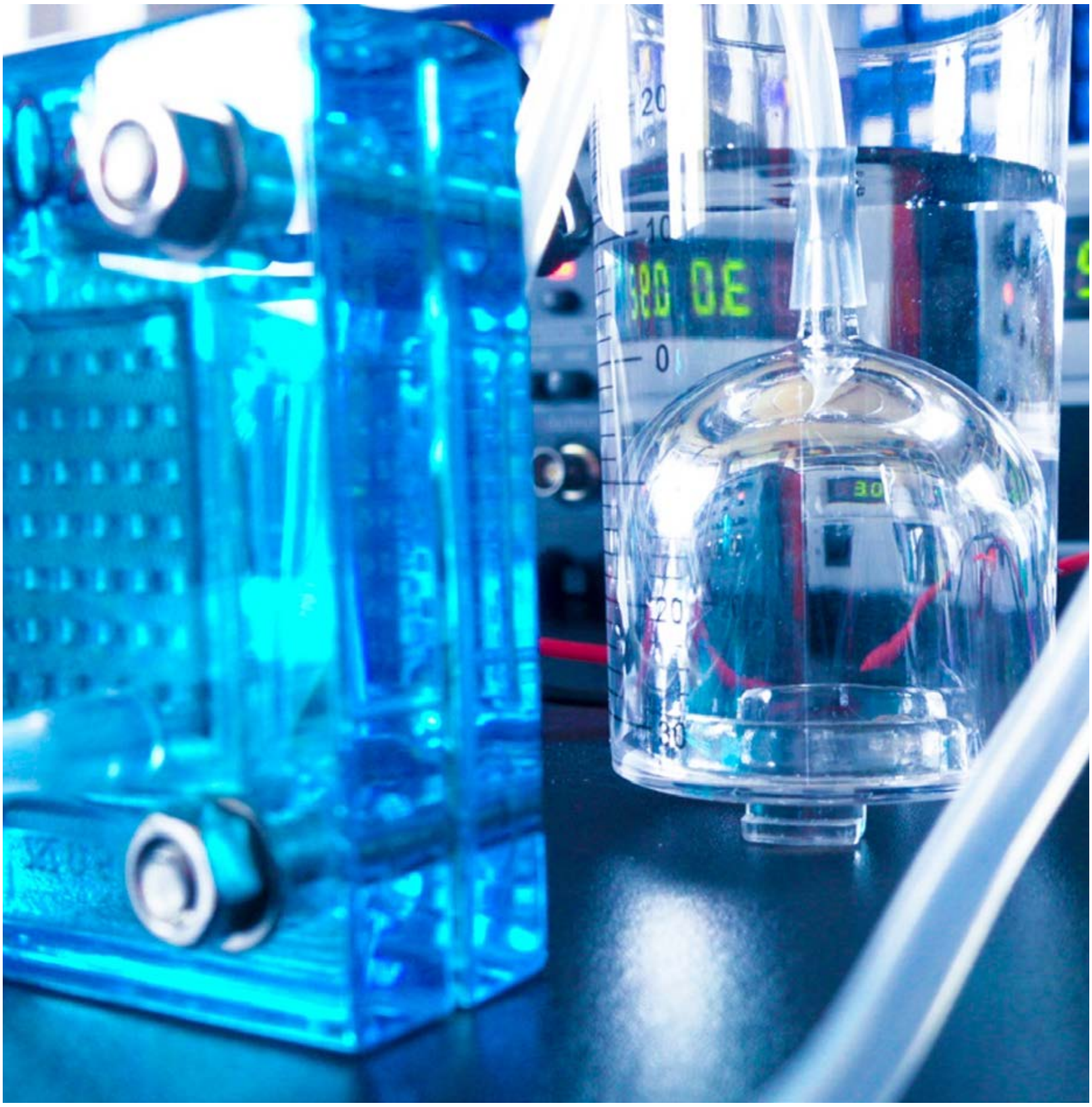
For wider application of low flashpoint fuels and hydrogen, further regulatory and standardization work will be needed to close identified gaps within current regulations, codes and standards. In addition to a summary of the current reference frame for fuel cells, the present study provides a list of the most relevant gaps identified for a wider application of fuel cell installations in shipping.

In the first part of the study, the three most promising types of fuel cell technology were selected. These were Solid Oxide Fuel Cell (SOFC), PEMFC and high temperature PEMFC. All these share the same current regulatory context. Inherently to its technological characteristics PEM FC poses a

S AND GUIDELINES
G

specific case, as PEM FC can only have hydrogen as primary fuel with immediate challenge to regulations. High temperature PEM and the SOFC will normally be fuelled by LNG, methanol or even low sulphur diesels. These fuels will be reformed in a lesser or greater degree prior to entering the fuel cell. PEM fuels cells can only run on hydrogen, leading to the question: How to allow/regulate possible hydrogen storage and use onboard? The answer to this question is building up today within the context of the IGF Code development. Ultimately, to be finally considered, even the latter fuel cells will be utilising hydrogen in the cell, meaning that the issue of hydrogen safety is present also there in form of possible leakages from piping, fixture and the cell itself.

This chapter will identify and assess current Regulations, Codes & Standards, including Guidelines, related to fuel cells and associated fuels. The fuels covered are LNG/CNG, methanol, ethanol, hydrogen, low flashpoint diesel and bio diesel.



EUROPEAN FRAMEWORK

The EU policy aiming at reducing emissions from shipping and introducing alternative fuels have led to introduction of important European legislation. The most important ones are outlined in this subsection.

After 1st January 2015, the EU Member States are required to ensure that ships in the Baltic, the North Sea and the English Channel use fuels with sulphur content not exceeding 0.10%. In other European sea areas, the limit is 0.5% by 2020. Operations with higher sulphur contents are still possible, but only if appropriate exhaust cleaning systems are in place. Previously, the maximum sulphur content of marine fuels was limited to 3.5%. The Directive on Sulphur Content in Marine Fuels (2012/33/EU) allows the use of LNG as an alternative fuel for compliance with more stringent emission standards.

A Baltic and North Sea NO_X Environmental Control Area is expected to be adopted by MEPC 71 (July 2017), and then becoming effective 1 Jan. 2021. If so, this will apply to ships constructed on or after Jan.1 2021. The requirements will be similar to the North American / U.S. Caribbean NECA.

For CO_2, amendments to MARPOL were adopted at MEPC 70 in 2016, the new regulation requiring global reporting of fuel consumption data. Guidelines are still under development. All vessels above 5000 GT need to report fuel consumption starting 1 January 2019. A plan for the data collection needs to be included in the SEEMP latest 31 December 2018. When the Administration has confirmed that the SEEMP contains the data collection plan, a Statement of Compliance will be issued. An annual fuel consumption report should be submitted and verified by the Administration within 1 June in the subsequent year. When the report is verified a new Statement of Compliance will be issued.

Simultaneously, the European Commission in 2015 launched a separate and rather similar initiative, the MRV regulation[1]. The MRV (Monitoring, Reporting and Verification) regulation aims to quantify and reduce CO_2 emissions from shipping and will create a new kind of benchmarking system in Europe. Ships above 5000 GT (all flags) must annually report CO_2 emission on voyages to, from and between EU ports

INTERNATIONAL RULES – IMO

Shipping is an international industry, and international environmental, security and safety standards for shipping are developed by the International Maritime Organization (IMO). IMO is a United Nation specialized agency.

The Directive on Sulphur Content in Marine Fuels (1999/32/EC) has been amended to include provisions of Annex VI of IMO's Marine Pollution Convention, MARPOL 73/78. However, the European Commission called for further action by the International Maritime Organization (IMO) to reduce emissions. Thus, an amended Annex VI was adopted in October 2008. MARPOL Annex VI lowers the maximum permissible sulphur content of marine fuels inside and outside of SECAs. These limits are now EU law outlined in Directive 2012/33/EU.

Maritime applications of fuel cell systems must satisfy (a) requirements for on-board energy generation systems and (b) fuel-specific requirements regarding the arrangement and design of the fuel handling components, the piping, materials and the storage.

In current regulations, these aspects are handled separately. In the present section, the relevant international regulations of the IMO for both aspects mentioned above are presented.

At international level IMO is the responsible body for drafting, discussing, approving, publishing and maintaining the main regulatory instruments that will be important for fuel cell installations in ships. The IMO structure is presented in Figure B.1 below providing an overview of the structure for this organization. Further to the main structure presented, the IGF and IGC codes are included close to the Sub-Committee on Carriage of Cargo and Containers – the one responsible for the work on the IGF Code. The IGF Code will, at international level, provide the necessary regulatory certainty for the adoption of low flashpoint marine fuels, by ships designed and built in compliance with the code.

Fuel cells will be a new part to be included in the IGF Code, at its first revision, due to take place within the 4-year cycle for SOLAS revisions.

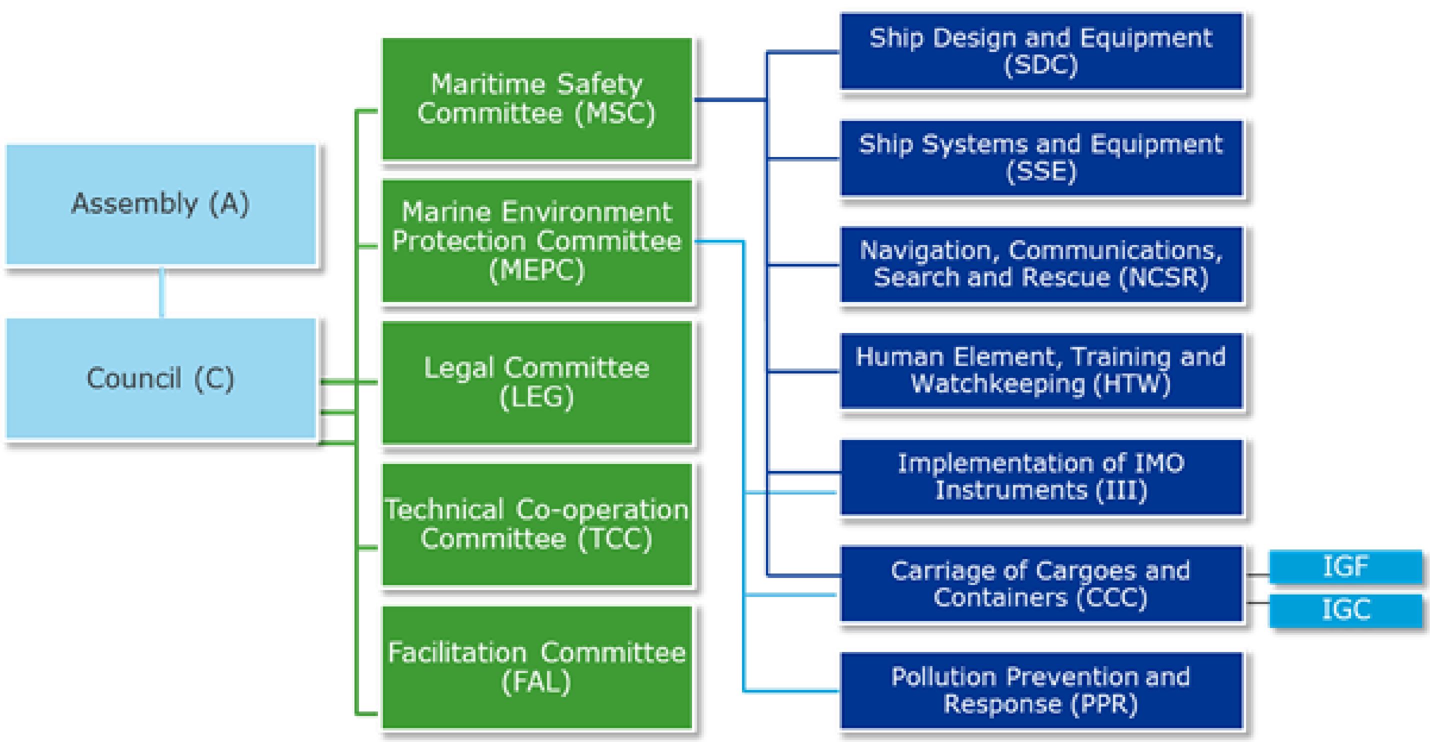


Figure B.1: Overview showing how IMO is organised

Solas

The International Convention for the Safety of Life at Sea (SOLAS) defines as an international agreed minimum requirement for the construction, equipment and operation of ships. Flag States must ensure that these minimum requirements are met.

Chapter II-1 - Construction - Subdivision and stability, machinery and electrical installations, specifies amongst other things the requirements for generators for electrical power generation.

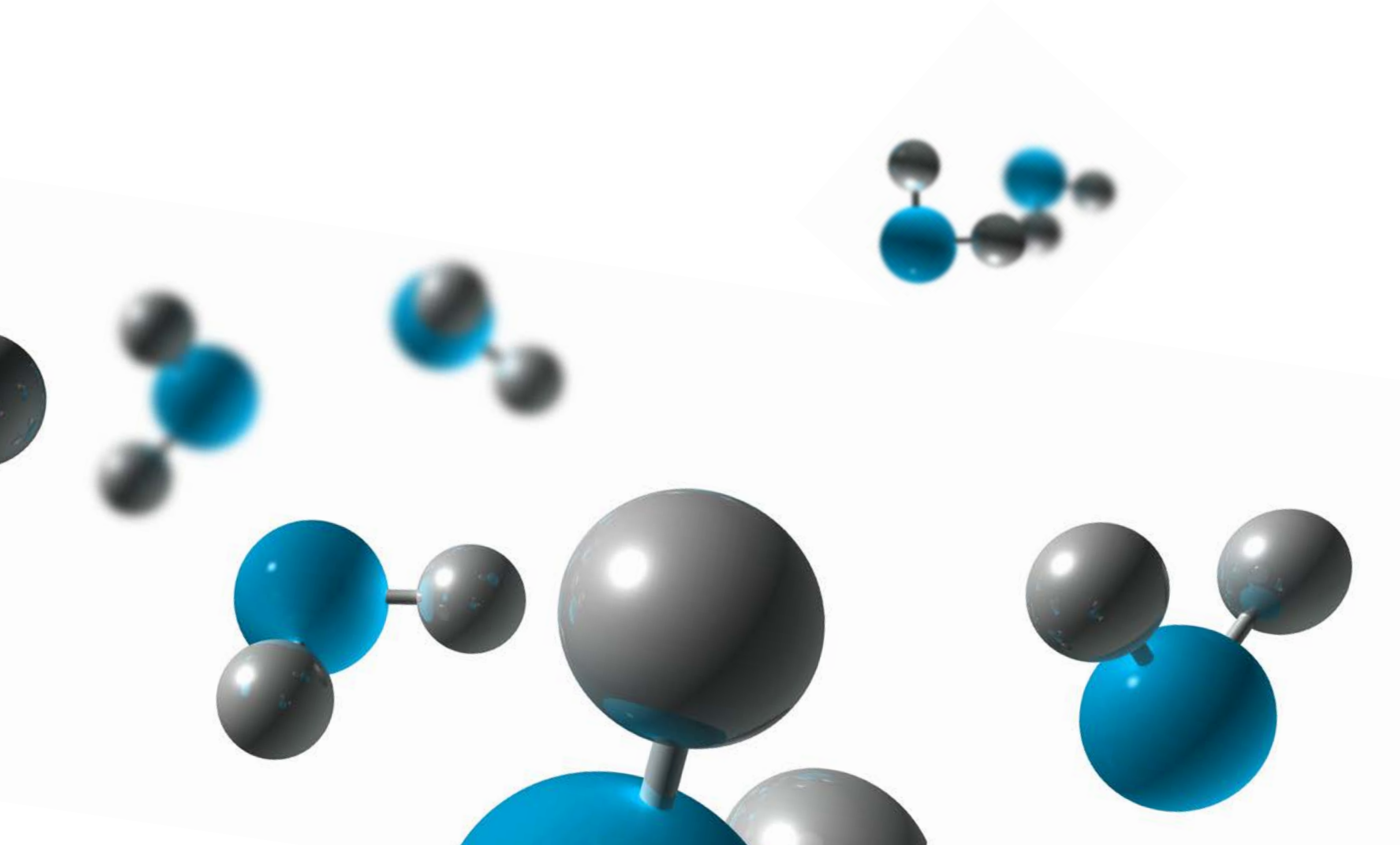
IMO has developed requirements for vehicle carriers carrying motor vehicles with compressed hydrogen or natural gas in their tanks for their own propulsion as cargo (SOLAS II-2 reg. 20.1). This is the part relevant to fuel cells. The IMO sub-committee on Fire Protection (FP) agreed to introduce new requirements for electrical equipment and wiring, ventilation and gas detection. Entry into force was on 1 January 2016.

International Code of Safety for Ships using Gases or other Low-Flash-Point Fuels (IGF Code)

Background

Based on the experience with the approval and operation of gas-powered ships, the Norwegian administration initiated the development of an international code for gas-powered ships in 2004. The former IMO Sub-Committee on "Bulk, Liquids and Gases (BLG)" started the development of a directive for natural gas-powered ships, which was adopted as a transitional guideline in 2009 (Interim Guidelines for Safety of Natural Gas Fuelling Engine Installation in Ships, Resolution MSC 285 (86)). It entered into force in 2010 and is applicable to the use of natural gas including CNG and LNG for internal combustion engines. Since the MSC.285 (86) is a transient directive line, it has no legally binding character. The MSC.285 (86) can be used by flag states to approve gas-powered ships, but they are not bound to them.

From the outset the goal was the development of an international standard, with the purpose to provide an international standard for ships other than vessels covered by the IGC Code, operating with gas or low-flashpoint liquids as fuel, which has a legally binding character for the flag states. Therefore, the MSC.285 (86) formed the basis for the further development of the International Code of Safety for Ships using Gases or other Low-Flash-Point Fuels (IGF Code). In addition to specific requirements for fuels with a flashpoint below 60°C, the IGF Code should also contain requirements for alternative energy converters such as fuel cell systems.



Status IGF Code per January 2017

The IGF Code development resulted in adoption by the MSC committee in June 2015, meaning that the code was formally approved. The IGF Code entered into force on 1 January 2017. The IGF Code was initially adopted only for natural gas and internal combustion engines at MSC95 June 2015. The IGF Code is mandatory for all gases and other low flashpoint fuels. However, it only contains detail requirements for natural gas (LNG or CNG) as fuel. Internal combustion engines, boilers and gas turbines are included as consumers. For other gases and low flashpoint fuels, the IGF Code Part A requires the alternative design method in accordance with SOLAS Regulation II-1/55 to be used demonstrating an equivalent level of safety.

A phase 2 development of the IGF Code initiated by IMO and the CCC subcommittee is currently developing technical provisions for methyl-/ethyl- alcohols as fuel and fuel cells. Fuel cells will be a new part E. This is aimed to be included in the IGF Code at its first revision, which is due to take place within the 4-year cycle for SOLAS revisions.

The regulations for fuel cells was initially intended to be included in the IGF Code Part A-1 applicable for natural gas as fuel, but at CCC3 in September 2016 it was decided to extend the scope by including the fuel cell regulations in a separate Part E in the IGF Code, meaning that any gases or other low flashpoint fuels can be used as fuel for the fuel cells, not only natural gas.

It should be noted that the fuel cell regulations under development in IMO will cover the fuel cell installation, but not the fuel storage and fuel supply system. If the fuel cell is using other gases or low flashpoint fuels than natural gas (covered by Part A-1 of the Code), the alternative design approach must be used in accordance with Part A of the Code for the fuel storage and fuel supply system until specific provisions for these aspects are developed for each of the low-flashpoint fuels in question.

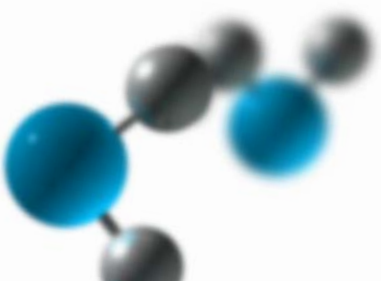
The draft regulations for fuel cells are still immature. Basic principles like relevant definitions, goal and functional requirements are still under discussion. The safety concept for the fuel cell installation and whether hydrogen rich fuel can be routed in double walled pipes between the reformer and the fuel cell is also under discussion in the ongoing IMO correspondence group reporting to CCC4.

There was no decision at CCC3 in September 2016 whether the technical provisions under development for methyl-/ethyl- alcohols as fuel should be included as an amendment of the IGF Code or whether it should be published as interim guidelines. This will be decided at a later stage. Due to time constraint, the working group at CCC3 made no progress in the development of the technical provisions for methyl-/ethyl- alcohol fuels. However, the development continues in the IMO correspondence group reporting to CCC4.

Also for methyl-/ethyl- alcohol fuels, basic principles like definitions and safety concept are still under discussion in the correspondence group. It has been a challenge that the first draft technical provisions were based on the IGF Code regulations for natural gas since methyl-/ethyl alcohols have different properties than natural gas and by that other safety challenges requiring other arrangements.

The aspects mentioned in the following bullet list have been discussed within the development of technical provisions in the new Part E regarding fuel cells. These aspects were discussed during the working group at CCC3 and will be further evaluated by the correspondence group and most likely by a working group at CCC4. The list below represents the status after CCC3, but until future adoption at MSC the draft wording is subject to change by the IMO correspondence group, and it can be changed due to submissions to CCC4:

- New definitions to be developed in relation to fuel cells should be kept in the existing part A of the IGF Code. The existing definitions need careful consideration.
- The goals and functional requirements to be met within the new draft part E of the IGF Code are provided by means of a reference to part A (at the beginning of the draft part E). In this context, the goals and functional requirements as referred to in chapters 9 (Fuel supply to consumers) and 10 (Power generation including propulsion and other gas consumers) of part A-1 of the IGF Code were combined. Further work with goals and functional requirements is expected
- Draft requirements indicate that exhaust gas systems and ventilations systems could not be combined.
- Draft requirements regarding the ventilation capacity and redundancy requirements based on the fuel release sources of the fuel power installation have been developed.



- It was discussed that the developed provisions should follow the shutdown and safety concept generally established in the adopted IGF-Code. System arrangement provisions have been developed, except for the use of the term "system" or "installation" within the scope of the shutdown activation.
- The different fuel cell technologies have different tolerance to fuel impurities in terms of power, potential long-term degradation and performance of the fuel cell. Therefore, the continuous monitoring of the purity of the fuel to the fuel cell has been proposed.
- The definition for "fuel cell spaces" as being structural space or non-structural enclosure containing elements of the fuel cell power installation was adjusted at CCC3. All current draft definitions still need further consideration.
- It was proposed to use the safety concepts in part A-1 of the IGF code related to ESD protected machinery spaces for fuel cell spaces. Work to develop this concept has started.
- It was also proposed that provisions for "gas safe fuel cell spaces" should not be ruled out.
- It was discussed that the last phrase of the draft provision 10.6.3.6.3, i.e. "that fuel cell spaces shall be arranged with a smooth ceiling sloping up towards the ventilation outlet", may be too prescriptive. There were also opinions that an Administration can always approve any other arrangements. However, there was no agreement on that specific provision and it would need further consideration.
- Some fuels have a very high auto-ignition temperature and, in such cases, the temperature limitation of external surfaces in the fuel cell spaces stated in the provision would only address the auto-ignition hazard, but the high temperature safety hazard would remain.
- Regarding hydrogen or hydrogen rich fuel piping provisions, it was agreed that they should be set out in an independent section in the draft part E.
- Additionally, ignition hazards related to double wall arrangements with ventilation for hydrogen pipes that may be created by static electricity generated by ventilation should also be considered within the technical provisions.
- A schematic diagram of a generic fuel cell system was developed which needs further adjustment to ensure that the terminology used in the diagram matches the text in the technical provisions. The diagram is shown in Figure B.2.

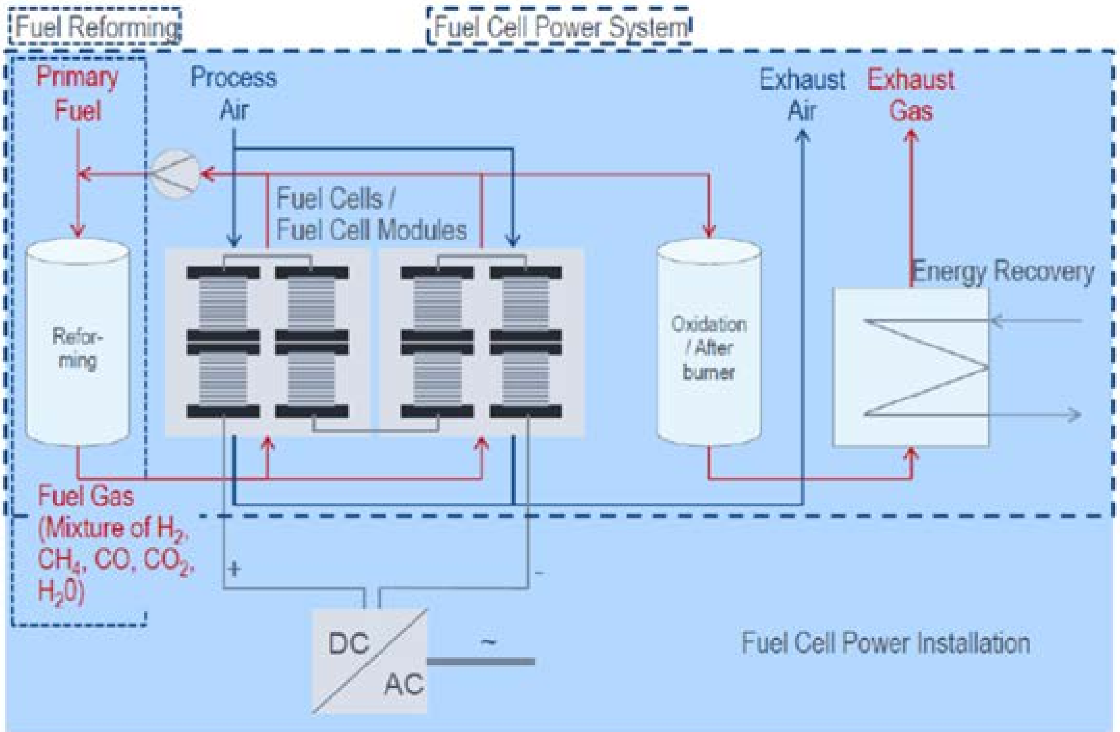


Figure B.2: Illustration showing the generic fuel cell system diagram currently being in discussion at IMO

International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)

The International Code for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) defines the requirements for the construction and operation of gas carriers and is part of SOLAS Chapter VI, Part C. The IGC Code was the first code to regulate the use of gas as a ship fuel, in this case for gas carriers (use of boil-off gas (methane) as a fuel). This Code is kept under review, considering experience and technological development, as in practical terms, any developments into the IGC Code are relevant for consideration also in the IGF Code. However, IMO principles mean that a specific ship should relate to only one code, meaning either the IGC or the IGF code. The development of the IGF-Code and IGC-Code is separated, which is seen on issues such as those concerning tanks below accommodation.

As the IGC code is specific for gas carriers and their fuel systems, its relevance for fuel cells in shipping is limited to the potential use of fuel cells and related fuels in gas carriers. The IGC Code covers hydrogen in the scope of the code. However, the code currently lacks specific requirements for hydrogen. The CCC (Carriage of Cargoes and Containers) sub-committee in IMO discusses introduction of requirements for carriage of liquefied hydrogen as cargo in this code. A first draft of the requirements for hydrogen was proposed at the previous CCC meeting. Work to develop the draft interim recommendations for carriage of liquefied hydrogen in bulk continued in a correspondence group and the result was reported to CCC3. CCC3 finalized the draft Interim recommendations for carriage of liquefied hydrogen in bulk and sent it to MSC97 for approval. The application of the recommendation is limited to the facilitation of the establishment of a tripartite agreement for a pilot ship. To this end, Kawasaki Heavy Industries, Ltd. has obtained approval in principle (AiP) from ClassNK, for its new cargo containment system for ships that carry liquefied hydrogen in bulk. The tank system is intended for transport of LH2 from Australia to Japan, among other purposely for the Olympic Games in 2020.

International Maritime Dangerous Goods Code (IMDG Code)

The IMDG Code covers hydrogen and other dangerous goods as packed cargo. Transport of such goods in the ship's own cargo tanks is not included. The IMDG code gives requirements for compressed hydrogen and refrigerated liquid hydrogen which are comparable to those for compressed natural gas and refrigerated liquid natural gas. As packed cargo, compressed and liquid hydrogen cannot be transported by cargo or passenger ships which carry more than 25 passengers or 1 passenger per 3m of overall length. In any case, liquid hydrogen cannot be stowed in under deck. Compressed and liquid natural gas have the same limitation in the IMDG code as packed cargo. However, as fuel, IGF code enables to store fuel natural gas on-board passenger ships carrying more than 25 passengers. Due to its properties, it should be anticipated that hydrogen will be considered at least as strict as natural gas. Initial restriction regarding storage quantities and location can be anticipated (e.g. storage on top deck).

CLASSIFICATION RULES APPLICABLE FOR FUEL CELL INSTALLATIONS

This chapter considers the relevant Class Rules issued - or under development - by the largest relevant classification societies. Table B.1 and Table B.2 give an overview. A detailed description of the rules and how the rules apply are given, with the example of DNV GL.

Short name	Assosiation	Title of document	Status
ABS	American Bureau of Shipping	Fuel cell Powered Ships Guide	In development
BV	Bureau Veritas	Guidelines for Fuel cell Systems On-board Comercial Ships	Released Apr 09
DNV GL	DNV GL	DNV GL rules for classification of Ships: Part 6 Ch. 2 Sec. 3: Fuel cell installation - FC	Released January 2016
	Det Norske Veritas	DNV Rules for Classification: Part 6-Chapter 23: Fuel cell Installations	Released July 2008 (expired)
	Germanischer Lloyd	GL Klassifikationsvorschriften: VI-Teil 3-Kapitel 11: Richtlinien für den Einsatz von Brennstoffzellen-System an Bord von Wasserfahrzeugen	Released 2002 (expired)
KR	Korean Register of Shipping	Guidance for Fuel cell Systems on Board of Ships GC-12CE	Released July 2014
LR	Lloyds Register	LR Technical Papers: Development of requirements for Fuel cells in the marine environment – Performance and prescription	Released 2006

Table B.1: Overview of applicable Class Rules for fuel cell installations and their status.

	ABS	BV	DNV GL	LR	KR
Own prescriptive rules	Directive under development. Since 2009	Directive published in 2009	Directive published in 2016	-	Directive published in 2014
Alternative authorization procedure	-	-	-	Risk-based process	-
Based on MSC.285(86) (LNG interim guidelines)	-	Yes	Yes	No	Yes
Regulated fuels	-	Natural gas, hydrogen	All fuels with flashpoint ≤60 °C	No; Risk-based process	All fuels with flashpoint ≤60 °C
Class approval mark	-	No	FC(Power) FC(Safety)	No	"FC-PWR" "FC"
Risk analysis required	Yes; No specific method	Yes; No specific method	Yes; FMEA	Yes; No specific method	Yes; FMEA
Complementary material requirements	-	Yes; Hydrogen (gaseous, liquefied)	Reference to general guidelines of DNV GL.	No	Reference to IEC 62282-3 and Rules for the Classification of Steel Ships (KR)

Table B.2: Overview of applicable class rules and key features.

In the following, DNV GL Rules "Fuel cell Installations" (Pt.6 Ch. 2 Sec. 3, edition October 2015[4]) will be used for providing an overview and exemplification of classification approach for fuel cell installations in shipping.

DNV GL Fuel Cell Rules cover aspects such as design principles, material requirements, arrangement and system design, fire safety, electrical systems, control monitoring and safety systems, manufacture, workmanship and testing.

Storage of compressed flammable gases as natural gas and hydrogen (above 10 bar) below deck will normally not be accepted, but the rules open for storage of compressed gas below deck on a case by case basis. Above deck storage will be less challenging. Storage of natural gas or LFL/hydrogen in enclosed spaces leads to requirements with respect to ventilation, ex-equipment etc. Double walled piping for low flashpoint fuels (methanol and ethanol) are covered by Rules for Low Flashpoint Liquid Fuelled Engines (DNV GL Pt.6 Ch.2 Sec.6).

In addition to prescriptive design requirements, DNV GL rules require a Failure Mode and Effect Analysis (FMEA) and a test program based on IEC standard 62282-3-1 "Stationary fuel cell power systems-Safety" for the fuel cell.

A number of marine hydrogen fuel cell projects were approved based on a previous GL guideline (formally not rules)[5], the most well-known being probably the Alsterwasser in Hamburg, see table 1 in the first part of the report. Now, the GL guideline can only be used on GL classed ships. The GL guideline did not require FMEA, however FMEA is required according to the IGF code (see above). The design criteria in the GL guideline were prescriptive.

The updated DNV GL fuel cell rules have kept the principles from the previous DNV fuel cell rules (e.g. risk based approach for the fuel cell itself, and prescriptive requirements for ship design, piping, fuel storage), and were developed combining the previous version of the DNV Fuel Cell Rules with the GL fuel cell guideline. The DNV GL FC rules include requirements regarding loss of power if the FC is source of main power and redundancy (not specified in previous GL guideline).

The current DNV GL FC rules are developed with hydrogen fuel in mind, without however containing specific provisions for high pressure hydrogen storage technologies.

In this context, other relevant rules include:
DNV GL Pt.6 Ch.2 Sec.6 Low Flashpoint Liquid Fuelled Engines, covering methyl alcohol and ethyl alcohol (methanol and ethanol as fuel). Vessels built in accordance with these requirements may be assigned the class notation LFL. There are no international requirements existing for these fuels.

DNV GL Pt.6 Ch.2 Sec.5 Gas Fuelled Ship Applications, where gas is defined as a fluid having a vapour pressure exceeding 2.8 bar absolute at a temperature of 37.8°C fuel. Vessels built in accordance with these requirements may be assigned the class notation Gas Fuelled.

Class rules applicable for battery fuel cell hybrid installations

To exemplify, the following is based on DNV GL battery Rules Pt.6 Ch.2 Sec.1. The scope for additional class notations Battery(Power) and Battery(Safety) cover safety related to battery installations in vessels. The rules in this section are considered to satisfy the requirements for specific types of battery installation and certification, in accordance with the following list:

- battery systems used as main source of power
- battery systems used as additional source of power
- battery systems used for miscellaneous services
- safety requirements for batteries other than Lead Acid and NiCd. Lead Acid and NiCd batteries are covered by another part of the rule set (Pt.4 Ch.8)
- requirements for certification of the batteries.

DNV GL Battery rules, with the class notations Battery(Power) and Battery(Safety) will be applicable for hybrid installations combining batteries and fuel cells. The choice of notation depends on how the batteries are used in combination with other power sources for the function in the ship. The class notation Battery(Power) is mandatory for vessels where battery power is used as propulsion power during normal operation, or when the battery is used as a redundant source of power. The notation Battery(Safety) is mandatory when the battery installation is used as an additional source of power for battery capacities exceeding 50 kWh. Battery(Safety) can also be selected (not mandatory) for battery systems with less than 50 kWh capacity.

Hybrid solutions using battery power to supplement fuel cells for peak energy demands and for load levelling are potentially attractive to ensure smooth operation of fuel cells. It may also result in a smaller fuel cell installation, and this can have a positive effect on system life expectancy and system costs.

Guidelines

The DNV GL Guideline for large maritime battery systems /6/ gives relevant input for hybrid configurations with batteries and it covers all the phases of a ship development project. The Guideline is in the process of being updated to a more comprehensive Battery Handbook that will provide valuable inputs regarding development of hybrid configurations combining fuel cells and batteries.

STANDARDS FOR FUEL CELL APPLICATIONS

The International Electrotechnical Commission (IEC) and the International Organization for Standardization (ISO) developed rules and standards to cover safety and test requirements of fuel cells primarily for road vehicles and small stationary power systems. The first larger number commercial developments of fuel cells are as power sources for stationary applications for the heat and power supply with up to 1.4MW electrical output /7/. Based on these developments the IEC reviewed and expanded their technical specifications to fuel cell technologies in all applications including but not limited to stationary power, transportation, portable power and micro power applications. The following standard series are recognized to be relevant for maritime applications and have been widely adopted in Germany, EU, Korea, Canada, South Africa and China, as additions to the national rules:

- IEC 62282
  - Fuel cell technologies
- ISO 16110
  - Hydrogen generators

The most relevant standards are enlisted and briefly described in the following.

IEC 62282-1:2012 "Terminology"
The first part of the standard series provides uniform terminology in the forms of diagrams, definitions and equations related to fuel cell technologies in all applications.

IEC 62282-2:2012 "Fuel cell modules"
This part provides the minimum requirements for safety and performance of fuel cell modules with or without an enclosure which can be operated at significant pressurization levels or close to ambient pressure. It applies to fuel cell modules with any kind of electrolyte chemistry.

IEC 62282-3-100:2012 "Stationary fuel cell power systems - Safety"
This standard is applicable to stationary fuel cell power systems intended for indoor and outdoor commercial, industrial and residential use in non-hazardous areas, with or without the ability to recover useful heat. It applies to all kind of fuels like natural gas and other methane rich gases, fuels from oil refining, liquids and hydrogen rich gaseous. Although this part does not cover propulsion fuel cell power systems, it is applicable to marine auxiliary power systems.

IEC 62282-3-200:2015 "Stationary fuel cell power systems – Performance test methods"
This part covers operational and environmental aspects of the stationary fuel cell power systems performance for systems with an electrical output of over 10 kW (systems with less than 10kW are dealt with IEC 62282-3-201).

IEC 62282-3-300:2012 "Stationary fuel cell power systems – Installations"
This part provides minimum safety requirements for the installation of indoor and outdoor stationary fuel cell power systems in compliance with IEC 62282-3-100.

IEC 62282-7-1:2010 "Single cell test methods for polymer electrolyte fuel cell (PEFC)"
This Technical Specification describes standard single-cell test methods for polymer electrolyte fuel cells (PEFCs). It provides consistent and repeatable methods to test the performance of single cells and cell components, including membrane-electrode assemblies (MEAs) and flow plates. This Technical Specification is also available for fuel suppliers to determine the maximum allowable impurities in fuels.

IEC 62282-7-2:2014 "Single cell and stack performance tests for solid oxide fuel cells (SOFC)"
This standard describes test methods for a single cell and stack that is to be employed in power generation systems using solid oxide fuel cells (SOFCs), but is not applicable to small button cells that are designed for SOFC material testing and provide no practical means of fuel utilization measurement. It is to be used for data exchanges in commercial transactions between cell manufacturers and system developers.

ISO 14687-3:2014 "Proton exchange membrane (PEM) fuel cell applications for stationary appliances"
The purpose of this part is to establish an international standard of quality characteristics of hydrogen fuel for stationary fuel cells.

ISO 16110-1:2007 "Hydrogen generators using fuel processing technologies - Safety"
Part 1 of this standard applies to packaged, self-contained or factory matched hydrogen generation systems with a capacity of less than 400 m3/h at 0 °C and 101,325 kPa, intended for indoor and outdoor commercial, industrial, light industrial and residential use. It applies to hydrogen generators using one or a combination of different fuels like natural gas and other methane-rich gases, fuels derived from oil refining, fossil fuel sources (e.g. methanol) and gaseous mixtures containing hydrogen gas. Hydrogen generators are referred to as devices that convert a fuel to a hydrogen-rich stream of composition and conditions suitable for the type of device using the hydrogen. This device can be a fuel cell power system, or a hydrogen compression, storage and delivery system. It aims to cover all significant hazards, hazardous situations and events relevant to hydrogen generators, with the exception of those associated with environmental compatibility.

These guidelines contain information on the individual components of a fuel cell as well as on the structure of a fuel cell system. Even if the primary applications are road vehicles and stationary power supplier, these guidelines may be consulted to orient fuel cell design for use on ships. In particular the regulation of different fuels, simplifies adaption to the environmentally conditions on a ship.

Since 2008 fuel cells for maritime and other purposes in Germany have been certified according to DIN EN 62282-2 which is based on the IEC 62282-2 standard/2/. Furthermore, the existing class guidelines for fuel cell installations on ships of the DNV GL /1/ and of other classes /3/, /4/ contain references to the IEC standards and recommend test procedures (manufacturer and sea trial) based on these standards.

The IEC is currently working on the extension of 62282-3-400, to regulate small stationary fuel cell power system with combined heat and power output and on 62282-8, to regulate Energy storage systems using fuel cell modules in reverse mode (coming into force 2019) /5/.

FUEL SPECIFIC STANDARDS AND REGULATIONS

When mentioning fuel cells, the fuel that immediately may come to mind will be hydrogen. This is indeed the fuel used by fuel cells in the core of its electrochemical working principle. It is however also the case that the hydrogen (or any form of H2 rich gas, usually called "syngas") can be obtained through reforming of a different fuel source, used for practical energy storage purposes. In any case hydrogen will be present in the close vicinity of the fuel cell. More specifically, hydrogen will be present through all the process lines between the reforming unit and the fuel cell. For storage, bunkering, distribution and handling, the applicable requirements are therefore those that apply for the fuel used before reforming. This is a concept of much relevance to the Regulatory frame, and it shows that the requirements for other low flashpoint fuels than hydrogen will also be important.

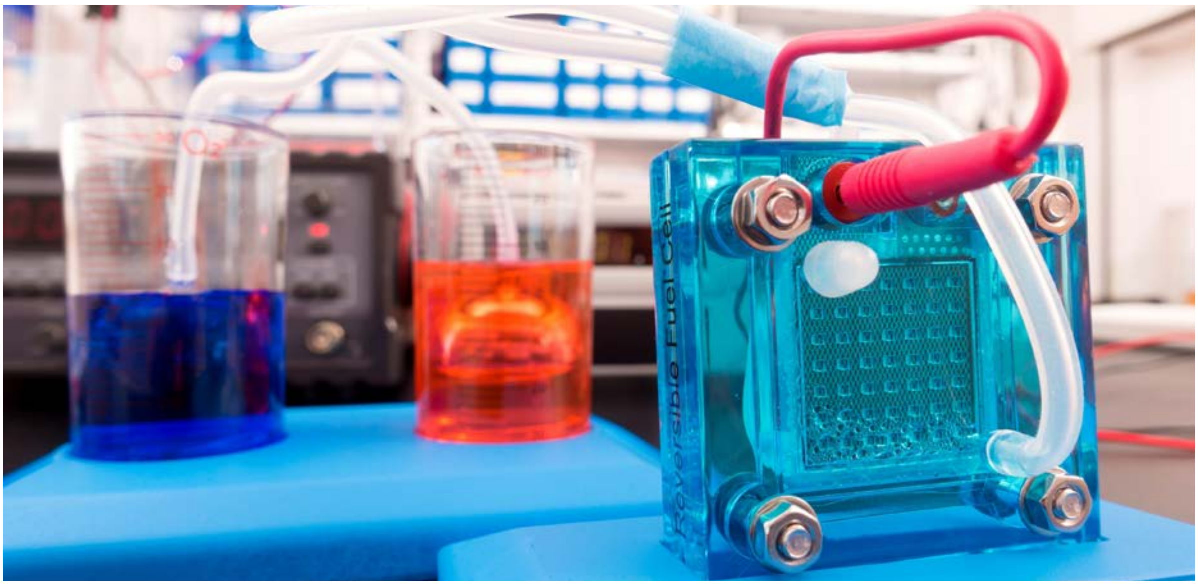
Notwithstanding any potential reservations regarding hydrogen as fuel for shipping, hydrogen has been used throughout the world as an industrial gas for a long time. Therefore, regulations, standards and codes covering industrial use are in place. Areas as land transport and local pipelines are also reasonable well covered. Hydrogen as fuel is a newer application, but the regulatory scheme for hydrogen refueling stations and fuel cell vehicles are becoming established.

ADR covers all road transport of dangerous goods as cargo. Just as for maritime, transport of own fuel is not included in ADR, but in other codes (ECE directives). ADR can be considered as the land transport parallel to the maritime code for transport of maritime dangerous goods as cargo (IMDG Code), and the structure of the IMDG Code and the ADR are consistent. Even though the IMDG Code and ADR cover hydrogen as cargo, but not as fuel, the codes can provide valuable input for developing requirements for hydrogen as a fuel in shipping. ADR includes provisions for both gas and liquid fuels and includes e.g. classification of dangerous goods according to the danger the different substances present, requirements for packing and tank provisions and provisions concerning the conditions of carriage, loading, unloading and handling.

Maritime transport using packages is covered by IMDG Code. A good starting point is ISO technical committee 197 Hydrogen technologies, offering standardization in the field of systems and devices for the production, storage, transport, measurement and use of hydrogen[4]. The ISO TC 197 also includes a H2 bunkering procedure for airports.

The workshop entitled "Putting Science into Standards" held at the Institute for Energy and Transport of the JRC in Petten 2014 analyzed the status of pre-normative research and standardization activities in power to hydrogen and hydrogen admixture in the natural gas system and identified involved stakeholders. The work is summarized in the report CEN – CENELEC, Sector Forum Energy Management/ Working Group Hydrogen.[5]

The international STCW code (Res.MSC.396(95) and Res.MSC.397(95)) - Standards of Training, Certification and Watchkeeping for Seafarers - applies for low flashpoint fuels.



Gas fuels

Existing pressure vessel rules is expected to form the regulatory basis and cover most needs for the physical storage vessels for pressured gas fuels to be used in fuel cells on-board ships. Road transport of compressed hydrogen is regulated by the UN Model Regulation, the European Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR) and the European Transportable Pressure Equipment Directive (1999/36/EC – "TPED"). The Seveso III Directive (Directive 2012/18/EU) is applicable in case of storage of more than 5 tonnes of hydrogen.

The UNECE Inland Transport Committee (ITC) provides an international legal framework and technical regulations for development of international road, rail, inland water and dangerous goods transport. In Europe, also, the EIGA IGC Doc 06/02 is relevant (European Industrial Gases Association), in addition to any local regulation. The codes covering own fuels include limitations regarding allowed quantities that can be stored in vehicle.

For pipeline transport, EIGA (IGC Doc 121/04) will apply in Europe, in addition to any local regulation

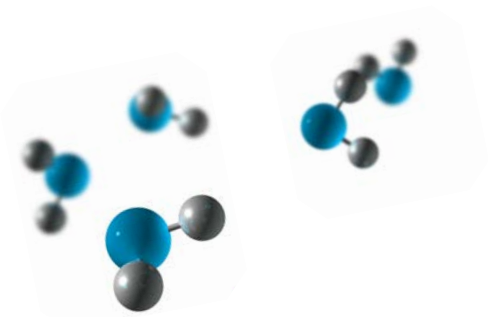
Regulations and standards for stationary gas fuel applications

This sub-chapter lists some of the most relevant European Directives and applicable standards for hydrogen fuel cell systems and components. This particular list was developed for an onshore building project, but it will also be applicable for most stationary hydrogen applications as well as many transport applications with hydrogen involving the referred system components.

Table B.3 gives a summary of relevant applicable regulations. These regulations are also considered applicable for maritime hydrogen projects.

Relevant Regulations	SYSTEM					
	Electrolyser	Fuel cell micro CHP	H_2 storage, piping	H_2 burner, boiler	Energy management, control system	Safety system
ATEX Directive (94/9/EC)	X	X	X			
Pressure Equipment Directive (97/23/EC)	X	X	X			
Gas Appliance Directive (2009/142/EC)		X		X		
Electromagnetic compatibility Directive (2004/108/EC	X	X		X	X	X
Low Voltage Directive (2006/95/EC)	X	X		X	X	X
Hot Water Boiler Directive (92/42/EEC)				X		

Table B.3: Overview of European Directives applicable for gas fuels



Electrolyser

ISO 22734-1: 2008 Hydrogen generators using water electrolysis process – Part 1: Industrial and commercial applications. This standard is applicable to hydrogen generators intended for indoor and outdoor commercial and industrial use (non-residential use).

ISO 22734-2: 2011 Hydrogen generators using water electrolysis process – Part 2: Residential applications. This standard is applicable to hydrogen generators intended for indoor and outdoor residential use.

Fuel cell-based micro cogeneration system

IEC 62282 Fuel cell Technologies. This is a series of standards divided into 7 parts, covering stationary, portable, and micro fuel cell power systems.

EN 50465 Gas appliances - Fuel cell gas heating appliances - Fuel cell gas heating appliance of nominal heat input inferior or equal to 70 kW.

ISO/DIS 14687-3 Hydrogen Fuel – Product Specification — Part 3: Proton exchange membrane (PEM) fuel cell applications for stationary appliances. This standard specifies the quality characteristics of hydrogen fuel in order to assure uniformity of the hydrogen product for utilisation in stationary proton exchange membrane (PEM) fuel cell power systems.

Hydrogen burner and boiler

The following natural gas guidelines are relevant as reference during the design of the burner and boiler system:

EN 303-X Heating Boilers. This is a series of standards divided into 7 parts, covering burners of various sorts, including those with forced draft burners.

ISO 23550/1/2 Safety and control devices for gas and/or oil burners and gas and/or oil appliances
IEC 60730-2-5 Ed 4.0: Automatic electrical controls for household and similar use - Part 2-5: Particular requirements for automatic electrical burner control systems.

Gas safety valve, class A, in accordance with EN 161.

Low flashpoint fuels other than hydrogen

Maritime low flashpoint fuels are defined as any fuel with a flashpoint below 60°C. The other low flashpoint fuels than hydrogen normally included are methanol, ethanol, low flashpoint diesel and bio diesel. Currently, the only international regulation at sea covering other low flashpoint liquid fuels than LNG/CNG is the IGF code. Specific regulations for other low flashpoint fuels can be added as new chapters to the Code, but in the meantime, ships installing fuel systems to operate on other types of low flashpoint fuels than LNG/CNG will need to individually demonstrate that their design meet the Code's requirements by the alternative design approach.
To demonstrate this, assessments need to be conducted. These should consider the real properties of the LFL fuels. Key properties are shown in Table B.4.

Properties	MGO	LNG	Methanol	Ethanol	Hydrogen
Physical State	Liquid	Cryogenic liquid	Liquid	Liquid	Cryogenic liquid
Boiling Temperature at 1 bar [°C]	175-650	-165	65	78	-252
Density at 15°C [kg/m3] (LNG as liquid shown at -165°C. Hydrogen at -252 °C)	Max. 900	(-165°C, 1 bar) 448	796	792	1,34 (Gas), 70,8 (Liquid)
Dynamic Viscosity at 40°C [cSt]	03. Mai	-	(at 25°C) 0.6	1.1	-
Lower Heating Value [MJ/kg]	43	(-165°C, 1 bar) 50	20	28	120
Lubricity WSD [µm]	280-400	-	1100	1057	-
Vapour Density air=1	>5	0.55	1.1	1.6	
Flash Point (TCC) [°C]	>60	-175	12	17	
Auto Ignition Temperature [°C]	250 - 500	540	464	363	585
Flammability Limits [by % Vol of Mixture]	0.3 -10	5-15	6 – 36	3.3-19	4-75

Table B.4: Chemical and physical properties of selected fuels[6]. The source of hydrogen properties are from ISOTR15916, which can affect whether the information is fully comparable.

Methyl-/ethyl alcohol fuels (Methanol/Ethanol)
The flashpoint of the methyl-/ethyl alcohol fuels commonly represented by methanol and ethanol are below the minimum flashpoint for marine fuels specified in the International Maritime Organizations (IMO) Safety of Life at Sea Convention (SOLAS). Hence, the IGF Code is applicable for such fuels. Guidelines are currently in draft for the use of methanol and ethanol fuels on ships, for future incorporation in the IGF Code. Methanol and ethanol is already in use on-board ships.

It was the expectation that a draft technical provision for using methyl/ethyl alcohol as fuel in ships were to be further developed during the IMO CCC3 meeting in September 2016, however owing to time constraints, this was not undertaken. Instead it was agreed to consider establishing a working group to finalize measures for:

- Fuel cells regardless of the feed fuel used;
- Ethyl/methyl alcohol; and
- Low-flashpoint oil fuels.

Inclusion of Ethyl/Methyl alcohols as ship fuels as IGF Code fuels has been recently discussed at IMO with technical provisions currently under drafting/finalization. Requirements for Ethyl/Methyl alcohols as fuels for shipping will either become part of the Code or constitute a possible Interim Guidance document /9/, expected by 2022 and with possible amendments to the IGF code in 2024.

Methanol as substance is toxic to humans, but currently not formally classed as toxic, but this may change with the revised IBC code (International Code for the Construction and Equipment of Ships carrying Dangerous Chemicals in Bulk). Due to risks associated with the toxicity, additional considerations during use are required to limit inhalation exposure and skin contact.

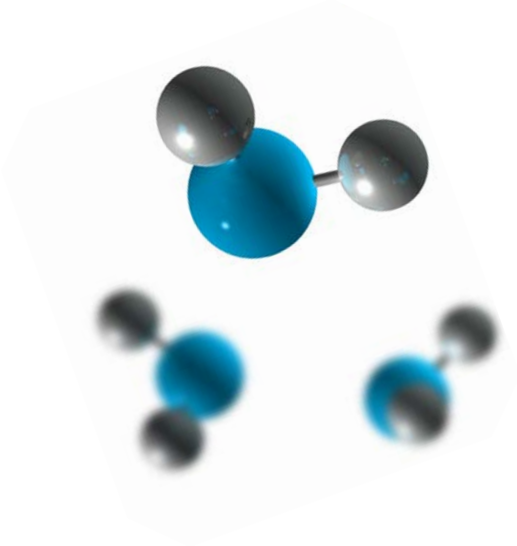
Ethanol is not classified as toxic to humans.

DNV GL have issued Rules for Low Flashpoint Liquid Fuelled Engines (LFL), Pt.6 Ch.2 Sec.6. The scope for additional class notation LFL fuelled includes requirements from the vessel's LFL fuel bunkering connection up to and including the consumers onboard. The rules in this section have requirements for arrangement and location of fuel tanks and all spaces with fuel piping and installations, including requirements for entrances to such spaces. Hazardous areas and spaces due to the fuel installations are defined. Requirements for control, monitoring and safety systems for the fuel installations are included, also additional monitoring requirements for engines and pumps. For tank design and piping detail, design reference is in general made to DNV GL Rules Pt.5 Ch.6. Requirements for manufacture, workmanship and testing are included, mainly referring to details given in Pt.5 Ch.6. DNV GL Class rules include requirements for the filling line to avoid static electricity and evaporation (by reducing free fall to a minimum), ref. DNV GL Class rules Pt.6. Ch.2 Sec.6. The DNV GL Class rules are equal for methanol and ethanol. Bunkering procedures are required to be approved, however, bunkering processes are not part of the scope for this section of the rules.

A separate notation with LFL rules for cargo exists, and the LFL fuelled ship notation includes procedures for loading of cargo.

For more information on Ethyl/Methyl alcohols as fuel for shipping the EMSA Study on the use of Ethyl/Methyl alcohols for Shipping can be consulted /10/.

Low flashpoint diesels and bio diesel
Low flashpoint diesel is currently not part of the terms of reference for the correspondence group of the IGF-code and was not part of the terms of reference of the working group at CCC3. There have been suggestions to revise the 60°C minimum for marine distillates and align it with the minimum flashpoint limit for automotive diesel, which is 52°C in the US and 55°C in Europe. However, MSC 96 which met in May 2016, decided that all issues concerning future regulations of ships using low flashpoint fuels should be addressed in the context of the IGF Code.



Hydrogen storage

ISOTR15916 Basis considerations for the safety of hydrogen systems

ISOTR15916 gives a very useful overview of safety relevant properties and related considerations for hydrogen. Annex C gives a good and very relevant overview of low temperature effects of hydrogen on materials, and the document also suggest suitable material selection criteria including how to consider hydrogen embrittlement.

Compressed gas hydrogen storage

European standards covering pressure vessels used for pressures exceeding 0.5 bar are harmonised with PED. EN 1252-1:1998 on storage tank materials, EN 1797:2001 on gas/material compatibility, and EN 13648 part 1, 2, and 3 on safety devices for protection against excessive pressure are some of the standards related to hydrogen storage.

ISO 15399 Gaseous Hydrogen - Cylinders and tubes for stationary storage. This standard covers cylinders and tubes intended for the stationary storage of gaseous hydrogen of up to a volume of 10 000 l and a pressure of 110 MPa, of seamless metallic or composite construction.

The EIGA code of practice IGC 15/06 covers storage of gaseous hydrogen. IGC 15/06 on gaseous hydrogen, compression, purification, and filling into containers and storage installations at consumer site shall serve as a guide for designers and operators of gaseous hydrogen stations and reflect the best practices currently available. It includes issues such as safety of personnel, operations instructions, protection, and emergency situations.

There are also some relevant American standards/ guidelines, e.g. through ASME and NFPA. US standards are not harmonised with EC directives, but they can still be used for practical purposes as long as there is no conflict with the European regulations.

Liquid hydrogen storage IGF Code/IGC Code

The IGC and IGF codes cover storage of liquefied gas on-board ships. The defined C-tank rules for storage of liquefied gas will in principle cover hydrogen cooled to liquefied form. Additional considerations will however be required due to the properties of hydrogen including the low storage temperatures. ISO/TC 220

This is a standard for Cryogenic vessels developed for land based application. Set of standards in the field of insulated vessels (vacuum or non-vacuum) for the storage and the transport of refrigerated liquefied gases of class 2 of "Recommendations on the Transport of Dangerous Goods - Model regulations - of the United Nations", in particular concerning the design of the vessels and their safety accessories, gas / materials compatibility, insulation performance, the operational requirements of the equipment and accessories.

Detection of leaks

ISO 26142:2010 Hydrogen detection apparatus - Stationary applications. This standard defines the performance requirements and test methods of hydrogen detection apparatus that measure and monitor hydrogen concentrations in stationary applications. The standard cover hydrogen detection apparatus used to achieve the single and/or multilevel safety operations, such as nitrogen purging or ventilation and/or system shut-off corresponding to the hydrogen concentration. The requirements applicable to the overall safety system and the installation requirements are excluded. This standard sets out only the requirements applicable to a product standard for hydrogen detection apparatus, such as precision, response time, stability, measuring range, and selectivity and poisoning. This standard is intended to be used for certification purposes.

Hydrogen piping network

The standard ISO 15649:2001 on piping for petroleum and natural gas industries is used as a guideline also for hydrogen technologies. This standard is applicable to piping within facilities and for packaged equipment, with exclusion of transportation pipelines and associated plant.

The standard EN 13480:2002 is divided in 7 parts specifying the requirements for industrial piping systems and supports made of metallic materials.

2 – BUNKERING

Bunkering requirements cover requirements to the equipment involved in the storage, transfer and transfer monitoring of the fuel in question.

Being a commodity cargo, ship handling of liquid low flashpoint fuels as cargo is a normal and everyday practice. Relevant for the ship, requirements for bunkering liquid LFL's as ship engine fuels are covered through classification rule such as DNV GL Low Flashpoint Fuels (LFL). Gaseous fuels and hydrogen bunkering is not covered by any classification rules.

Some attempts have been seen to develop a marine bunker station for H_2, e.g. in the port of Hamburg in connection with onshore filling stations, but due to local considerations, the plans were not executed.

Another example is the current plans of the Port of San Francisco, looking at the possibility of developing a hydrogen fuelling station which will fill boats and private automobiles. The plans are part of a goal to develop a zero-emissions ferry service in San Francisco Bay.

The set-up of bunkering of hydrogen for the first ship projects would be a process involving many local authorities. As a case-study example, the Norwegian current situation is outlined below.

1. The Norwegian "Forskrift om håndtering av farlig stoff" (code on handling of dangerous goods)[7] is applicable for onshore storage and use of hydrogen, published by the Directorate for Civil Protection and Emergency.

2. The Seveso III Directive (Directive 2012/18/EU) is applicable in case of storage of more than 5 tonnes of hydrogen. The Seveso directive aims at the prevention of major accidents involving dangerous substances, and at limiting the consequences of such accidents should they nevertheless happen, for human health and for the environment.

3. In cases involving more than 5 tons the Norwegian Directorate for Civil Protection (DSB) must be involved in the approval process. This might also be applicable for sites storing smaller quantities of hydrogen, e.g. due to the site placement (subject to DSB assessment). In line with practise from hydrogen filling stations for cars and buses, a risk assessment of the hydrogen production and/storage facility will be required. DSB has developed a relevant guidance document[8]. Evaluation of 3rd party risk and required safety distances will normally be part of this assessment.

BUNKERING OF LIQUID FUELS

In this report the term "bunkering" is used as applied in general Class terminology, i.e. for loading of fuel on-board the vessel. This is different from the term "loading", which in Class terminology means loading of cargo onto the vessel (such as methanol or LNG).

The land side part of the bunkering operation is not part of the IGF-Code. Therefore, other standards for safe bunkering of the relevant fuels are needed to support the implementation of bunkering technology for maritime use. In general, bunkering including bunkering of LNG must be discussed with the port authority, as no uniform approach by different states exists.

To establish a general guideline required to protect the safety of people, property and the environment when developing and operating bunker facilities for low flashpoint fuels, it is helpful to look at guidelines for similar substances. Liquefied Natural Gas (LNG) is a mature fuel. With a low flashpoint and cryogenic temperature, it is a good reference available for hydrogen. Thus, although LNG and hydrogen is different fuels, any new H2 project will lean heavily towards what is being done in LNG business.

Some available regulative documents support bunkering of LNG, notably the ISO/TS 18683 - Guidelines for systems and installations for supply of LNG as fuel to ships, issued Jan 2015. ISO TS 18683 was developed to clarify the aspects of bunkering of LNG fuel in a port environment. The standard gives guidance on the minimum requirements for the design and operation of the LNG bunkering facility, including the interface between the LNG supply facilities and receiving ship. The standard provides requirements and recommendations for operator and crew competency training, for the roles and responsibilities of the ship crew and bunkering personnel during LNG bunkering operations, and the functional requirements for equipment necessary to ensure safe LNG bunkering operations of LNG fuelled ships. The standard is applicable to bunkering of both seagoing and inland trading vessels. It covers LNG bunkering from shore or ship LNG supply facilities, and addresses operations required such as inerting, cooling down, and loading.

The standard ISO 20519 "Ships and marine technology – Specification for bunkering of gas fuelled ships" is under preparation for its final publication. This standard will cover aspects as vessel and transfer system design requirements, emergency release system (breakaway) and emergency shut-down system, hoses, bunkering connections. Although it is a standard for gas fuelled ships, the standard appears to focus on LNG.

Over the last years, several guidelines designed to handle LNG bunkering have been published. While some of these are briefly outlined in the following, the DNV GL Guideline is described in more detail on the next page:

- IACS LNG bunkering Guidelines (No 142)[9] was published in June 2016. The document provides recommendations for the responsibilities, procedures and equipment required for LNG bunkering operations and sets harmonised minimum baseline recommendations for bunkering risk assessment, equipment and operations.
- The Society for Gas as a Marine Fuel (SGMF) has released the "LNG Bunkering – Safety Guidelines" (Feb 2015). The document includes chapters on LNG hazards, safety systems, bunkering and specific safety guidance for ship to ship, shore to ship and truck to ship bunkering.
- The International Association of Ports and Harbors (IAPH) issued check lists for LNG bunkering.
- Bureaus Veritas (BV) has also released LNG Bunkering Guidelines.

In Norway, bunkering of LNG to passenger vessels is subject to approval from the Norwegian Directorate for Civil Protection independent on whether the bunkering is from a permanent facility of from a truck. Requirements have not yet been developed for bunkering of hydrogen or other gaseous low flashpoint fuels as fuel in maritime applications. Liquid hydrogen is commercially available on trucks hence the current practices applied for hydrogen being transported as cargo should be consulted.

At the MSC 96 in May 2016, an agreement was made to invite ISO to develop a standard LNG bunkering safety checklist.

DNV GL Recommended Practice (RP) for bunkering LNG

The DNV GL recommended practice DNV GL-RP-G105 Development and operation of liquefied natural gas bunkering facilities provides guidance to the industry on development, organizational, technical, functional and operational issues in order to ensure global compatibility and secure a high level of safety, integrity and reliability for LNG bunkering facilities.

The functional requirements are based on the international standard ISO/TS 18683 Guideline for systems and installations for supply of LNG as fuel to ships, described in the section above, while the risk assessment is based on ISO/TS 16901 Guidance on performing risk assessment in the design of onshore LNG installations including the ship/shore Interface.

This RP stretches across processes from an early strategy phase through to the operation of an LNG bunkering facility, covering following main topics:

- Development of LNG bunkering facilities
- Risk assessment for LNG bunkering facilities
- Safety management system (SMS) requirements
- Operation of LNG bunkering facilities
- Determination of the quantity and properties of supplied LNG

Figure B.3 illustrates the different types of bunkering scenarios covered by this RP: terminal-to-ship, truck-to-ship and ship-to-ship transfers. In contrast to the ISO/TS 18683 the practices presented may, with special considerations, also be used for other bunkering scenarios, like the use of portable tanks referred to as "cassette bunkering". As for the vessels this RP is applicable to IMO regulations, both IGC and IGF code, as well as inland shipping.

Regarding simultaneous operations on land and sea (e.g. cargo handling, passenger operations, ship traffic close to the bunkering location, etc.), the RP addresses the risk management requirements and discusses the methodologies available.

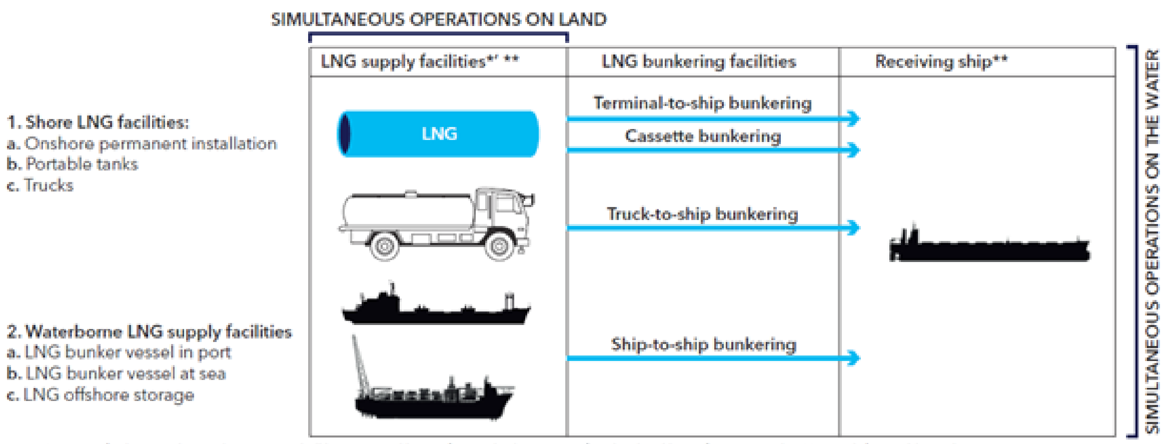
The scope of application covers at least three organizations involved in the LNG bunkering, the organization

- supplying the LNG to the receiving vessel (bunker operator),
- managing the receiving vessel (ship manager) and
- providing the regulatory regime (port and/or national authority).

The RP contains the note that the operator of the terminal where the bunkering takes place may also be involved in the LNG bunkering, depending on local conditions. The terminal operator is mainly involved in the integration of the facilities safety management systems.

Regulatory requirements and the RP represent the minimum obligations the LNG bunkering operations should meet. The operator of the bunkering facility (in agreement with other stakeholders) may decide to build and operate to meet higher standards with regard to safety, reliability or environmental protection. In the case of any conflict between regulatory requirements and this RP, the former shall prevail.

For the vessels involved the RP assumes that the bunker vessels are designed and build according to the IGC Code and applicable Class Rules. Receiving vessels shall be designed and build according to the IGF Code and applicable Class Rules and/or equivalent codes for inland shipping. It is assumed that inland vessels that are not covered by IMO will also be designed in accordance with local and equivalent regulations.



* LNG storage facilities, trailers and containers shall be governed by secific standards or national and/or local laws. If necessary, this RP may defines additional requirements
** Supplying and receiving vessels shall be governed by specific standards

Figure B.3: Bunkering operations covered by DNV GL-RP-G105

Development of liquefied natural gas bunkering facilities
The RP contains guidance on technical requirements for the planning, design and development of LNG bunkering facilities starting with the characterization of the responsibilities of the individual parties involved in the relevant bunkering configuration. An important point is a risk assessment, which depending on the bunkering scenario is categorized into a standard and a non-standard assessment. To ensure the safety the RP describes in detail the selection, implementation and evaluation on both standards and a bow-tie model.

Thereafter the RP describes the technical requirements of components and emergency systems which are used before, during and after the bunkering process and how these rely on different international rules and standards.

Safety Management System
According to ISO/TS 18683, bunkering operations shall be developed and conducted under the control of a recognized safety management system (SMS). The RP contains recommended practices that may be used by the parties involved in LNG bunkering for developing and implementing an adequate safety management system. More specifically, the RP identifies the "common ground" for the different stakeholders involved to ensure the interfaces are dealt with properly.

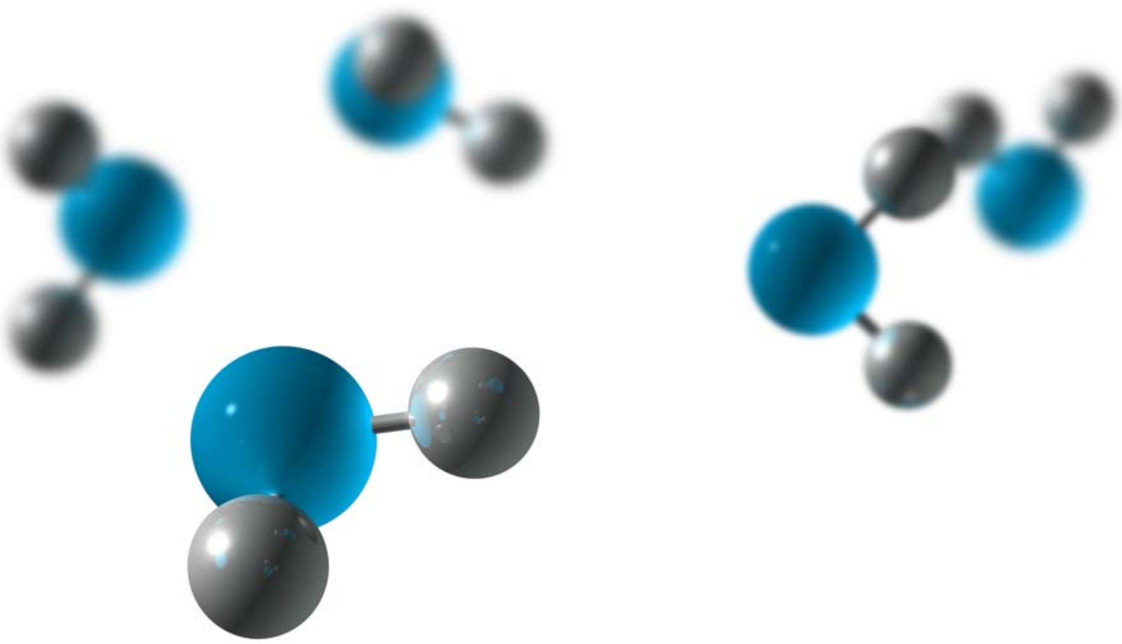
Generally, the SMS will be implemented as part of the involved organizations' operational procedures. The RP provides background information regarding the common safety management system principles and safety management systems in general. Recommendations specific to the SMS of parties involved in LNG bunkering operations are also addressed and discussed.

Operation of liquefied natural gas bunkering facilities
The RP also contains guidance on the operation of LNG bunkering facilities.

A high level of safety, integrity and reliability in the operation of LNG bunkering facilities shall be safeguarded and given high priority by all parties involved.

On operation of LNG bunkering facilities, the RP provides both responsibilities of the involved participants and descriptions of the technical requirements and the process of the bunkering.

Determination of liquefied natural gas quantity and properties
The RP includes recommendations that can be used by the parties involved in LNG bunkering to develop and implement a measurement system for determining the quantity and essential properties, referred to as the quality, of the transferred LNG. This system ensures transparency in billing and that the use of LNG as a fuel is safe and fit for purpose. During bunkering, the energy content and essential properties of the transferred LNG shall be determined. More specifically, the LNG energy content shall be the basis for the billing (custody transfer), while the properties determine the LNG's fitness for purpose. The receiving ship shall be able to rely on the specification of fuel quality for safe use.



BUNKERING OF GASEOUS FUELS

The land side part of the bunkering operation is not part of the IGF-Code. Therefore, other standards for safe bunkering of the relevant fuels are needed to support the implementation of bunkering technology for maritime use. The ships side of the bunkering operation (from the bunkering flange on the ship side) is covered by the IGF-Code.

For bunkering of compressed hydrogen gas, experience and standards used in land based applications will be relevant. A starting point will be the currently available systems for filling of hydrogen on hydrogen cars, trucks and buses. Upscaling issues will need to be addressed, considering the temperature requirements for safe hydrogen refuelling as too high temperatures in the receiving tanks must be avoided.

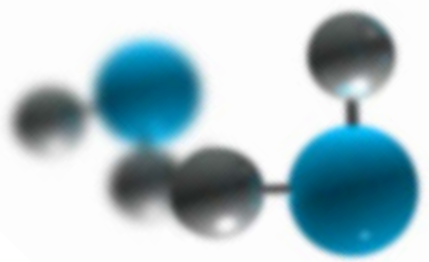
SAE J2601 is an industry standard on the protocol for fuelling road vehicles developed by SAE (Society of Automotive Engineers). It gives tables of ramp-up rate of the tank pressure during fuel transfer but its target is limited to transfers of relatively small amounts. It appears to be the only published fuelling protocol for fuelling of hydrogen vehicles up to 700°700 bar tanks[10]. The SAE J2602 will be a good starting point, but current ongoing standardisation initiatives should also be consulted.

Other relevant standards are:

ISO 17268:2012 Gaseous hydrogen land vehicle refuelling connection devices
This standard defines the design, safety and operation characteristics of gaseous hydrogen land vehicle (GHLV) refueling connectors consisting of, as applicable, a receptacle and a protective cap (mounted on vehicle), and a nozzle. It applies to refueling connectors which have working pressures of 110 bar, 250 bar, 350 bar and 700 bar.

ISO/TS 19880-1:2016 Gaseous hydrogen – Fuelling stations – Part 1: General requirements
This standard recommends the minimum design characteristics for safety and, where appropriate, for performance of public and non-public fuelling stations that dispense gaseous hydrogen to light duty land vehicles (e.g. Fuel cell Electric Vehicles). The recommendations are in addition to applicable national regulations and codes, which can prohibit certain aspects of this stanard. ISO/TS 19880 is applicable to fuelling for light duty hydrogen land vehicles, but it can also be used as guidance for fuelling buses, trams, motorcycles and fork-lift truck applications, with hydrogen storage capacities outside of current published fuelling protocol standards, such as SAE J2601.

It provides guidance on elements of a fuelling station as hydrogen production/delivery system, delivery of hydrogen by pipeline, liquid hydrogen storage, hydrogen purification systems, as applicable and gaseous hydrogen dispensers.



3 – REGULATORY GAPS

INTRODUCTION

The objective of this chapter is to identify and describe existing gaps. In cases where the gaps are not yet solved, and no concrete actions to deal with the gaps are identified, work has been undertaken to attempt to suggest possible actions to deal with the identified gaps. In line with what has been done in previous studies, the gaps have been classified under three categories:

Legal Gap:
Legal gaps are gaps for the use of fuel cells and associated fuels and the development fuel infrastructure that severely limit or even block the use of fuel cells for ships. These gaps are typically gaps in legislation and regulations.

Harmonization Gap:
Harmonization gaps are gaps in the EU-wide harmonization of methods, rules, guidelines, provisions and safety aspects for fuel cells and associated fuels. Examples are bunkering procedures.

Knowledge Gap:
Specific knowledge gaps are points where more research is needed in the implementation and development of fuel cells for maritime use, and in relation to associated fuels. Recommendations formulated for these gaps are suggestions for improvement, as well as R&D and product development.

In the following subsections, the gaps are presented and sorted according to their key area of relevance. Therefore, the gaps have been categorized according to the general main system components required for a fuel cell system on-board a ship. The bunkering of the fuel, the on-board fuel storage, and the fuel cell systems with its main sub-components are considered in separate sections.

Another recent study evaluated gaps for completing an EU-wide framework for marine LNG distribution, bunkering and use /11/. Many of the gaps and recommendations identified in /11/ will also be applicable for fuel cell installations including relevant fuels. The identification and assessments related to these LNG specific gaps are not repeated in this report. For exemplifying however, the following list provides examples of gaps identified in /11/ for LNG that are considered applicable for gases and other low flashpoint fuels. The list is not complete. (Reference in parenthesis is to the Gap numbering in /11/):

- Develop a European standard for small scale bunkering stations (EMSA Gap 8)
- Develop an EU harmonized approach for risk assessment (including criteria) for non-Seveso small scale establishments and activities (EMSA Gap 9)
- The concept of safety zones and the approach to define the limits should be accounted for in bunker procedures (EMSA Gap 9.3a).
- Specify harmonized approach to determine internal safety distances (separation distances) for small scale installations. The approach should be implemented or applied in relevant guidelines that specify minimum requirement for the operation and design (EMSA Gap 9.3b).
- Guarantee that crew training requirements for these fuels, in particular hydrogen, exist for use in domestic waters (for all EU inland waterways) (EMSA Gap 10.1).
- Establish an approach for fuel slip management (in particular hydrogen), i.e. considering boil-off gas, vapour management and emergency venting (EMSA Gap 16).
- Draft a list of rules, requirements, criteria and conditions that can be applied in permitting and supervision of small scale installations (EMSA Gap 20-2).
- Initiate a process to ensure early involvement and cooperation between project developers, local and regional authorities, port authorities, NGO's, fire brigades and other stakeholders to get an idea on the suitability of locations for onshore bunkering facilities (particularly relevant for hydrogen), to guarantee a smooth permitting process and to identify potential showstoppers in an early stage (EMSA Gap 21).

Due to the very central role of the IGF code, the main gaps associated with the status and foreseen development of this code has been summarized in a separate subsection below, see page 75.

SUMMARY OF IDENTIFIED GAPS

Table B.5 provides an overview of the main gaps identified. The gaps are further detailed in the subsequent sections.

High level Gap Description	Recommendation/Assessment	Gap Category*	Ref. to report
IGF Code:			
- use of fuel cells - use of other low flashpoint fuels than LNG/CNG - bunkering of gaseous H_2, other low flashpoint fuels and LH_2	Further development of IGF code needed. Detailed safety studies. Use existing standards for non-maritime applications as input.	L, H, K	page 75
Bunkering:			
Rules for bunkering of liquid hydrogen	Review of applicable land based standards. Risk studies and a qualification process to develop rules and bunkering procedures.	L, H, K	page 76
Gaseous hydrogen	Review of applicable land based standards. Risk studies and a qualification process to develop bunkering procedures.	L, H, K	page 76
Low Flashpoint Liquids	Bunkering procedures for LFL's Safety zones for gas vapour from tanks	L, H, K	page 77
On-board storage:			
Storage of compressed hydrogen	Qualification of pressure tanks for maritime use with compressed hydrogen gas. Safety studies considering hydrogen pressure tanks and requirements for safe solutions. Development of provisions for possible high pressure storage technologies in enclosed areas.	L, H, K	page 78
Storage of liquid hydrogen	Possible storage related failure modes need to be understood, and land based solutions adjusted if necessary for safe application.	K	page 79
Fuel cell System:			
Safe handling of hydrogen releases	Review of and update of fuel cell rules and regulations. Risk studies to improve understanding of possible safety critical scenarios including fire and explosion to recommend risk controlling measures.	L, H, K	page 79
Ventilation requirements	The fuel specific properties must be considered. Relevant and realistic hydrogen dispersion simulations needed to evaluate and/or update ventilation requirements.	L, H, K	page 80
New arrangement designs	Need for improved understanding of system design issues, new technology challenge existing regulations	L, K	page 80
Piping to fuel cell system	Knowledge and safety assessments needed to identify needs to adjust LNG requirements for the use of LH.	L, K	page 81
Reforming of primary fuel	Reformer safety issues should be explored and documented	L, K	page 81
Ship life phases:			
Best practices/Codes for hydrogen, LFL fuels and fuel cell installations	Procedures should be developed for commissioning, docking, maintenance to reflect the properties of hydrogen and other LFL fuels.	L, H	page 81
Fuel specific:			
Hydrogen	Comprehensive safety studies considering hydrogen specific properties, behaviour and conditions needed for the use of hydrogen in shipping applications	L, K	page 82

* L: Legal, H: Harmonisation, K: Knowledge

Table B.5: Gap table – high level summary of identified gaps

IGF CODE – MAIN GAPS

The IGF Code entered into force on 1 January 2017. It is separated into two kinds of chapters: fuel specific and fuel independent chapters.

The IGF Code is mandatory for all gases and other low flashpoint fuels. However, for the time being, the fuel specific part only contains detailed requirements for natural gas (LNG or CNG) as fuel. To use natural gas in fuel cells, reforming of the gas is needed in smaller or greater extent depending on type of fuel cell. The reformer convert natural gas into a hydrogen rich gas which can be used by the fuel cell. To establish fuels cells in the maritime industry, the IGF-Code will also need to be developed to cover other fuels like low flashpoint diesel and hydrogen, which are potential fuels for a fuel cell application.

Internal combustion engines, boilers and gas turbines are included as consumers. For other gases and low flashpoint fuels, the IGF Code Part A requires the alternative design method in accordance with SOLAS Regulation II-1/55 to be used demonstrating an equivalent level of safety.

A phase 2 development of the IGF Code initiated by IMO and the CCC subcommittee is currently developing technical provisions for methyl-/ethyl- alcohols as fuel and fuel cells.

Fuel cells will be a new part E. This is aimed to be included in the IGF Code at its first revision, which is due to take place within the 4-year cycle for SOLAS revisions. During the development of these technical provisions it should be considered that the fuel cells power systems differ depended on the used technology, e.g. PEM or SOFC. The technical provisions under development should be technology independent but cover the safety relevant aspects of a fuel cell application. The IGF-Code should be open for new developments within this fast-developing segment of fuel cells.

The main gaps related to the IGF code are summarised in the subsections below. The specific gaps related to bunkering are covered in chapter "Bunkering" on the next page and the specific gaps related to the fuel cell system are covered on page 79.

IGF-Code GAP: Use of other LFL fuels than LNG/CNG

Detailed and prescriptive requirements for storage and use of hydrogen and low flashpoint diesel (including bio diesel) as fuel in ships are missing. Integration into IGF Code is needed.

Legal
Use of LFL fuels is regulated by the IGF code from Jan 2017, but detailed requirements e.g. for hydrogen and low flashpoint diesel storage and use are lacking. Development is ongoing for detailed provisions for methyl/ethyl alcohols, but not for hydrogen or low flashpoint diesels. For the latter, only the alternative design approach exists.

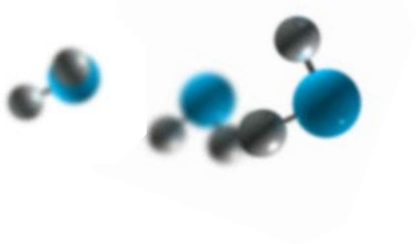
Knowledge
Detailed safety studies should be undertaken to provide input to the required development.

GAP: Use of fuel cells in ships

Finish the development under IGF code for detailed and prescriptive requirements for fuel cells as power generating equipment in ships.

Legal
Use of fuel cells is not regulated. Continued work agreed under the IGF code working group. This includes agreeing on the definition of the fuel cell System, the elements to be included within the system boundaries and the requirements for fuel cell installations.

Knowledge
Detailed safety studies needed for fuel cell room and safety system design.



BUNKERING

In general, onshore facilities including interfaces to ship systems (including bunkering of LNG) must be discussed with the port authority, as no uniform approach by different states exists. Local authorities may require a QRA (Risk Assessment) as part of their approval.

GAP: Bunkering of liquid hydrogen (Legal, Harmonisation, Knowledge)

Legal

Bunkering rules for liquid hydrogen do not exist. Based on this, the ship side of the bunkering process will have to be approved following the alternative design approach as specified in IGF code. Current procedures for bunkering of LNG is based on cryogenic insulation to protect the ship steel from spills and leakages in the bunkering station and double piping when going inside the vessel. This, together with experiences for bunkering of liquid hydrogen onshore would form a knowledge basis for establishing the first requirements for bunkering of liquid hydrogen to a ship. It is uncertain to what degree the solutions developed for LNG will be feasible and applicable for liquid hydrogen. It is possible that N2 filling of voids/double pipes may be required or be necessary. A water curtain on the ship-side is required for bunkering of LNG according to IGF, and this is likely to be expected for LH as well.

Harmonisation

There is a need to develop bunkering procedures for liquid hydrogen.

Knowledge

Ships have more dynamic loads compared to land applications. Ships will require certain ductility (need certain margins) for the materials applied. It appears to be new territory to establish the most appropriate ways to test the ductility for the low temperatures of liquid hydrogen. Applicable land based industry standards and applications should be reviewed and be used as input. Then a tailored qualification process can be undertaken focusing on the additional challenges for low temperature use on ships. As an example, ship based applications might require thicker materials. The general approach for approval for use on board ships requires testing for each ship to ensure that the material specification is correct. Use down to -165°C has been validated, but there is very limited experience for the much lower temperatures required for liquid hydrogen storage. Material certification at cryogenic temperatures requires testing of material at relevant design temperature including a margin to verify the materials' properties. For design temperatures equal to liquid hydrogen, testing procedures according to standard certification may be challenging and require further considerations.

Gas dispersion and safety analyses will be needed to build knowledge on liquid hydrogen leak behaviour.

Knowledge whether the very low temperatures required for liquid hydrogen bunkering will demand different solutions and materials than LNG (see also harmonization above) is therefore needed. It is uncertain to what degree the very low bunkering temperatures will result in higher susceptibility for unwanted temperature/pressure deviations in the bunkering line. Another issue that call for improved knowledge is the potential vapor dispersion in case of accidental LH2 release.

GAP: Bunkering of compressed gaseous hydrogen (Legal, Harmonisation, Knowledge)

Legal / Harmonization

The land side of the bunkering process is not part of the IGF-Code. There is some experience on bunkering of gaseous fuels to ship applications and there is also some limited experience with bunkering of small hydrogen gas volumes. In addition, current standards and practices from land based applications can provide relevant input, and experiences from use of natural gas will be useful, but a need for regulations as well as harmonization for maritime use is anticipated.

There is a need to develop bunkering procedures for bunkering of compressed gaseous hydrogen.

Knowledge

Issues related to upscaling she systems currently available for filling of hydrogen cars and trucks/buses need to be explored and the technology need to be qualified for larger filling volumes and relevant marine impacts. Further risk studies (including evaluation of gas leaks, gas dispersion, and relevant consequences) and a qualification process to ensure development of applicable requirements are needed to provide input to standardization work.

GAP: Bunkering of LFL fuels (Legal, Harmonisation, Knowledge)

Legal

According to the IGF-Code, it is not permitted to release flammable gases to the surroundings during bunkering. For cargo vessels, loading methanol as cargo, methanol gas will usually be formed and can be released to the atmosphere through the vent mast. The solution used for previous methanol fuel projects in ships has been to arrange a vapour return line to the filling truck. In cases where vapour return is not feasible, the risks involved should be identified and evaluated through the alternative design approach.

For passenger vessels, the potential release of flammable and toxic gases will also need to consider safety zones and potential risk for passengers.

Harmonisation

For LNG bunkering, gas emissions are not allowed during the bunkering operation. This is handled by accumulation of pressure in pressurised tanks or other solutions for atmospheric tanks.

If methanol is bunkered without vapour return line, a full discharge of tank vapors through the PV valves will take place. Hence it must be handled differently compared to LNG.

Based on current DNV GL Rules for low flashpoint fuels, which in this case have the same requirements as LFL cargo rules, bunkering of methanol and ethanol demands a 10 meter hazardous zone from the outlet of the PV valve. If this were to be changed for LFL fuels, calculations and modelling would be needed to support any proposal.

There is a need to develop bunkering procedures for bunkering of LFL fuels.

Knowledge

There is relevant experience for bunkering of methanol, e.g. for supply vessels. However, most of the experience is for methanol loaded as cargo, which is different from bunkering of a fuel.

There is a need to assess the methanol specific safety aspects for bunkering operations. This should be used to provide input to evaluate requirements for safety distances and hazardous zones. Methanol is heavier than air and a methanol release will behave different compared to LNG. Methanol will leak as a liquid, but there might be some evaporation. It is also known that methanol can catch fire in a mixture with water or air. The Technical Research Institute of Sweden currently undertakes R&D related to these topics and has recently informed the ongoing IMO correspondence group for phase 2 development of the IGF code about their work.

Methanol has potential issues regarding toxicity, and LNG has additional challenges as a cryogenic liquid. Thus, for passenger ships in particular, there is a need to evaluate possible consequences including the need for safety zones.

More knowledge is needed to address the risks and identify safe means of handling. It is uncertain whether e.g. the LFL vapor could be handled safely and efficiently with a vapor return system, or whether burning of the vapor is feasible.

ON-BOARD STORAGE

GAP: Qualification is needed of pressure tanks with compressed hydrogen gas for maritime use (Legal, Harmonisation, Knowledge)

Legal

The possible allowed locations of pressure tanks are still an open issue. To date there have been limitations regarding such storage in enclosed areas (below deck areas). Different solutions have been seen in the past. As an example, the Alsterwasser in Hamburg was approved with pressurized hydrogen tanks below deck. This approval was based on a previous GL guideline (formally not rules) /8/, which now can only be used on legacy GL classed ships. The guideline did not require FMEA, however FMEA is required according to the IGF code. The design criteria were prescriptive. The current DNV GL FC rules have kept the principles from the first issue of the DNV fuel cell Rules and the prescriptive requirements for ship design, piping fuel storage from the GL guideline. The current DNV GL fuel cell rules opens for storage in enclosed spaces if certain conditions are satisfied. This will require a case by case assessment. The rules are developed with hydrogen in mind, but do not contain specific provisions for high pressure hydrogen storage technologies.

Harmonisation

Further qualification activities are needed to qualify pressure tanks for maritime use with compressed hydrogen gas (CGH2). Existing pressure vessel rules as well as rules for Compressed Natural Gas will apply and provide valuable input. This includes the Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR) and the European Transportable Pressure Equipment Directive (1999/36/EC – "TPED"), and the standards mentioned on page 63 Pressure tanks approved for use on roads will not automatically be approved for use on ships. There are different standards with different approval conditions that could be used as basis. Further work is therefore required to develop harmonized requirements for maritime use of compressed hydrogen gas.

Knowledge

More documentation providing an improved understanding regarding safety related behavior of hydrogen is needed. This includes safety studies considering hydrogen leakage and pressure tank requirements to establish the conditions required to consider these sufficiently safe. One example is ventilation requirements. The IGF code requires equivalent safety. This can be challenging to demonstrate. In the process required, it will be important to utilize existing experiences gained from industrial use and use of hydrogen as an energy carrier in the land based transport sector (for example for cars and buses).

Considering that hydrogen can behave different from other gases including natural gas, it is important to include H2 properties in the safety assessments. Important and relevant properties include the low ignition energy and wide flammability range. Will it be possible to keep H2 concentrations below the flammable limit in case of a leak, and if not how should the situation be handled? Risk reducing measures will be important to evaluate. There are many possible measures and their efficiency/effect should be evaluated, one example is the possibility to use inert gas. Another whether existing equipment ex criteria are sufficient, and whether risk assessments are needed to validate and/or adjust existing criteria.

A range of solution including different materials to contain pressurized hydrogen is available and new materials are under development and coming into the market. For all these, maritime experience is lacking. Similarly as for cars and buses, weight is also an issue for maritime applications, hence making low weight solutions attractive. Hydrogen fuel cell cars are currently available with storage tank pressure of up to 700 bar (e.g. Toyoata Mirai and Hyundai ix35 FCEV). For such applications traditional and rather heavy steel tanks will typically be less attractive than light weight composite tanks.

In this context it is important to understand the possible interactions between hydrogen and different materials. Possible challenges that need considered include how the materials endure long term exposure from relevant marine conditions (e.g. weather impacts, temperature ranges, stresses, corrosion). Pressure tanks also have to be designed for cycling within defined pressure ranges to ensure durability of interior liners.

GAP: Lack of understanding of failure modes for liquid hydrogen tanks (knowledge)

Knowledge
For storage of hydrogen in the liquid form, there is uncertainty regarding possible failure modes, for example consequences of losing vacuum insulation of the liquid storage tanks when used in a ship application. Further understanding and knowledge of possible failure modes is to be documented.

Ships have more dynamic loads compared to land applications. Ships will require certain ductility (need certain margins) for the materials applied. It appears to be new territory to establish the most appropriate ways to test the ductility for the low temperatures of liquid hydrogen. Applicable land based industry standards and applications should be reviewed and be used as input. Then a tailored qualification process can be undertaken focusing on the additional challenges for low temperature use on ships. As an example, ship based applications might require thicker materials. The general approach for approval for use on board ships requires testing for each ship to ensure that the material specification is correct. Use down to -165°C has been validated, but there is very limited experience for the much lower temperatures required for liquid hydrogen storage.

FUEL CELL SYSTEM

GAP: Safety aspects concerning release of hydrogen within the fuel cell system (Legal, Harmonisation, Knowledge)

Legal
Currently, equipment that are not explosion protected may be accepted in a fuel cell room provided that the ventilation rate is sufficient to avoid gas concentrations in the flammable range in all leakage scenarios. There is uncertainty whether this is the best solution and further evaluation is needed. These evaluations need to consider the relevant safety aspects.

Use of hydrogen fuel cells in shipping may be in a hybrid configuration together with batteries. In this case both the fuel cell rules and the battery rules will apply, possibly with overlaps or interference. The current Classification battery rules might be of relevance also in the context of fuel cell installations. A review of the battery rules in the context of hydrogen and fuel cells will therefore be relevant; to harmonize safety requirements and to gather synergies and learning points.

Knowledge
More knowledge is needed to close the current legal gaps. Further knowledge of hydrogen behavior and possible safety critical scenarios including fire and explosion behavior is needed to recommend the most efficient risk controlling measures.

H2 ignition and explosion scenarios in the case of H2 and other low flashpoint fuel leakages are an area requiring more knowledge. This includes, but is not limited to, issues such as fuel cell compartment interior design, ventilation and flow dynamics inside the fuel cell compartment, double wall piping forced ventilation systems, ignition sources such as static electricity from high pressure gas forced through material cracks etc.

A risk based approach would be useful in order to develop an understanding of the total risk picture. A risk based approach can be used to identify possible leak sources/locations and sizes as well as possible causes of ignition. Together with simulations of gas releases, such an approach can help highlight the effects of measures as gas detection, shutdown (ESD), shutdown times, location of possible ignition sources and more.

Simulations of relevant releases of flammable gas in a FC room context can improve knowledge and understanding of the relevant safety aspects. As an example, such simulations can be used to assess the dispersion of flammable gas and the effect of ventilation in the room. This can provide an understanding regarding whether ventilation can lead to maintaining hydrogen concentrations below flammability limits in case of leak from the FC system.

To improve calibration and validation of current simulations tools, larger scale experiments of relevant dispersion/fire/explosion scenarios are needed. In the context of this project, the case considered most relevant is to evaluate the FC room and its relevant ventilation conditions. Similar large scale experiments have previously been undertaken for LNG at Spadeadam test site in the UK. There is a need to develop similar knowledge for hydrogen.

Structural strength of walls and decks to withstand explosions may be requested demonstrated, or alternatively; explosion hatches may be required. Calculation models for structural response to hydrogen explosions need validating experiments to improve predicting capabilities. Solutions regarding possible handling of explosion overpressures need to be explored. Such solutions could include pressure release panels, in which case technology for such panel design and in maritime environments are needed.

GAP: Ventilation requirements for fuel cell rooms should be validated (Legal, Harmonisation, Knowledge)

Legal
For LNG, the ventilation requirement is said to be 30 air changes per hour for the room. Hydrogen has different properties to LNG related to flammability and how easily hydrogen might ignite. Due to the differences in properties and behavior between LNG and hydrogen, the most appropriate requirements for safe handling of hydrogen might be different for the same for LNG. The safety related basis for this requirement therefore need further validation.

Knowledge
It appears that the 30 air change per hour criteria is not based on calculations of real scenarios; hence it is not scientifically based. More knowledge is therefore required on how different ventilation conditions (air change per hour and possibly varying ventilation conditions in a fuel cell room) might affect the likelihood of ignition, fire and explosion in case of leakage of a flammable gas.

The properties of hydrogen are in many ways different to natural gas. Hydrogen has a wider range of flammability, it is easier to ignite and it is lighter. Ventilation is considered a potentially key main barrier towards unsafe situations, but the knowledge regarding the efficiency of ventilation to prevent unwanted hydrogen incidents are lacking.

Due to the properties of hydrogen, efficient detection and possible shutdown by ESD (emergency shutdown) will be important in order to minimize the leak volumes of flammable gas. The safety system needs to be efficient to minimize the risk for ignition/fire/explosions. Efficient ventilation can reduce the concentration of flammable gas, but unless carefully considered, it could also dilute flammable gases to a more ignitable concentration range. Careful risk based evaluations are therefore critical to obtain an optimal design. Vent panels can be a solution to prevent worst case consequences of explosions.

Many experiments with hydrogen are performed in research projects, however due to the many different properties, it is recommended to perform dedicated experiments in a realistic fuel cell room, and/or simulations.

GAP: Fuel cells open for new arrangement and vessel design solutions (Knowledge / Legal)

New design issues and system solutions that accompany fuel cells and novel fuels challenge the existing rules and regulations. The below is a non-complete list.

Knowledge / Legal
The modularization offered by fuel cells offer several interesting vessel design aspects, such as improved safe-return-to-port solutions through power autonomous zones. The decentralization of power will also likely minimize the energy content of fuel leakages from any given system and thus helps limiting the consequences of a leakage scenario. However, decentralization of power systems challenges the current IMO /SOLAS regulations which in principle require centralized arrangements of power generation systems.

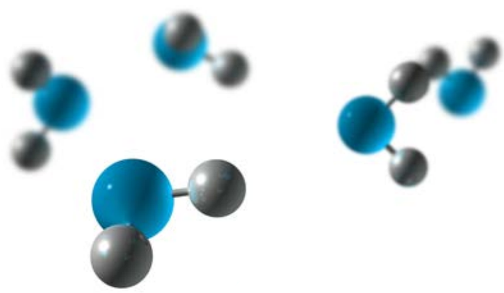
Some FC suppliers request classification societies to develop system type approval schemes due the modular nature of some FC's. Standards for interfaces and integration would then be an issue, as well as international agreed definition of system interfaces and compartments and zones in relation to fuel cells (what is included in the fuel cell delivery, what is vessel interior).

Fuel cell installation guidelines will need to be developed.

Documentation of total efficiency, operational functionality and reliability of combined and hybrid systems are much asked for in the industry, such as different combinations of FC's with waste heat recovery units and batteries, and in combination with incumbent technology. Demonstration project is suggested or similar manner of documentation, such as through modelling & simulation.

Prescriptive requirements for fuel cells which open for different technical solutions without need for separate safety cases is much wanted.

Development of more compact fuel cell systems in cooperation with regulative developments are much wanted, to accelerate and ease the development of fuel cell systems thereby increasing rate of technology uptake in the industry.



GAP: Piping to fuel cell System (Legal, Knowledge)

Knowledge basis for requirements for handling of LH_2 in pipes is needed.

Legal / Knowledge
Double walled vacuum insulated pipes are currently being applied for LNG. A similar solution could be feasible for liquid hydrogen, but this would need to be validated. It is uncertain whether the solution applied for LNG will provide sufficient cooling to avoid unwanted evaporation of liquid hydrogen in the pipes. It is anticipated that some liquid hydrogen will evaporate, and the system need to be designed to handle this safely. Alternatives including re-liquefaction or other handling needs should be considered.

GAP: Fuel cell – Reforming of primary fuel

Legal / Knowledge
In general, more knowledge regarding the requirements for the fuel cell reformers are needed; way of operation, supporting fluid requirements including water with possibility for dissolved H2, heat balances etc.

If the reformer should experience loss of fuel flow, the reformer temperature will rise due to missing cooling effect from fuel conversion, and this may possibly cause further damages to the reformer (fire hazard). The effect of this to the reformer is not known. Possibly, requirements may be placed on the reformer that loss of fuel shall not lead to unsafe situations.

DIFFERENT LIFE PHASES OF A SHIP (LEGAL, HARMONISATION)

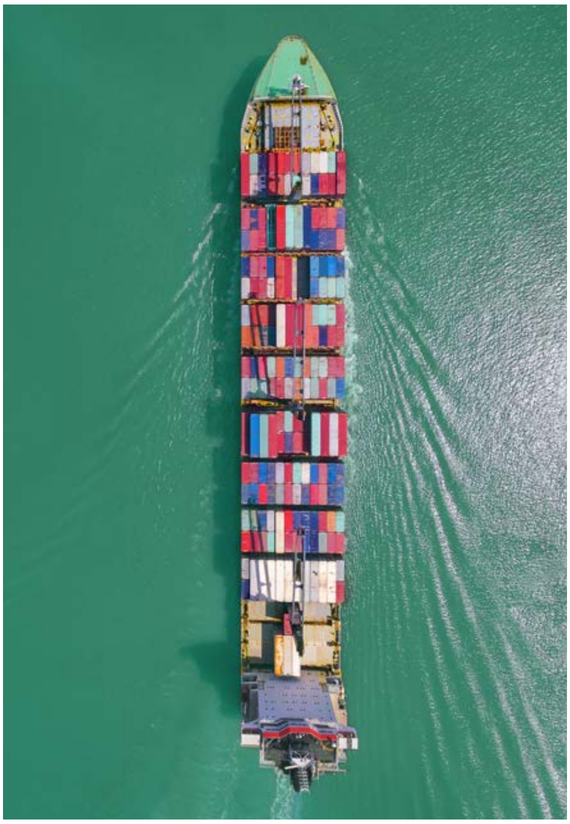
The phases of a ships life may be divided into:

- New-build/retrofit
- Commissioning and testing
- Operation including maintenance
- Docking
- Scrapping

Legal / Harmonisation
Generally, there is seen a need to establish best practices /codes or similar regarding safe handling of onboard hydrogen and fuel cell installations in all the phases listed above. Issues include, but are not limited to:

- Gas tanks may need to be emptied during docking
- Liquefied hydrogen tanks may need to be specially considered regarding pressure build up during docking
- Requirements for safety and procedures in relation to maintenance on parts of the systems, where gas is still present in other parts of the system
- Recommended practices/ procedures for handling H_2 and other LFL equipment should be developed
- Specially developed safety training may be required

Considering that even if the fuel used for the fuel cell is not hydrogen, ultimately after reforming and through the fuel cell electrochemical reaction, hydrogen is either a working medium, or a by-product of the process. Thus, the issue of hydrogen safety is present also there in form of possible leakages from piping, fixture and the cell itself.



SAFETY ISSUES FOR FUEL FOR FUEL CELLS (LEGAL, KNOWLEDGE)

GAP: Insufficient understanding of hydrogen safety aspects for code development (Legal, Knowledge)

In the future hydrogen and other gases are foreseen to be covered by the DNV GL gas fuelled rules. Currently there is a gap as these rules don't include hydrogen specific requirements. The following summarize other knowledge gaps related to hydrogen as fuel.

Knowledge / Legal

Further studies are required to develop safety related understanding of properties and conditions affecting safety of hydrogen in shipping applications. This includes validation of current models used to study hydrogen behavior and the study assumptions. The results should be used as input to development of relevant codes, e.g. IGF code and Class rules. The following gives examples of needed activities:

- Relevant leakage scenarios need to be determined, preferably based on experience data and hazard/risk based assessments. Assessments can include consideration of likelihood of gas detection, valve (ESD) shutdown etc. Input to be considered includes typical volumes of interiors of fuel cells, pipe volumes, ESD valve locations, pipe pressures etc. Experience data and practices from other hydrogen applications should be examined for relevance e.g. data relating to leak frequencies and ignition probabilities.
- Permeability of hydrogen and possible consequences need to be considered in specifications of permitted materials.
- Leak detection, fire and explosion risk including differences between hydrogen and natural gas behavior (e.g. higher buoyancy, range of flammability).
- Hydrogen leaks in enclosed spaces. Simulation of different ventilation conditions (preferably with validated CFD codes) to determine how risk for ignition and explosive atmospheres can be minimized. Simulations to determine design scenarios regarding fire and explosion. Improve understanding of hydrogen dispersion and fire behavior compared to other gases (e.g. effects of high flame temperature and radiation, invisible flame). Use this as input to evaluate design and risk reduction measures. With improved understanding and models, practical guidelines and standards can be obtained. These can cover design of ventilation systems, room and ceiling shapes, explosion release vent panel dynamics and design, room volumes impact on risk, gas detection strategies and design, leak control with ESD and pressure relief philosophy, active and passive fire protection philosophy and design, as well as emergency response and extinguishing strategies.
- There is uncertainty regarding whether hydrogen in double piping should be a recommended or required safety provision for hydrogen in enclosed spaces, or if double piping might add a safety risk by confining hydrogen leaks and may be reducing the possibility for quick dilution and lowering of H2 concentration. Due to the risk of ignition even without active ignition sources, it must be considered if only nitrogen filled double piping can be accepted (and not ventilated double piping as used for natural gas).
- Hydrogen leaks outdoors; determine relevant leak and environmental conditions (e.g. wind conditions) and their effects. Simulations to establish requirements for hazardous zones.

CFD models for hydrogen exist and these can be used. However, models are subject to inaccuracies and differences between model and experimental results are therefore often observed [11, 12]

The modelling can be improved and validated by performing experiments of ventilation, gas dispersion and explosions in replicas of maritime fuel cell rooms.

Previous hydrogen experiments, e.g. from large multinational projects like Hysafe NoE[13] , SUSANA[14] and HySea[15] have been used to test and develop current models. No experiments have been performed for realistic maritime enclosures such as fuel cell or hydrogen storage rooms. Experiments have typically been for small gas volumes and different shapes than expected for a fuel cell room. Leak and ventilation characteristics are expected to be different. It is therefore recommended to perform hydrogen experiments in mock-ups of realistic maritime rooms. Experimental results will improve understanding of dispersion and explosion mechanisms; what leak conditions (rates and durations) will result in a gas cloud large enough to threaten integrity of the room in case of a deflagration explosion? How much hydrogen can leak if damaging explosion pressures should be avoided? How effectively can ventilation be in preventing ignition/fire/explosion? What is the optimal room design, e.g. effect of smooth ceiling? What are the expected consequences on walls including possible collapse? How to design vent release panels?

With calibrated models, more accurate fire and explosion risk assessment of fuel cell rooms can be established.

The Norwegian Maritime Directorate (NMA) has expressed and underlined that more experience for research and testing are needed before use of hydrogen in a commercial ferry. As the safety of the technology is not considered well-defined and mature, NMA have indicated that extensive testing of hydrogen solutions in relevant on-shore simulation laboratories and possibly on test-ships with only a limited safety crew would be required to gain their Flag State approval.

GAP: Liquid hydrogen (LH_2) (Legal, Knowledge)

Legal / Knowledge

As for hydrogen gas, further studies are required also to develop safety related understanding of properties and conditions affecting safety of liquid hydrogen (LH_2) in shipping applications. In this report, issues dealing with LH_2 gaps have been included in the sections where relevant.

LFL fuels are foreseen to be covered by the DNV GL Class notation LFL-fuelled.

The following gives some examples of needed activities:

- Liquid hydrogen is associated with very low temperatures. Temperature effects on steel need to be considered and requirements need to reflect such conditions. Cryogenic hydrogen has a lower temperature than cryogenic natural gas. Such leaks hitting critical structures and their possible cool down and embrittlement effects need to be considered for assessing when cryogenic spray protection is needed and if the requirements need to be adjusted compared to LNG. This will form important input to further Rules and Regulative developments.
- Liquid hydrogen leaks outdoors; determine relevant leak and environmental conditions (e.g. wind conditions) and their effects. Simulations should be considered to establish requirements for hazardous zones.
- Leak detection and how liquid hydrogen will evaporate and behave is expected to be different from LNG (e.g. higher buoyancy, range of flammability) and a hydrogen gas leak.

C

SAFETY ASSESSMENT OF GENERIC FUEL CELL APPLICATIONS ON RO-PAX VESSELS AND GAS CARRIERS

INTRODUCTION

The European Maritime Safety Agency (EMSA) contracted DNV GL to provide a technical study on the use of fuel cells (FCs) in shipping to evaluate the potential and constraints as prime mover and energy sources in shipping /12/. The study provides in chapter A an overview of fuel cell projects and identifies the most promising fuel cell technology for ship applications. Chapter B of the study provides a description of the current applicable standards and possible regulatory gaps. Chapter C describes the approach and results of the risk assessment in task 3 of the "Study on the use of Fuel Cells in Shipping", to analyse possible safety challenges for maritime fuel cell applications on vessels engaged in international voyage. For the assessment generic concepts of fuel cell installations and their integration on a RoPax vessel and a Gas Carrier were developed. These generic concepts are based on the most promising fuel cell types identified in chapter A, namely the PEM, HT-PEM and SOFC. These three fuel cell types are further considered to cover well the technology span of fuel cells today; from low, medium to high temperature cells, respectively. Three fuel types are considered; LNG, methanol and hydrogen.

OBJECTIVE

The objective of the safety assessment is to review generic fuel cell installations on a RoPax vessel and a Gas Carrier to identify possible hazards related to the usage of different types of fuel cells and fuels. The main goals of the safety assessment are to provide:

- An overview of differences between fuel cell (FC) systems /arrangements in shipping in terms of used technologies, safety challenges, practicability
- An overview of areas were further investigation should be done
- Recommendations to optimize the level of safety
- Input to future contribution to the IMO IGF Code development

GENERIC FUEL CELL APPLICATIONS

During the ongoing development of requirements for maritime fuel cell applications at the IMO a generic Fuel Cell Power Installation scheme is used as a baseline to illustrate a fuel cell system structure with the relevant main components. During the safety assessment workshop of this fuel cell study it was recognized that this scheme will not cover all possible fuel cell applications. For this reason, the scheme "Components of a typical fuel cell power installation - revised illustration" in the following Figure C.1 was generated which is the baseline for the safety assessment structure (see Appendix on page 101).

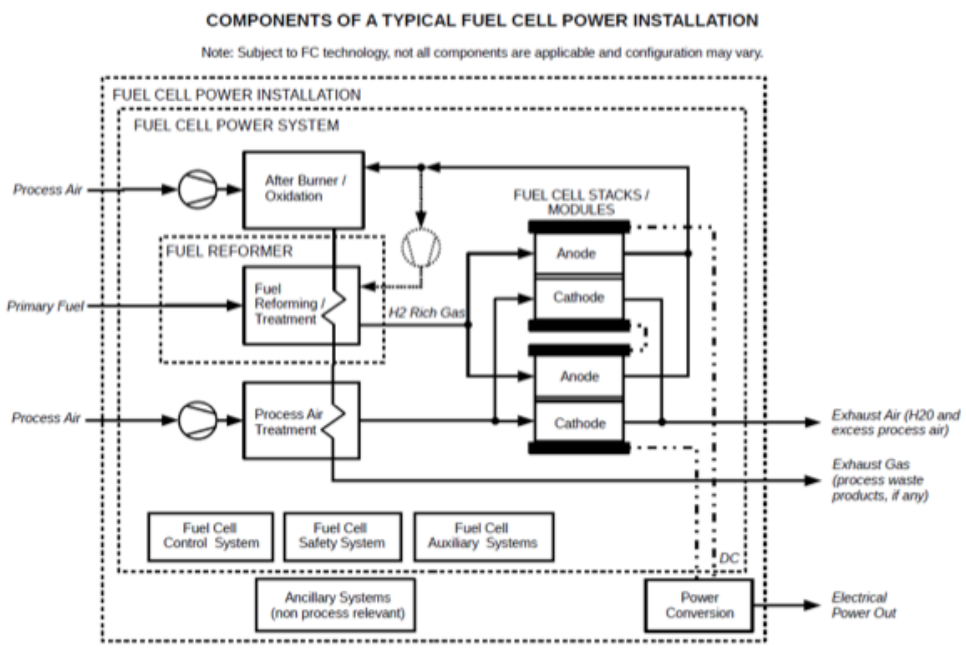


Figure C.1: Components of a typical fuel cell power installation - revised illustration Selected Scenarios

Selected Scenarios

The safety assessment will be done exemplary for six different scenarios as shown in Table C.1. For these scenarios two ship types and three FC types are considered. The FC types are the three most relevant types identified in chapter A of this report, namely the high temperature solid oxide fuel cell (SOFC), the high temperature PEM and the PEM. A note should be made regarding the classification of fuel cell types. High temperature fuel cells (HT FC) are cells with operating temperatures of ca. 650°C or higher. This includes normally the molten carbonate fuel cell and the solid oxide fuel cell. In comparison, low temperature fuel cells operate below 100°C, such as the PEM cell. It should be noted that the high temperature PEM is operating somewhat above 100°C, but is in reality a medium temperature fuel cell, not a high temperature cell.

Table C.1: Reference scenarios

Scenario	Ship type	Fuel Cell type
1	RoPax ferry	**1: SOFC** with reformer, exhaust cat and heat recovery system, NG as primary fuel
2		**2: HT PEM FC** with reformer system, Methanol as primary fuel
3		**3: PEM FC** directly fueled with hydrogen
4	Gas Carrier	**1: SOFC** with reformer, exhaust cat and heat recovery system, NG as primary fuel
5		**2: HT PEM FC** with reformer system, Methanol as primary fuel
6		**3: PEM FC** directly fueled with hydrogen

High level integration concept on a RoPax ferry

As baseline for the safety assessment a high level FC integration concept for an existing RoPax ferry (MS MARIELLA operated by Viking Lines) was generated. It was decided that the purpose of this kind of FC application will be the total energy supply of the vessel including the provision of propulsion energy. Depending on the selected fuel cell technology the following main components are to be installed onboard:

- Fuel tanks (tank types depending on the primary fuel selected)
- Reformer system (if not using Hydrogen as primary fuel)
- FC modules
- Electrical engines
- Buffer system (Batteries)

These main components were exemplary arranged in the following General Arrangement Plan of the MS MARIELLA, thus providing a case to be used in the safety assessment (Figure C.2).

The upper left part of Figure C.2 shows the conventional Main Engine Room (MER) adjacent to the cabins. For the high level concept it is assumed to replace the conventional diesel engines with fuel cell modules. In the lower part of Figure C.2 the deck below the engine room is illustrated. For the high-level concept; electrical engines, a reformer and a battery room were introduced (reformer and batteries installed in the former oil settling and service tank room). The conventional diesel tanks will be replaced by suitable fuel tank types for the selected primary fuel. For a discussion on the limitations of this concept, see next page.

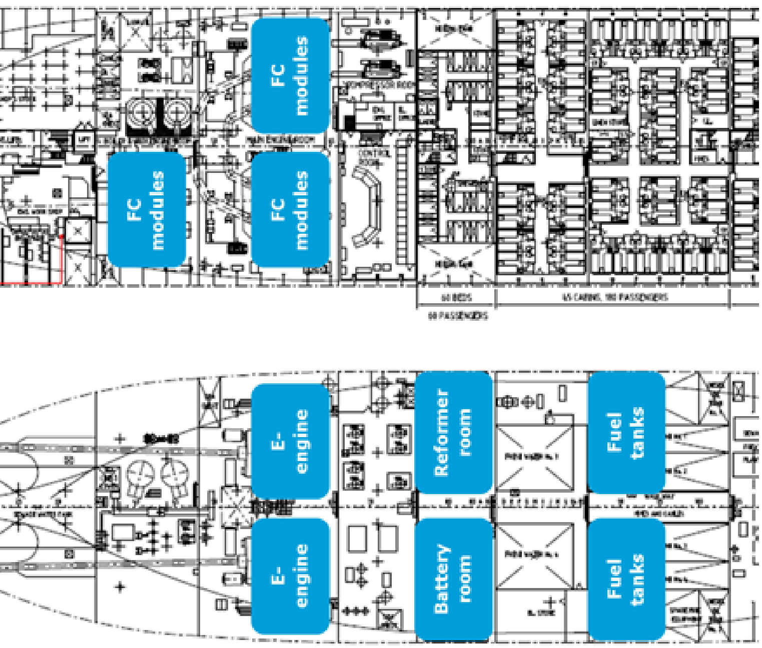


Figure C.2: High level FC integration concept on a RoPax ferry (baseline used for discussion in the Safety Assessment)

High level integration concept on a Gas Carrier
For the Gas Carrier it was decided that the replacement of the main engine is not suitable. The main propulsion of the Gas Carrier include 2-stroke diesel/gas engine(s) alternatively steam turbines, and the total installed power is high. Further advantages of the fuel cell like noise and vibration reduction are not relevant for this kind of commercial vessel at the moment. For this reason a partly replacement of the auxiliary engines was considered. The purpose of this application is the auxiliary power supply with reduced emission during port stay. For a discussion on the limitations of this concept, see following section.

Operational modes considered
For the assessment two operational modes are considered:

- Normal operation
- Bunkering operation

Normal operation means that the fuel cells are consuming primary fuel and generating electrical power for the total energy supply of the ship (in case of the RoPax ferry) or for auxiliary power supply (in case of the gas carrier).

Bunkering means the loading of primary fuel from a bunker source outside the vessel to the fuel tanks of the vessel.

LIMITATIONS

The risk assessment in chapter C of the EMSA study is limited to a 'simplified FSA' analysis following the FSA methodology, as described on the following page, covering step 1, 2, 3 and step 5 of the methodology in terms of a qualitative risk assessment. The simplified analysis follows the FSA methodology but will not cover all FSA steps and not the full scope of all steps as defined in the FSA guidelines. This is related but not limited to

- Step 3 will not cover the assessment of interdependencies and side effect of the identified Risk Control Options (compare section 7 of /12/)

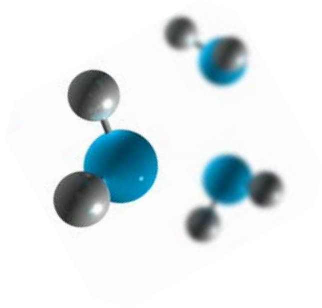
- A qualitative Cost-Benefit Assessment will be done while using the ALARP-principle in the context of step 2 and 3 of the study. This does not cover the requirements of FSA step 4. Detailed Cost-Benefit Assessments should be done in a potential follow up study

- "Recommendations for decision-making" are limited to the listing of control options which keep risks as low as reasonable practicable based on the comparison of all identified hazards and their underlying causes. A detailed analysis of all significantly influenced entities and the auditable and traceable presentation of the results should be done in a follow up study in which concrete proposals for the addition / change of the IGF Code and other possibly effected regulation will be formulated

The objective of the assessment are three concept designs of fuel cell systems integrated in two reference ships as described on page 87. Recommendations will be made to finalize the FSA studies for these two ship types. Further ship types should be assessed in possible follow up studies.

Limitations of the RoPax concept
The purpose of the concept is not to show an implementable concept. The high level concept is provided as baseline for the discussion. The weakness of the concept is among others the considered installation area: For the time being fuel cell technology needs significantly more installation area than conventional ship power plants. The same applies for the fuel storage of the selected alternatives fuels. Most of them need more installation area than the storage of conventional diesel. This means that with the current technology state of the art, less cabin and / or vehicle space is available. This is to be considered for both new building and retrofit.

Limitations of the Gas Carrier concept
The advantages of a fuel cell installation onboard a gas carrier are the given measures for the cargo. The whole deck area is already defined as hazardous area. Suitable fuels could be provided by the cargo. However the defined purpose of the installation reduces the positive effects due to limited operation times (operation only during port stay).



1 – METHODOLOGY APPLIED

FORMAL SAFETY ASSESSMENT

The Risk Assessment study will be based on the Formal Safety Assessment Methodology /13/ as illustrated in Figure C.3 and described below.

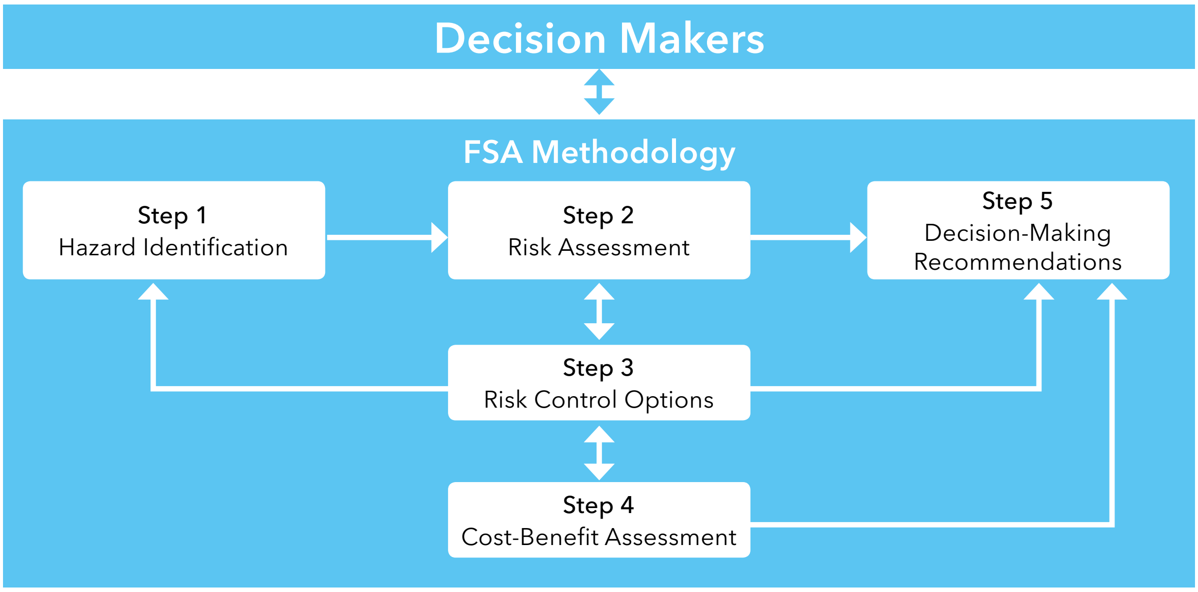


Figure C.3: Flow chart of the FSA Methodology /13/

The Formal Safety Assessment (FSA) is a structured and systematic methodology, aimed at enhancing maritime safety, including protection of life, health, the marine environment and property, by using risk analysis and cost-benefit assessment. The FSA can be used as a tool to help in the evaluation of new regulations for maritime safety and protection of the marine environment.

For the current project case a "simplified FSA" analysis is used following the FSA methodology and covering steps 1, 2, 3 and step 5 of the methodology in terms of a qualitative risk assessment. It should be noted, that this simplified approach follows the FSA approach but will not cover all FSA steps and not the full scope of all steps as defined in the FSA guidelines (see section "Limitations" on page 88).

The FSA methodology was also applied to follow the process of clear documentation and formally recording in a uniform and systematic manner, thus allowing follow up studies to finalize the remaining steps of the FSA.

FAILURE MODE AND EFFECT ANALYSIS (FMEA)

The Failure Mode and Effect Analysis (FMEA) is an established Risk Assessment technique according to the FSA Guidelines /13/ and is described in IEC 60812 /14/. The systematic procedure is used for the analysis of a system to identify the potential failure modes, their causes and effects on system performance.

Each item in the system is identified at a required level of analysis. The effects of item failure at that level and at higher levels are analyzed to determine their severity on the system as a whole. Any compensating or mitigating provisions in the system are taken account of and recommendations for the reduction of the severity are determined. The FMEA also includes an estimation of the probability of occurrence of the failure modes. This enhances the analysis by providing a measure of the failure mode's likelihood. The analysis indicates single failure modes which may cause system failure. FMECA (Failure Modes, Effects and Criticality Analysis) is an extension to the FMEA where the failure mode analysis yields also the criticality analysis. Criticality determination includes a means of ranking the severity of the failure modes to allow prioritization of countermeasures. This is done by combining the severity measure and frequency of occurrence to produce the total criticality measure.

WORKSHOP

For the workshop, the approach as illustrated in the following Figure C.4 was applied with some modifications to align with the FSA approach and concept to be assessed.

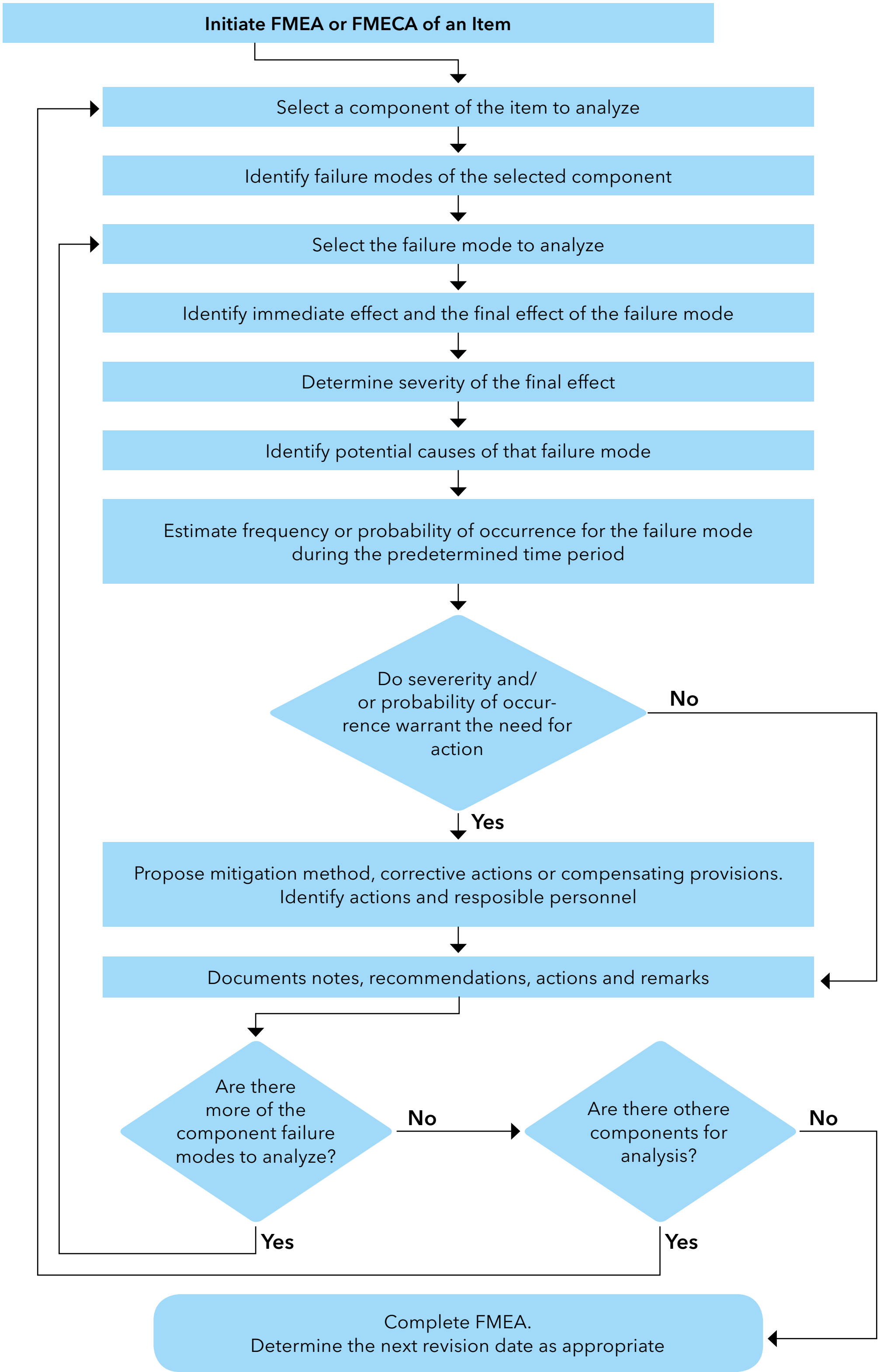


Figure C.4: Process flow diagram FMECA workshop /14/

RISK REDUCING PHILOSOPHY AND ALARP PRINCIPLE

Criticality of the subject in question can be presented in a criticality matrix. It should be noted that there is no universal definition of criticality but that criticality needs to be defined by the analyst and accepted by the project or program management. The definitions differ widely between different application sectors. The proposed criticality matrix is illustrated in Figure C.5.

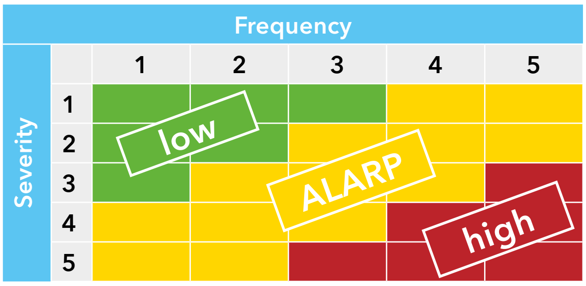


Figure C.5: Proposed criticality matrix

The overall risk reducing philosophy is defined by compliance with applicable safety regulation and state of the art for safety. The ALARP principle (As Low As Reasonable Practicable) is applied to effectively manage risks that are not addressed by the overall risk reducing philosophy. The ALARP principle is defined in the FSA guideline as follows:

It states that there is a risk level that is intolerable above an upper bound. In this region, risk cannot be justified and must be reduced, irrespectively of costs. The principle also states that there is a risk level that is 'broadly acceptable' below a lower bound. In this region risk is negligible and no risk reduction required. If the risk level is in between the two bounds, the ALARP region, risk should be reduced to meet economic responsibility:

Risk is to be reduced to a level as low as is reasonably practicable. The term reasonable is interpreted to mean cost-effective. Risk reduction measures should be technically practicable and the associated costs should not be disproportionate to the benefits gained. This is examined in a cost effectiveness analysis.

This definition of the risk reducing philosophy and ALARP principle was applied for the FMEA workshop. Within the workshop the risk assessment team (see Appendix on page 100) utilizes this philosophy and principle to identify and define "recommended actions" with the objective of reducing the risks of the assessed reference scenario. The ranking of failures (risk rating scales see Appendix on page 102) and categorization of the single failure scenarios will be illustrated in the risk matrix with colored marking as shown in the following Table C.2.

Table C.2: Categorisation of failure scenarios

High Risk	**Unacceptable risk** Risk cannot be justified and must be reduced by additional measures
ALARP	**ALARP** Risk is to be reduced to a level as low as is reasonably practicable
Low Risk	**Broadly acceptable risk** Risk is negligible and no risk reduction required

2 – ASSESSMENT FINDINGS

During the safety assessment workshop altogether 213 failure scenarios were identified whereof 146 scenarios were ranked against the severity, occurrence and detectability of failure. Most of the 67 failure scenarios not considered for the ranking are related to the storage, distribution and preparation of LNG and Methanol as well as failures related to fire scenarios which will be covered by requirements of the IGF Code. Further failures which were similar for different sub-systems or components were documented but not considered several times for the ranking. Firstly, hazards for each component of the system were identified and ranked according to the rating scales (see Appendix on page 102) taking into account assumed already existing safeguards (controls) in the generic fuel cell system. The initial rating of failures is illustrated by the following criticality matrix, see Figure C.6. The considered safeguards for the initial ranking can be found in the Result Tables.

Then, for altogether 100 failure scenarios further recommendations were discussed in order to reduce the risk. The revised rating of the failure scenarios, taking all further recommendations into account, is illustrated by the following criticality matrix in Figure C.7. The risk potential of all 9 failure scenarios rated to be in the "unacceptable risk" area of the criticality matrix were reduced by further recommended actions. Following these actions, all failure scenarios were brought to the "acceptable" or "ALARP" region of the revised criticality matrix.

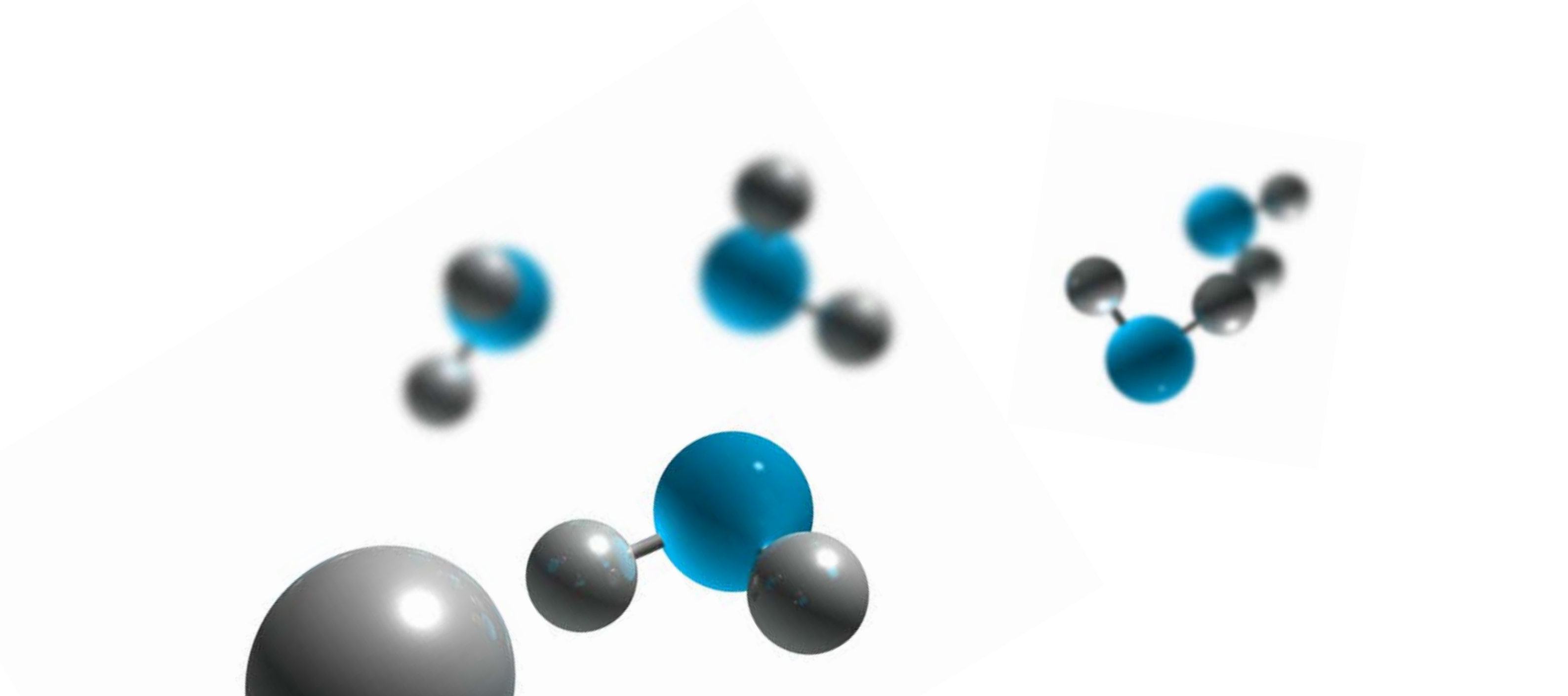
The complete list of all failure scenarios including further recommended actions can be found in the "Result Tables".

Severity, Si \ Frequency of Occurrence, Oi	1	2	3	4	5
1	2			3	9
2			2	6	
3		9	55	29	
4			22	3	
5		2	6		

Figure C.6: Criticality Matrix of overall 146 initially rated failure scenarios

Severity, Sr \ Frequency of Occurrence, Or	1	2	3	4	5
1	2		3	3	6
2			5	3	
3		9	78	24	
4			13		
5		2			

Figure C.7: Criticality Matrix of overall 146 revised rated failure scenarios



FINDINGS SEPARATED BY FC TYPES

To get an overview of the differences in failure mechanism between the different FC types, the overall results illustrated in the criticality matrixes in Figure C.6 and Figure C.7 were distributed in six further criticality matrixes. These criticality matrixes illustrate now, in Figures C.8 to 13, the distribution of the overall 146 failure scenarios in own separate criticality matrixes for the three fuel cell types HT FC, HT PEM FC and PEM FC each for the initial and revised rating. Thus, from the 146 overall failure scenarios 47 failure scenarios are belonging to the HT FC, 50 failure scenarios to the HT PEM FC and 49 to the PEM FC.

The comparison of the initial rating of failure scenarios for individual FC types shows that the number of failure scenarios and distribution in the matrixes are almost similar, (see Figure C.8, Figure C.10 and Figure C.12). This is related to the fact that most of the failure mechanisms are similar among the different fuel cell types. Differences are related to the use of different fuels, the potential use of reformer systems and different operational temperatures which vary from 80°C for PEM FCs up to 1000°C for HT FCs. These differences are listed in the following, focusing on the most critical scenarios in the red area as well as scenarios ranked with severity 4 or 5 in the ALARP area of the criticality matrixes.

1. Strong exothermic reaction of reformer material
2. Internal leakage in FC Module
3. Leakage of hydrogen rich gases
4. Failure of electrical power output conditioning system
5. Thermal runaway of onboard energy buffer
6. Loss of active purging system
7. Vehicle crash penetrating Fuel Cell Power System Installations (RoPax ferry)

The scenarios and further recommended actions are described more in detail in the following sections. The most relevant failure scenarios for the HT FC type are the "Strong exothermic reaction of reformer material" and the "Leakage of hydrogen rich gases". Since reformer systems is likely used for the HT FC type, the high operational temperature in the reformer and in the FC module itself could lead to an immediate self-ignition of hydrogen rich gases when accidental released to the atmosphere.

For 33 failure scenarios of the HT FC further recommended actions were identified and considered for the revised rating as shown in Figure C.9. No failure scenario remains in the red "unacceptable" area of the criticality matrix.

		Frequency of Occurrence, Oi				
		1	2	3	4	5
Severity, Si	1	1			1	3
	2			1	3	
	3		3	16	9	
	4			8	1	
	5			2		

Figure C.8: Criticality Matrix of 47 initially rated HT FC related failure scenarios

		Frequency of Occurrence, Or				
		1	2	3	4	5
Severity, Sr	1	1		1	1	2
	2			3	1	
	3		3	25	7	
	4			4		
	5					

Figure C.9: Criticality Matrix of 47 revised rated HT FC related failure scenarios

For the HT FC altogether 73 failure scenarios were identified whereof 47 failure scenarios were ranked against the severity, occurrence and detectability of failure. Most of the 26 failure scenarios not considered for the ranking are related to the storage, distribution and preparation of LNG as well as failures related to fire scenarios which are already covered by requirements of the IGF Code. Further failures which were similar for different sub-systems or components were documented but not considered several times for the ranking.

Altogether 11 scenarios were initially ranked in red area or with severity 4 or 5 in the ALARP area of the criticality matrix (Figure C.8). These 11 most critical scenarios for the HT FC are related to

For the HT PEM FC altogether 73 failure scenarios were identified whereof 50 failure scenarios were ranked against the severity, occurrence and detectability of failure. Most of the 23 failure scenarios not considered for the ranking are related to the storage, distribution and preparation of Methanol as well as failures related to fire scenarios which will be covered by requirements of the IGF Code. Further failures which were similar for different sub-systems or components were documented but not considered several times for the ranking.

Altogether 9 scenarios were initially ranked in red area or with severity 4 or 5 in the ALARP area of the criticality matrix (Figure C.10). These 9 most critical scenarios for the HT PEM FC are related to the same failure scenarios as the HT FC.

The most relevant failure scenarios for the HT PEM FC type are the "Strong exothermic reaction of reformer material" and the "Leakage of hydrogen rich gases". In comparison to the HT FC some of these failures are ranked less severe as the release of hydrogen rich gas out of the HT PEM FC module will not lead to an immediate self-ignition due to lower temperatures.

For 37 failure scenarios of the HT PEM FC further recommended actions were identified and considered for the revised rating as shown in Figure C.11. No failure scenario remains in the red "unacceptable" area of the criticality matrix.

		Frequency of Occurrence, Oi				
		1	2	3	4	5
Severity, Si	1	1			1	3
	2			1	2	
	3		3	19	11	
	4			7	1	
	5			1		

Figure C.10: Criticality Matrix of 50 initially rated HT PEM FC related failure scenarios

		Frequency of Occurrence, Oi				
		1	2	3	4	5
Severity, Si	1	1		1	1	2
	2			2	1	
	3		3	28	9	
	4			3		
	5					

Figure C.11: Criticality Matrix of 50 revised rated HT PEM FC related failure scenarios

For the PEM FC altogether 69 failure scenarios were identified whereof 49 failure scenarios were ranked against the severity, occurrence and detectability of failure. Most of the 20 failure scenarios not considered for the ranking are related to fire scenarios which are in principal covered by requirements of the IGF Code. Further failures which were similar for different sub-systems or components were documented but not considered several times for the ranking.

Altogether 13 scenarios were initially ranked in red area or with severity 4 or 5 in the ALARP area of the criticality matrix (Figure C.12). These 13 most critical scenarios for the PEM FC are related to

1. Internal leakage in FC Module
2. High energy collision penetrating LH2 tank
3. Rupture of CH2 tank containment system
4. Leakage of hydrogen rich gases
5. Failure of pressure reduction
6. Failure of electrical power output conditioning system
7. Thermal runaway of onboard energy buffer
8. Loss of active purging system
9. Leakage during bunkering of hydrogen
10. Vehicle crash penetrating Fuel Cell Power System Installations

The scenarios and further recommended actions are described more in detail in the following sections.

The use of reformer systems for the PEM FC type is most unlikely as this will reduce the overall efficiency significantly. The most relevant failure scenarios for the PEM FC type are the related to the bunkering, storage and distribution of hydrogen and related scenarios for the accidental release of hydrogen also out of the PEM FC module. Self-ignition during these accidental releases is also possible due to e.g. electrostatics. These effects should be further studied. For 29 failure scenarios of the PEM FC further

		Frequency of Occurrence, Oi				
		1	2	3	4	5
Severity, Si	1				1	3
	2				1	
	3		3	19	9	
	4			7	1	
	5		2	3		

Figure C.12: Criticality Matrix of 49 initially rated PEM FC related failure scenarios

		Frequency of Occurrence, Oi				
		1	2	3	4	5
Severity, Si	1			1	1	2
	2				1	
	3		3	25	8	
	4			6		
	5		2			

Figure C.13: Criticality Matrix of 49 revised rated PEM FC related failure scenarios

recommended actions were identified and considered for the revised rating as shown in Figure C.13. No failure scenario remains in the red "unacceptable" area of the criticality matrix.

MOST CRITICAL FC RELATED FINDINGS

In the following sections 27 of the 33 most critical hazards are assessed. The most critical hazards are all unacceptable hazards located in the red area of the initial criticality matrix. Further considered are hazards which potentially cause most harm. These hazards are rated with severity 5 and 4, located in the ALARP region adjacent to the red region of the initial criticality matrix (compare Figure C.6). The remaining 6 of 33 most critical items are assessed on page 98.

Strong exothermic reaction of reformer material

Charging the catalytic reformer material with oxygen, leads to a strong exothermic reaction. Three mechanisms leading to this effect were identified:

- Loss of integrity of the fuel reformer (item 1.1.2.1.2 and 2.1.2.1.2);
- Reformer pressure lower than exhaust air pressure (item 1.1.2.1.7 and 2.1.2.1.8);
- Loss of primary fuel for fuel reforming (item 1.1.2.1.2 and 2.1.2.1.2)

Mechanical damage, welding failure or untight connections could lead to a loss of integrity of the fuel reformer of the HT FC or HT PEMFC. The ingression air will lead to a strong exothermic reaction with the catalytic material. Temperatures of about 1000°C for the HT FC and about 600°C for the HT PEMFC can be expected. Self-ignition of remaining gases in the reformer cannot be excluded (Failure ID 1.1.2.1.2-5: Si = 5 & Oi = 3; and Failure ID 2.1.2.1.2-4 Si = 4 & Oi = 3).

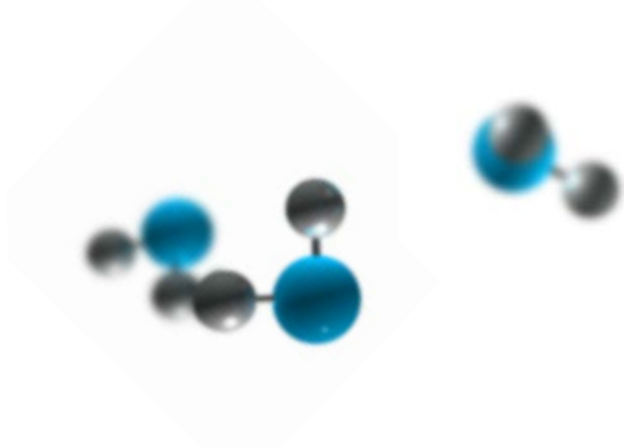
Two further recommended actions were identified during the FMEA workshop. The reformer temperature should be monitored and the fuel supply to the reformer stopped in case of reaching limiting values. The entry of oxygen in the reformer should be avoided by e.g. purging with inert gas. Taking the further recommended actions into account, the revised assessment was judged to be as low as reasonable practicable (Sr = 4 & Or = 3 and Sr = 3 & Or = 3, respectively).

Mechanical damage of the reformer could also lead to a reduction of the internal reformer pressure. In this case the Reformer pressure of the HT or HT PEMFC is lower than the exhaust air pressure and oxygen ingresses into the reformer leading to the same effect as describe above (Failure ID 1.1.2.1.7-2: Si = 5 & Oi = 3 and Failure ID 2.1.2.1.8-2: Si = 5 & Oi = 3).

Three further recommended actions were identified during the FMEA workshop. In addition to the two further recommended actions of the previous described failure scenario it was recommended to switch off the exhaust gas fan to avoid forced ventilation into the reformer. Taking the further recommended actions into account, the revised assessment was judged to be as low as reasonable practicable (Sr = 4 & Or = 3 and Sr = 4 & Or = 3, respectively).

Further consideration was given to the loss of primary fuel for fuel reforming of the HT or HT PEMFC due to failure of the fuel storage and distribution system (Failure ID 1.1.2.1.2-2: Si = 4 & Oi = 3 and Failure ID 2.1.2.1.2-2 Si = 4 & Oi = 3). In this case the reformer temperature will rise due to missing cooling effect from fuel conversion resulting in possible further damages to the reformer (fire hazard).

One further recommended action was identified during the FMEA workshop. For the design of the reformer possible effects regarding the loss of primary fuel are to be considered. The design of the reformer unit has to withstand loss of fuel without leading to unsafe situation. Taking the further recommended actions into account, the revised assessment was judged to be as low as reasonable practicable (Sr = 3 & Or = 3 and Sr = 3 & Or = 3, respectively).



Internal leakage in FC Module

Cracking of fuel cell plates may cause internal leakages in all three types of Fuel Cell Modules, leading to high stack temperatures and internal oxidation processes or internal fire. The stack temperature and voltage monitoring will lead to a shut down of the corresponding stack (Failure IDs 1.1.2.1.4-3, 2.1.2.1.4-3 and 3.1.2.1.2.-2: all Si = 4 & Oi = 4).

Two further recommended actions were identified during the FMEA workshop. The amount of fuel in the fuel cell space and the corresponding consequences shall be evaluated for each configuration. Safety devices are to be designed to handle maximum credible release scenario. Combustible material in fuel cell modules shall be minimized. Taking the further recommended actions into account, the revised assessment was judged to be as low as reasonable practicable (all to Sr = 3 & Or = 4).

High energy collision penetrating LH_2 tank

A high-energy collision by another ship or due to vehicle accident on board of the RoPax vessel has the potential to penetrate the fuel storage room and further damage the tank containment system. Immediate ignition due to the mechanism of the collision cannot be excluded (Failure ID: 3.1.1.1-2: Si = 5 & Oi = 2).

Four further recommended actions were identified during the FMEA workshop. The distance between tank and ship side has to be clarified to reach the same safety level as a conventional fuelled vessel / LNG fuelled vessel. A detailed assessment of hydrogen release scenarios in respect to ignition and dispersion should be done. The storage of hydrogen tanks below accommodation should be evaluated. The tank location should be evaluated with respect to collision probability both for potential ship collisions and as well for vehicle accidents on board for the RoPax vessel. Taking the further recommended actions into account, the revised assessment was judged to be as low as reasonable practicable (Sr = 5 & Or = 2).

Rupture of CH_2 tank containment system

Cracks of the pressure tank structure due to fatigue will result in a tank rupture with potential damage of the ship structure (Failure ID 3.1.1.1-4: Si = 5 & Oi = 2). It shall be ensured, that a suitable pressure relief system for the hold space of the tank according to IGF-Code section 6.7.11 is provided (considered as controls / existing safeguard). No further recommended actions were identified during the FMEA workshop. The revised assessment was judged to be as low as reasonable practicable (Sr = 5 & Or = 2).

Leakage of hydrogen rich gases

Mechanical damage, welding failure or untight connections of piping of all three types of Fuel Cell Modules leads to the release of hydrogen rich gas with potential self-ignition (Failure ID 1.1.2.1.3-1, 1.1.2.1.4-2 and 3.1.2.1.2-1: all Si = 4 & Oi = 3).

Two further recommended actions were identified during the FMEA workshop. It shall be ensured, that the piping and modules are installed in an ESD protected fuel cell space with appropriate gas detection, ventilation, fire detection and fire extinguishing systems (considered as controls / existing safeguards). Further, a detailed assessment of hydrogen rich gas release scenarios in respect to (self-) ignition and dispersion behavior should be done. The distance requirements to the outer shell for fuel piping shall be also applied to fuel cell stacks in order to reduce collision effects.

Taking the further recommended actions into account, the revised assessment was judged to be as low as reasonable practicable (Sr = 3 & Or = 3).

Failure of fuel pressure reduction

A failure of the pressure reducer downstream the CH_2 storage tank damages of downstream components are to be expected (Failure ID 3.1.1.5-1: Si = 4 & Oi = 3). It shall be ensured, that a pressure relief device is installed to protect systems in case of failure of the pressure reducer (considered as control / existing safeguard). No further recommended actions were identified during the FMEA workshop. The revised assessment was judged to be as reasonable practicable (Sr = 4 & Or = 3).

Failure of the electrical power output conditioning system

For the electrical power output conditioning system the two following failures were assessed:

- Internal short circuit
- Wrong conversion

Due to an electrical failure an internal short circuit in the electrical power output conditioning system might occur. The short circuit will lead to high voltage at grid level in the Fuel Cell Module resulting in high stack temperature with potential fire (failure ID 1.1.2.2-2, 2.1.2.2-2 and 3.1.2.2-2: all to Si = 4 & Oi = 3).

One further recommended action was identified during the FMEA workshop. It shall be ensured that circuit breaker at each consumer is installed and the converter is designed to handle short circuits (considered as control / existing safeguard). Further consideration to electrical reverse power should be given. Taking the further recommended action into account, the revised assessment was judged to be as low as reasonable practicable (Sr = 3 & Or = 3).

Converter control failure could lead to a wrong conversion on faulty frequencies. A damage of the FC control system cannot be excluded (Failure ID 1.1.2.2-4, 2.1.2.2-4 and 3.1.2.2-4: all Si = 4 & Oi = 3).

One further recommended action was identified during the FMEA workshop. It shall be ensured, that decentralized grids are designed for load fluctuations. Taking the further recommended action into account, the revised assessment was judged to be as low as reasonable practicable (Sr = 4 & Or = 3).

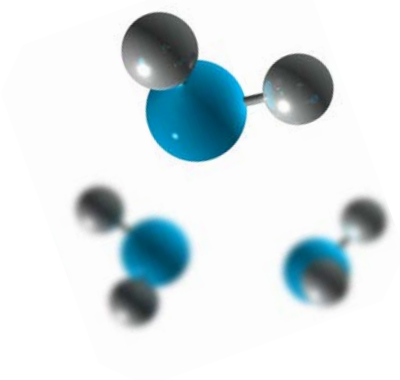
Thermal runaway of onboard energy buffer

Internal battery failure lead to thermal runaway and external fire (Failure ID 1.1.5-2, 2.1.5-2 and 3.1.5-2: all Si = 4 & Oi = 3).

One further recommended action was identified during the FMEA workshop. Functional safety requirements for battery installation are to be considered as e.g. defined in DNV GL guideline for large maritime battery systems. Taking the further recommended action into account, the revised assessment was judged to be as low as reasonable practicable (all to Sr = 3 & Or = 3).

Loss of inert gas system

The loss of the inert gas system due to already consumed inert gas can lead to unsafe situation (Failure ID 1.1.6-1, 2.1.6-1 and 3.1.6-4: all Si = 4 & Oi = 3). It shall be ensured, that the inert gas storage is monitored and an alarm will be processed when the level of a last complete inerting is reached (considered as control / existing safeguard). No further recommended actions were identified during the FMEA workshop. The revised assessment was judged to be as low as reasonable practicable (Sr = 4 & Or = 3).



MOST CRITICAL VESSEL SPECIFIC FINDINGS

Leakage during bunkering of hydrogen

Material failure, welding failure and untight connections could lead to external leakages at the bunker station, transfer system and the bunker source (Failure ID 3.2-2, 3.2-3 and 3.2-4; all Si = 5 & Oi = 3).

Three further recommended actions were identified during the FMEA workshop. Hazardous Areas, safety and security zones are to be established and aligned according to the behaviour, dispersion and ignition characteristics / mechanism of hydrogen (different to natural gas).

For RoPax vessels special attention to possible impact on passengers and vehicle traffic during bunkering shall be paid. Safety and security zones are to be established to establish a safety barrier to unauthorized people and to avoid unauthorized people entering the bunkering area. Most credible release scenarios are to be analysed according to possible influence on passengers, crew and ship; especially for this ship type influences on balconies, cabins, open passenger decks, open roro-and cargo decks, passenger bridges as well as passenger ways and vehicle routes on terminal side shall be taken into account.

For liquid gas carriers special attention shall be paid to the primary fuel if it is different from the cargo. In this case additional means for bunkering of the primary fuels are necessary which differ from the normal cargo transfer. Additional gas detection systems, safety and security zones (e.g. in case of truck to ship bunkering), training and instruction may be necessary

Taking the further recommended action into account, the revised assessment was judged to be as low as reasonable practicable (all to Sr = 4 & Or = 3).

Vehicle crash penetrating Fuel Cell Power System installations

Human error during the vehicle transfer on the RoPax vessel could lead to a crash with potential damage of fuel cell spaces and including components (Failure ID 1.1.7-9, 2.1.7-9 and 3.1.7-9: all Si = 4 & Oi = 3).

Three further recommended actions were identified during the FMEA workshop. The distance requirements to the outer shell for fuel piping shall be also applied to fuel cell stacks in order to reduce collision effects or effects due to vehicles crash. Shells of fuel cell spaces facing the car deck, where parts of the fuel cell power installation and related fuel storage, distribution and storage systems are installed, must be protected against possible mechanical impact of vehicles or cargo. Fuel piping routed through the RoRo deck must be protected against possible mechanical impacts by vehicles or cargo.

Taking the further recommended action into account, the revised assessment was judged to be as low as reasonable practicable (all to Sr = 3 & Or = 3).

OTHER VESSEL SPECIFIC FINDINGS

Fuel Cell Power Installations are integrated in the ship wherefore the failure scenarios are almost the same. For some items the consequences differ as describe for the bunkering scenario (see top of the page). The following additional vessel specific findings were identified during the FMEA workshop

- Failure during the cargo transfer of the LGC could lead to a loss of primary fuel if the fuel is used from the cargo for auxiliary power supply by FC during port stay (Failure ID 1.1.7-3, 2.1.7-3, 3.1.7-3). A separation of the ESD systems of primary fuel and cargo system should be considered
- Fire on the car deck or the open deck of the RoPax vessel could damage fuel piping routed through these decks (Failure ID 1.1.7-6, 2.1.7-6, 3.1.7-6). Fuel piping routed through the RoRo deck should be protected against potential fire impact

3 – RECOMMENDATIONS

The safety assessment showed that some specific items in relation to the use of fuel cell power systems on board ships shall be further studied:

Influence of different fuel behavior

1. Hazardous Areas, safety and security zones should be aligned according to the behavior and dispersion characteristics of methanol (behavior is different to natural gas). Toxicity of methanol is to be considered;

2. Consideration shall be given to diffusion effects and embrittlement of hydrogen through materials;

3. A detailed assessment of hydrogen rich gas release scenarios with respect to (self-) ignition and dispersion shall be done;

4. Hazardous area definition and vent mast outlet distances shall be analyzed due to the behavior and dispersion characteristics of hydrogen (low and high pressure release)

5. Hazardous Areas, safety and security zones shall be established and aligned according to the behavior, dispersion and ignition characteristics / mechanism of Hydrogen (different to natural gas)

6. Consideration shall be given to the different properties of hydrogen in comparison to LNG in respect to ignition, dispersion mechanism and lower temperature

Storage of hydrogen as fuel

7. The distances between hydrogen tank(s) and ship the ship structure shall be clarified to reach the same safety level as a conventional fuelled vessel / LNG fuelled vessel

8. The storage of hydrogen tanks below accommodation shall be evaluated

9. The location of hydrogen tanks should be evaluated with respect to collision probability

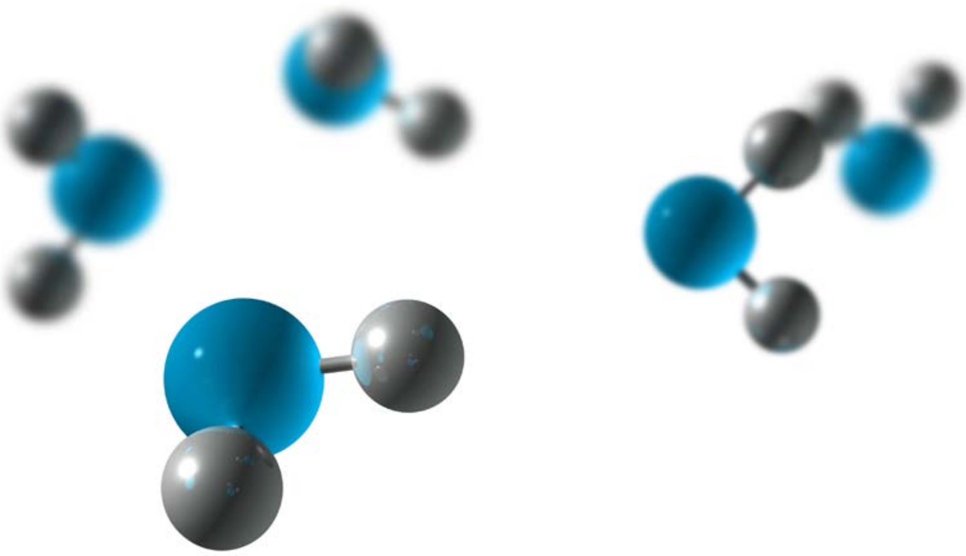
Further aspects

10. Consideration should be given to possibly ventilate or inert the cold box in case of leakage into space not normally to be entered (due to the behavior of hydrogen)

11. Consideration should be given to possibly ventilate or inert secondary barrier space in case of leakage into space not normally to be entered (due to the behavior of hydrogen)

12. Redundancy requirements for buffer system should be investigated

Further recommended actions are enlisted in the FMEA Result Tables.



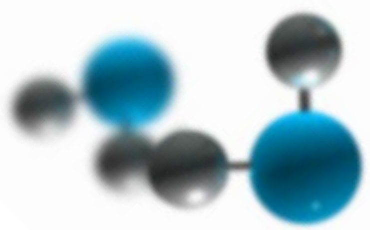
APPENDIX

ASSESSMENT TEAM

A thorough FMEA is a result of a team composed of individuals qualified to recognize and assess the magnitude and consequences of various types of potential inadequacies in the product design that might lead to failures. Advantage of the team work is that it stimulates thought process and ensures necessary expertise. The following experts participated on the FMEA workshop:

Table C.2: Assessment team

No	Name	Company	Expertise / Function	Day 1	Day 2	Day 3
1	Ricardo Batista	EMSA	Observer	x	x	x
2	Keno Leites	TKMS	FC Design and arrangement	x	x	x
3	Ragnar Christenson	Meyer Werft	FC Design and arrangement	x	x	x
4	Daniel Sahnen	Meyer Werft	Methanol Fuel System design	x		
5	Mr. Rudolph	Meyer Werft	Electrical Integration			x
6	Jesper Sörensen	Serenergy	FC Manufacturer	x	x	x
7	Oliver Posdziech	sunfire	FC Manufacturer		x	
8	Ms. Löwe	TUB	FC Design and arrangement	x	x	x
9	Norbert Dannenberg	TKMS	Electrical Integration			x
10	Martin Lobmeyer	ATG	FC boat operator			x
11	Tomas Tronstad	DNV GL	Project manager	x	x	
12	Lars Langfeldt	DNV GL	Facilitator	x	x	x
13	Benjamin Scholz	DNV GL	IMO Rules, Fuels and Fuel Cells	x	x	
14	Dietl Clemens	DNV GL	Hydrogen Risk Assessment	x	x	
15	Matthias Schmidt	DNV GL	Fuels and Fuel Cells		x	x
16	Urs Vogler	DNV GL	Risk Assessment			x



SYSTEM STRUCTURE FOR THE RISK ASSESSMENT

For the risk assessment a structure of the assessed fuel cell power installations containing all relevant main components was developed. The following structure will be applied for all three reference fuel cell systems and is based on Figure C.1: Components of a typical fuel cell power installation - revised illustration:

1. Fuel System

a. Fuel tank system
b. Distribution line between tank and fuel preparation
c. Fuel preparation
d. Distribution line to Fuel Cell Power System

2. Fuel Cell Power Installation

a. Fuel Cell Power System
   - Piping between fuel preparation and FC power system (primary fuel line)
   - Fuel Reforming
   - Piping between reformer and fuel cell
   - Fuel Cell (FC) Module
   - Process Air
   - Afterburner
   - Heat (energy) recovery
   - Exhaust gas line

b. Electrical power output conditioning
c. Net integration
d. Fuel Cell control system
e. Fuel Cell safety control system

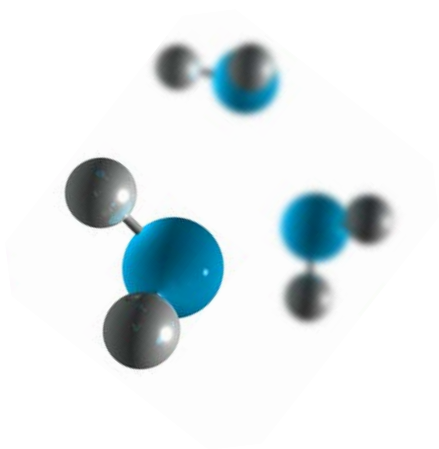
3. Ventilation system for ESD protected fuel cell spaces

4. Ventilation system for gas safe fuel cell spaces

5. Onboard energy buffer

6. Active purging system

7. External events



RATING SCALES

In the following the proposed rating scales for the severity, occurrence and detectability of failures are described, see Table C.4 to Table C.6. The focus is set on the determination of the safety and availability of the system. Environmental and Reputational issues will be assessed in individual case.

Table C.4: Severity Rating Scales

Severity Rating Scale		Si – initial Severity (incl. existing safety measures) Sr – revised Severity (incl. recommended safety measures)
	Description	**Criteria**
1	no effect	the failure does not affect normal operation of the system
2	minor effect	no breakdown and disturbed operation of the system with the possibility of further operation
3	moderate effect	damage and/or breakdown of the system, repair required, no damage of other system components
4	major effect	injured people and/or major damage/loss of the system/other systems
5	hazardous effect	fatalities and/or loss of the system as well as damage/loss of other systems

Table C.5: Occurrence Rating Scales

Occurrence Rating Scale		Oi – initial Occurrence (incl. existing safety measures) Or – revised Occurrence (incl. recommended safety measures)
	Description	**Criteria**
1	at no time	not possible: if a disturbance cannot occur because of physical reasons
2	very rare	technical excluded: if a disturbance can only occur as with appearance of a minimum of two failures. (characteristic experience: once in 100 years of operation)
3	rare	not probable: under the assumption that the disturbance will not occur in the lifetime of the component. (characteristic experience: once in 10 to 100 years of operation)
4	sometimes	low probability: under the assumption that the disturbance will occur during the lifetime of the component. (characteristic experience: once in 1 to 10 years of operation)
5	frequently	low probability: under the assumption that the disturbance will occur during the lifetime of the component. (characteristic experience: once in 1 to 10 years of operation)

Table C.6: Detection Rating Scales

Detection Rating Scale		Di – initial Detection (incl. existing safety measures) Dr – revised Detection (incl. recommended safety measures)
	Description	**Criteria**
1	ever	the disturbance will cause an alert or will initiate a shut off
2	often	the disturbance is detectable according to deviation of process parameter (e.g. increase of temperature)
3	unlikely	the disturbance is detectable in principle. but currently there is no possibility to detect the disturbance (e.g. corresponding sensor not present)
4	very unlikely	it is possible to detect the disturbance physically. but it will not be assumed that the disturbance will be detected (e.g. accumulation of gas)
5	never	physically not possible to detect the disturbance

ABBREVIATIONS

AC	Alternating Current
ACU	Absorption Chiller Unit
AFC	Alkaline Fuel Cell
ALARP	As Low As Reasonably Practicable
BOP	Balance of Plant - the ancillary system required to operate the fuel cell
CH_2	Compressed Hydrogen
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CFD	Computational Fluid Dynamics
DC	Direct Current
Di	initial detectability
DMFC	Direct Methanol Fuel Cell
Dr	revised detectability
EMSA	European Maritime Safety Agency
FC	Fuel Cell
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes, Effects and Criticality Analysis
FSA	Formal Safety Assessment
HT FC	High Temperature Fuel Cell
HT PEM FC	High Temperature Polymere Electrolyte Membrane Fuel Cell
IGF Code	International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels
IMO	International Maritime Organization
kW	Kilowatt - power measure
LCA	Life Cycle Analysis
LGC	Liquefied Gas Carrier
LH_2	Liquefied Hydrogen
LTPEM	Low Temperature PEMFC
MCFC	Molten Carbonate Fuel Cell
NO_X	Nitrous Oxides
Oi	initial occurrence
Or	revised occurrence
PAFC	Phosphoric Acid Fuel Cell
PEM FC	Polymere Electrolyte Membrane Fuel Cell
RoPax Ferry	Roll On/Roll Off Passenger Ferry
Si	initial severity
SOFC	Solid Oxide Fuel Cell
SOLAS	Safety of Life at Sea - International convention for safety of ships
SO_X	Sulphurous Oxides
Sr	revised severity

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FOOTNOTES

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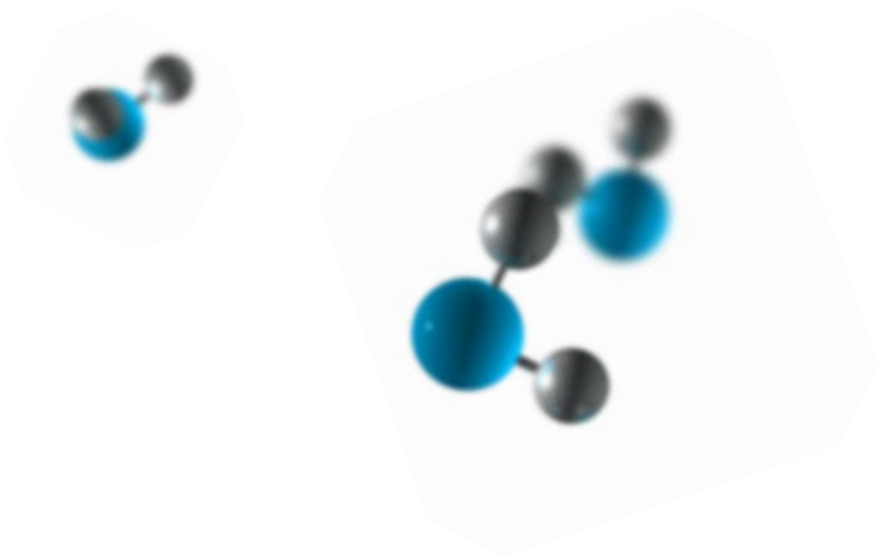

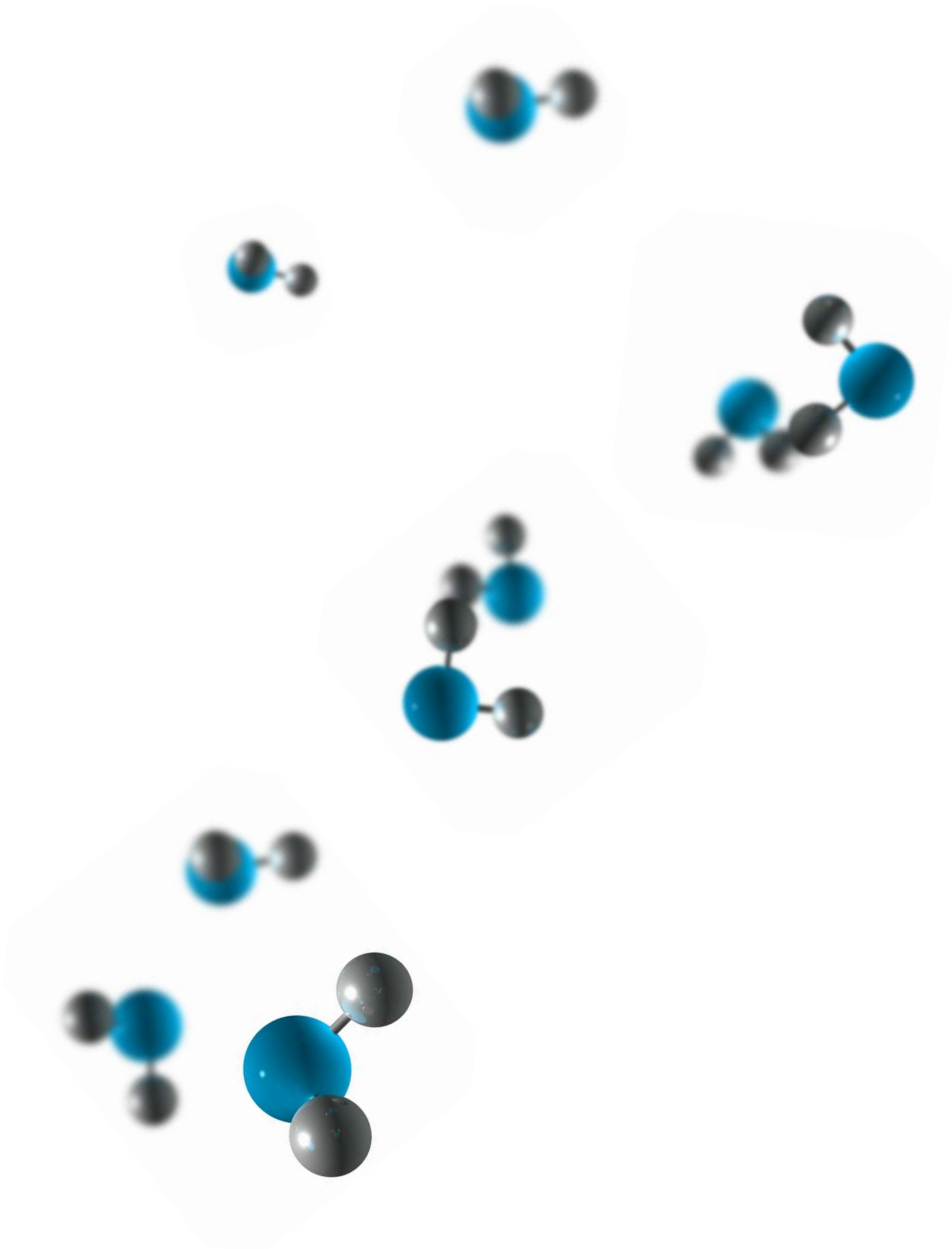

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