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# FUTURE FUEL – FUEL CELLS FOR SHIP BOARD USE INCLUDING PROPULSION

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## INTRODUCTION

Ships are a relatively fuel-efficient means of moving bulk cargo. The crucial role of international shipping in supporting global commerce, carrying as it does an estimated 90% of world trade. The volumes are huge: for containerised cargo alone, the equivalent of 125 million twenty-foot containers was shipped worldwide. It is these quantities that make shipping such a significant contributor to greenhouse gas emissions, accounting for almost 5% of total man-made carbon dioxide emissions , according to the latest comprehensive study by the International Maritime Organisation (IMO) – and $CO_2$ emissions from ships are projected to be more than double by 2050.The IMO is working towards global agreements on $CO_2$ – so far it has achieved an energy efficiency standard for new ships from 2015 – but progress is slow, leading to threats from the European Union to impose its own limits within its waters. But air pollution is as much a concern as GHG emissions. While a country may impose strict limits on the quantities of pollutants that can be emitted by road transport, necessitating the use of catalytic converters on vehicle exhausts, its harbours will host ships for which limits are much looser. Even ships burning cleaner diesel fractions may emit more than necessary, due to a lack of exhaust after treatment. Ships number is in the tens of thousands, so how severe can the effect on air quality really be?. In 2009, a study by the University of Colorado found that “globally, commercial ships emit almost half as much particulate matter pollutants into the air as the total amount released by the world’s cars”, with much of this close to shore. However, regulatory limits on these pollutants are becoming progressively tighter, with certain Emissions Control Areas deemed especially sensitive and subject to a higher level of protection. Something of a revolution in shipping is needed. While obviously much can be accomplished by fairly simple measures, some shipbuilders and operators are on to this gradual evolution with more daring concepts and even proposing fully ‘zero-emission’ ships. So is it possible that fuel cells have a role to play in international shipping?

**Key Words:** *fuel cells*, *Proton Exchange Membrane (PEMFC), Molten Carbonate (MCFC),Millennium Cell- Seaworthy Systems*, *Natural Gas*

## HISTORY AND DEVELOPMENT

The European Commission FCSHIP (fuel cell ship), study concluded in 2004, that the use of fuel cells in ships was feasible. The subsequent METHAPU project set out to evaluate solid oxide fuel cell technology running on methanol for ship’s auxiliary power: a 20 kW fuel cell system from Finnish company Wärtsilä was installed on the deck of the car carrier MV Undine, owned and operated by Wallenius Wilhelmsen Logistics. The 2009/2010 trial showed that the use of fuel cell technology and an alternative fuel poses no more of a risk to a commercial vessel than conventional equipment and fuel, laying the foundation for further deployment. The Fellowship project has tested fuel cell technology integrated with a ship’s propulsion system. Eidesvik Offshore ASA is a specialised fleet operator working in supply, subsea operations, seismic surveying and cable installation; it has a progressive environmental policy and introduced the first gas-fuelled supply ship in 2003. There are now several LNG-fuelled ships in its fleet, among them the Viking Lady. The gas–electric propulsion system of the Viking Lady facilitated the installation, in September 2009, of a 330 kW molten carbonate fuel cell from MTU Onsite Energy, without the need for pre-reforming.

During the trial, the fuel cell logged 18,500 successful operating hours, providing supplementary power to the ship at an electrical efficiency of over 52% at full load. The next phase of FellowSHIP, now underway, is installing a battery pack for energy storage to create a true hybrid propulsion system for the Viking Lady. Eidesvik operates in the Baltic and North Seas. These are both Emissions Control Areas where limits are much stricter since January 2015, so it is not surprising that there is interest in adopting liquefied natural gas (LNG) for shipping in this area – there is a strong business case for doing so. These ships would be ‘fuel-cell-ready’ from a fuel supply point of view.

Professor Zuomin Dong of the University of Victoria, Canada, who has conducted extensive research into hybrid electric and fuel cell propulsion for vehicles and ships, predicted that “LNG-fuelled engines could become the stepping stone for the wide adoption of LNG-fuelled fuel cells as prime movers” for ships. The driver for adoption would be the greater fuel efficiency of fuel cells, but he expects a lengthy transition period via diesel–electric propulsion and/or fuel cell.The 600-passenger Hornblower Hybrid ferry operating in New York harbour has incorporated hydrogen fuel cell and has a power management system that allows the captain to switch power sources as required and combines diesel engines, solar panels, wind turbines and a 32 kW PEM fuel cell from Hydrogenics (hydrogen is stored in an on-board tank).

Scandlines operates a number of ferries in the Baltic Sea; for the 18.5 km crossing between Denmark and Germany over the Fehmarn Belt, a ferry leaves from each harbour every 30 minutes, around the clock and throughout the year. Each crossing consumes almost a ton of fuel oil and emits almost three tons of $CO_2$. That's over 100,000 tons of $CO_2$ emitted annually for just this route, along with almost 3,000 tons of SOx and NOx. To remain competitive, Scandlines needs to find an alternative and it wants that alternative to be zero-emission.

FutureSHIP, a subsidiary of Germanischer Lloyd, has developed a concept for Scandlines that uses fuel cells as the primary source of propulsion: 8.3 MW fuel cells draw fuel from 140 $m^3$ hydrogen tanks, sufficient for a passage of 48 hours at 17 knots. To be truly zero-emission, the idea is to use excess wind energy in Denmark and Germany to renewably produce hydrogen. The most exciting aspect of this design is that FutureShip says it could be implemented on the Baltic ferries within the next five years, as it uses existing technology and the ferries would cost only about 25% more to build than a conventional design. A number of small ferries and boats have already shown the benefits of having fuel cells on board. Although we may have to wait a few years, it seems probable that fuel cells are also a serious prospect in larger ocean-going vessels.

**TYPES OF FUEL CELLS**

Alkaline (AFC)

Proton Exchange Membrane (PEMFC)

Phosphoric Acid (PAFC)

Direct Methanol Fuel Cell (DMFC)

Molten Carbonate (MCFC)

Solid Oxide (SOFC)

**Proton Exchange Membrane (PEMFC**)

The proton exchange membrane fuel cell (PEMFC) uses a water-based, acidic polymer membrane as its electrolyte, with platinum-based electrodes. PEMFC cells operate at relatively low temperatures (below 100 degrees Celsius) and can tailor electrical output to meet dynamic power requirements. Due to the relatively low temperatures and the use of precious metal-based electrodes, these cells must operate on pure hydrogen. PEMFC cells are currently the leading technology for light duty vehicles and materials handling vehicles, and to a lesser extent for stationary and other applications. The PEMFC fuel cell is also sometimes called a polymer electrolyte membrane fuel cell (also PEMFC).Hydrogen fuel is processed at the anode where electrons are separated from protons on the surface of a platinum-based catalyst. The protons pass through the membrane to the cathode side of the cell while the electrons travel in an external circuit, generating the electrical output of the cell. On the cathode side, another precious metal electrode combines the protons and electrons with oxygen to produce water, which is expelled as the only waste product; oxygen can be provided in a purified form, or extracted at the electrode directly from the air.

**Molten Carbonate (MCFC)**

MCFC are high-temperature fuel cells that operate at temperatures of 600 °C and above. Molten carbonate fuel cells (MCFCs) are currently being developed for natural gas, biogas (produced as a result of anaerobic digestion or biomass gasification), and coal-based power plants for electrical utility, industrial, and military applications. MCFCs are high-temperature fuel cells that use an electrolyte composed of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic matrix of beta-alumina solid electrolyte (BASE). Since they operate at extremely high temperatures of 650 °C and above, non-precious] metals can be used as catalysts at the anode and cathode, reducing costs. Improved efficiency is another reason MCFCs offer significant cost reductions over phosphoric acid fuel cells (PAFCs). Molten carbonate fuel cells can reach efficiencies approaching 60%, considerably higher than the 37–42% efficiencies of a phosphoric acid fuel cell plant. When the waste heat is captured and used, overall fuel efficiencies can be as high as 85%. Unlike alkaline, phosphoric acid, and polymer electrolyte membrane fuel cells, MCFCs don't require an external reformer to convert more energy-dense fuels to hydrogen. Due to the high temperatures at which MCFCs operate, these fuels are converted to hydrogen within the fuel cell itself by a process called internal reforming, which also reduces cost.

Molten carbonate fuel cells are not prone to poisoning by carbon monoxide or carbon dioxide — they can even use carbon oxides as fuel — making them more attractive for fueling with gases made from coal. Because they are more resistant to impurities than other fuel cell types, scientists believe that they could even be capable of internal reforming of coal, assuming they can be made resistant to impurities such as sulfur and particulates that result from converting coal, a dirtier fossil fuel source than many others, into hydrogen. Alternatively, because MCFCs require $CO_2$ be delivered to the cathode along with the oxidizer, they can be used to electrochemically separate carbon dioxide from the flue gas of other fossil fuel power plants for sequestration.

The primary disadvantage of current MCFC technology is durability. The high temperatures at which these cells operate and the corrosive electrolyte used accelerate component breakdown and corrosion, decreasing cell life. Scientists are currently exploring corrosion-resistant materials for components as well as fuel cell designs that increase cell life without decreasing performance.

**Solid Oxide (SOFC)**

A fuel cell is like a battery that always runs. It consists of three parts: an electrolyte, an anode, and a cathode.For a solid oxide fuel cell, the electrolyte is a solid ceramic material. The anode and cathode are made from special inks that coat the electrolyte. Unlike other types of fuel cells, no precious metals, corrosive acids, or molten materials are required.Next, an electrochemical reaction converts fuel and air into electricity without combustion.A solid oxide fuel cell is a high temperature fuel cell. At high temperature, warmed air enters the cathode side of the fuel cell and steam mixes with fuel to produce reformed fuel… which enters on the anode side.Next, the chemical reaction begins in the fuel cell. As the reformed fuel crosses the anode, it attracts oxygen ions from the cathode. The oxygen ions combine with the reformed fuel to produce electricity, water, and small amounts of carbon dioxide.The water gets recycled to produce the steam needed to reform the fuel. The process also generates the heat required by the fuel cell.As long as there's fuel, air, and heat, the process continues producing clean, reliable, affordable energy.

**Direct Methanol Fuel Cell (DMFC)**

It is similar to the PEM cell in that it uses a polymer membrane as an electrolyte. However, the platinum-ruthenium catalyst on the DMFC anode is able to draw the hydrogen from liquid methanol, eliminating the need for a fuel reformer. Therefore pure methanol can be used as fuel, hence the name.Methanol offers several advantages as a fuel. It is inexpensive but has a relatively high energy density and can be easily transported and stored. It can be supplied to the fuel cell unit from a liquid reservoir which can be kept topped up, or in cartridges which can be quickly changed out when spent.DMFCs operate in the temperature range from 60ºC to 130ºC and tend to be used in applications with modest power requirements, such as mobile electronic devices or chargers and portable power packs.

**Phosphoric Acid (PAFC) fuel cells**

Phosphoric acid fuel cells (PAFCs) consist of an anode and a cathode made of a finely dispersed platinum catalyst on carbon and a silicon carbide structure that holds the phosphoric acid electrolyte. They are quite resistant to poisoning by carbon monoxide but tend to have lower efficiency than other fuel cell types in producing electricity. However, these cells operate at moderately high temperatures of around 180ºC and overall efficiency can be over 80% if this process heat is harnessed for cogeneration.

This type of fuel cell is used in stationary power generators with output in the 100 kW to 400 kW range to power many commercial premises around the world, and they are also finding application in large vehicles such as buses. Most fuel cell units sold before 2001 used PAFC technology.

**Alkaline (AFC) fuel cells**

AFCs use an alkaline electrolyte such as potassium hydroxide in water and are generally fuelled with pure hydrogen. The first AFCs operated at between 100ºC and 250ºC but typical operating temperatures are now around 70ºC. As a result of the low operating temperature, it is not necessary to employ a platinum catalyst in the system and instead, a variety of non-precious metals can be used as catalysts to speed up the reactions occurring at the anode and cathode. Nickel is the most commonly used catalyst in AFC units.Due to the rate at which the chemical reactions take place these cells offer relatively high fuel to electricity conversion efficiencies, as high as 60% in some applications.

**Why are they so promising?**

- Nearly Zero Emissions
- High Electrical Efficiencies
- Modular Distributed Power Homes outside the power grid (‘PIMBY’)
- Mobile Power
- Silent Operation
- Freedom from fossil fuels like
    - Methane (CH4, or natural gas)
    - Propane
    - Diesel
    - Hydrogen
    - Methanol and
    - Bio Fuels
    - Ethanol
    - Sodium Borohydride
    - Ammonia

**European Union Fuel Cell Technology – Ships**

**Reviewing different fuels:**

LNG

Low S Diesel

Compressed and liquefied H2

Reviewing fuel cells for ship service and propulsion power

**Fuel Cell Issues:**

Fuel Cell Reliability

Marine Environmental Criteria (ship motion, humidity, etc.)

High Temperature

Component Construction (electrolytes, corrosive materials)

Transient Loads

Expensive components

Platinum, Gold

**Reformer Issues**

Processing (Reformer) technology:

The more complex the fuel, the more complex the process to extract hydrogen from it

Impurities

Additional challenges for a marine environment

**Fuel Cell System Issues**

- Fuel Safety issues for non-traditional fuels
- Unfamiliarity & Concerns of Volatility
- Pipe lines & Leak sensors
- Storage
- Processing
- Restrictions and Limitations of Materials.

**Properties of $H_2$**

- Physical data Appearance:
- colourless gas
- Melting point: -259˚ C
- Boiling point: -253˚ C
- Critical temperature -240˚ C
- Vapor density: 0.07 (air = 1)
- Flammability range in air: 4 - 75%
- (Natural Gas: Explosive limits: 5 - 15%)

**Gaseous Fuel Storage Issues**

High Pressure Tank

Not as much energy stored as equivalent volume of gasoline

– High Pressure composite tank standards were quite new

– Hydrogen precipitation issues

Cryogenic Tank High degree of insulation

Reliquefaction not practical

Metal Hydride Storage Low pressure Very Heavy!

Storage issues Regulatory / municipality concerns

**Are Fuel Cells Dead?**

Absolutely not!

The fuel cell and hydrogen revolution is still happening, but much quieter and slower than first thought.The following is far from all-inclusive, but hopefully will prove illustrative of the work that has been accomplished, and will soon be done….

**Carbon Molecular Nanostructure Technology**

Research by National Renewable Energy Laboratory (NREL) and others

Developing a solid-state storage system that is safer than physical storage systems, and could potentially store more hydrogen per unit volume.Solid-state systems composed of microscopic carbon tubes chemically or physically bind hydrogen to a solid material.

**Millennium Cell- Seaworthy Systems**

Releases Hydrogen stored in sodium borohydride (NaBH4 - made from sodium borate or “borax”) (“FREEDOM FUEL”)

Sodium borohydride is nonflammable, non-explosive and safe to produce, store and transportLimited amount of gaseous fuel present in the system at any given time

Produces about the same amount of energy per gallon as that of gasoline.

**Fuel Cell Standards**

ANSI Z 21.83 (Fuel Cell Power Plants)

IMO (IMDG),

US DOT CFR 49

ASME

PTC 50 (Fuel Cell Power System Performance)

B31.12 (Hydrogen Piping)

NFPA

853 (Installation of Stationary FC Power Plants)

70 (NEC) Article 692 (Fuel Cells)

52: (NEC) Article 692 (Fuel Cells)

50A, 50 B, 54, 55 – Hydrogen related

CSA (Component Acceptance Service)

PEM FC

Residential FC

Portable FC

Appliances Hydrogen Generators

ISO TC 197 (Hydrogen Technologies)

UL 1741 (Inverters, Converters and Controllers)

2264 (Hydrogen Appliances)

2265 (Replacement FC Power Units for Appliances)

IEC TC 105 (62282-3-1 - Fuel Cell Power Plants)

Also: IEEE, SAE, ICC, NES

**The Era of Natural Gas?**

LNG Supply and Demand

Natural gas will be playing a greater role in the global energy mix

Increased use for transportation and power plants

– OSVs, ferries, container carriers, tankers, offshore drilling units Environmental drivers

– Emission Control Areas (ECAs)

US becoming an exporter

LNG Demand in China, Japan & India

### The Age of Natural Gas

Natural gas will be playing a greater role in the global energy mix for the foreseeable future US is poised to become a new exporter of LNG

LNG as fuel for the marine industry will increase dramatically

OSVs, ferries, container carriers, tankers, offshore drilling units

Many ‘Golf cart’ efforts

Possible use of MCFCs?

By 2030 shale sources will likely make up 1/3 of the total US oil and gas production

Environmental drivers

– Emission Control Areas (ECAs)

Engineers Devise New Way to Produce Clean Hydrogen (Duke University)

Significant Improvement in Performance of Solar-Powered Hydrogen Generation

National Institute of Standards and Technology (NIST) have shed new light on what may become a cost-effective way to generate hydrogen gas directly from water and sunlight.

Metal-Free Catalyst Outperforms Platinum in Fuel Cell Researchers from South Korea, Case Western Reserve University and University of North Texas have discovered an inexpensive and easily produced catalyst that performs better than platinum in oxygen-reduction reactions.

## CONCLUSION

**Feasibility and Design Implications of Fuel Cell Power for Ships:**

**The study indicates,**

“…fuel cell powered equipments has tremendous potential in reducing fuel consumption and NOx emissions. The associated economic and environmental benefits present a great incentive for naval and maritime industry to pursue fuel cell technology for the next generation green cargo ships.”

“The extended range and improved endurance, together with the reduced fuel cost and environmental impact, also represent a unique opportunity for military sealift ships.” National and regional incentive schemes for environmentally friendly technologies could also play a central role regarding when fuel cells can become cost competitive. Increased availability of alternative fuels, such as LNG and hydrogen, may also accelerate introduction.

It is concluded that fuel cells for shipping require further R&D before this technology can complement existing powering technologies. However, in the near future we might expect to see successful niche applications for some specialised ships, particularly with hybrid systems. Good deal of further study and research needed.