A HYDROGEN FUELLED FAST MARINE TRANSPORTATION SYSTEM

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ABSTRACT:

Hydrogen may offer considerable potential as a marine fuel. The lower fuel mass when compared with existing hydrocarbon fuels can usefully increase payload which in turn benefits the economics of oceanic transport and provides the opportunity to compete in new markets. The potential to virtually eliminate pollution at the point of use may prove significant at a time when exhaust emissions from shipping are becoming a matter of global concern. The potential for hydrogen in the marine environment, the current state of transferable technologies, the particular technical and economic issues that need to be addressed are considered in the context of a design study being conducted on a high speed foil-assisted catamaran capable of transporting 600 industry standard containers at speeds of up to 64 knots (118.5 km/hr) over trans-Pacific and trans-Atlantic trade routes. It is concluded that such a vessel is technically feasible and could achieve door-to-door delivery times as part of an integrated transport chain otherwise only possible by airfreight but at a fraction of the cost.

KEYWORDS : *Marine fuel, container transport, gas turbines, maritime economics*

1. INTRODUCTION

Whilst the majority of transport related hydrogen research is, perhaps understandably, concerned with road vehicles hydrogen may also offer considerable potential as an aviation and marine fuel. Hydrogen fuelling of aircraft has already been investigated in some detail [1, 2] but hitherto very little research has been conducted into hydrogen fuel in marine transport applications. The only reported work concerns experiments on a small, 260kW, gas turbine installation in a US Navy landing craft which was successfully converted to hydrogen fuelling [3]. This paper examines the potential for hydrogen fuelling of ships and considers some of the particular technological issues involved. Work on the design of a hydrogen fuelled high-speed Foil-Assisted Catamaran (FAC) containership is reported.

As with other transport applications, hydrogen as a marine fuel offers a much higher gravimetric energy density than current hydrocarbon fuels and the potential to minimise harmful exhaust emissions at the point of use. In the case of land vehicles the relatively poor volumetric energy density achieved by even the most effective of the storage options [4] can be a limiting factor but for ships, particularly the larger container vessels, it can be the mass of fuel carried rather than its volume that is of greatest concern. Especially, when requiring operational fuel ranges sufficient for ocean crossings. Reducing this fuel mass can usefully increase payload which in turn benefits the economics of operation. This is particularly the case with high-speed vessels where the mass of the hydrocarbon fuel load is proportionally greater, particularly in comparison to the payload, making economic exploitation of such ships extremely difficult. For liquid hydrogen use in high-speed ships it can generally be assumed that the hydrocarbon fuel weight can be reduced by a factor of 2.8 and that the fuel volume needs to be increased by a factor of 4. These fuel mass reduction and fuel volume increasing factors are readily derived [1] from the heating values and densities of liquid hydrocarbon and hydrogen fuels. These fuel related mass and volume factors provide some indication of the fuel mass reduction potential available for high-speed ships, generally having a hydrocarbon fuel mass larger than the actual payload of the vessel [5].

With regard to marine based exhaust emissions, larger vessels tend currently to be fuelled by the heavier grades of hydrocarbon that remain after gasoline, kerosene and the lighter fuel oils have been distilled from the feedstock. Such heavy fuel oils contain relatively more sulphur than lighter fuel oils and as a result sea and port based emissions tend to be higher than for lighter fuel oils. For example, maritime transport accounts for about 3% of global petroleum consumption but contributes 14% of NO_x and 16% of SO_x globally [6]. However, proportionately, CO_2 emissions are relatively low since the thermal efficiency of the engines (or combined cycle turbines) used in large vessels [7] tend to be amongst the highest of all prime movers and can rival that of static combined cycle generating plant. Despite this high efficiency, significant quantities of CO_2 are released during passage and sequestration is not feasible. Nonetheless, concern about marine pollution has led the EU to consider taxation of these marine emissions and is also a driver in US hydrogen marine research [8, 6, 9]. It is expected that such emission taxation will be in the form of a carbon trading scheme and will significantly influence economic operations of members of the marine shipping community. These developments suggest that there is likely to be a growing interest in hydrogen as a marine fuel. Replacing hydrocarbon marine fuels with hydrogen would eliminate SO_2, significantly reduce NO_x and transfer CO_2 emissions from the point of use, the ship, to a possible onshore hydrogen fuel terminal. Would such a terminal use natural gas as a hydrogen feedstock, then CO_2 recovery and sequestration from hydrogen production become a potential option. Carbon sequestration is being actively considered by both Governments and the oil industry [10]. For example, CO_2 pressurisation of depleted oil wells can be used to enhance oil recovery and is currently proposed for the North Sea oil fields [11]. Whilst the technique increases production costs by some 7% the overall economics are positive.

Whilst the potential advantages of hydrogen for land-based and marine, and indeed aviation, transport are similar the means of energy conversion are likely to be different. Judged by current volumes of research, fuel cells combined with electric propulsion would appear to be the favoured replacement for the internal combustion engine in road vehicle applications. However, the upper boundary of fuel cell output [12] based upon current technology would appear to limit their application to small commercial vessels (e.g. fishing boats or coastal ferries) or fast pleasure craft. An ocean going container ship or bulk carrier may have a nominal engine rating of 50 MW and ratings of 100 MW and above are envisaged for future designs [13]. Smaller, but faster, passenger ships and fast ferries also have propulsion requirements measured in tens of MW [14]. It seems likely, therefore, that, at least in the short to medium term, the prime mover for hydrogen-fuelled ships will need to be a suitably modified Internal Combustion Engine (ICE) or gas turbine. Fortunately there is much transferable technology available from other sectors.

Considerable research has already been undertaken by automotive companies [15] into hydrogen fuelling of ICE. Whilst these are very much smaller, and in most cases of somewhat different design, to the engines used for ship propulsion the principle is nevertheless proven. It is possible that gas turbines will be the preferred choice of prime mover for a hydrogen fuelled ship because of their high power density and relative ease of installation (marine turbines tend to be leased by their manufacturers as 'drop in' power modules [16] on full service contracts). Once again, the feasibility of hydrogen fuelling has already been demonstrated in other sectors and in these cases the power ratings are of the same order as envisaged for marine propulsion. In addition to specific research on the potential of hydrogen as an aviation fuel [1], aero-derivative gas turbines are widely employed in refineries (driving generators and compressors) where the fuel is hydrogen-rich process gas of up to 97% purity and the 100% purity hydrogen gas case has already been reviewed in some detail [17-19]. The hydrogen combustion process taking place inside the annular combustors of these aero-derivative gas turbines does generate NO_x emissions. The formation of NO_x is mainly depended on the combustion chamber pressure & combustion flame temperature and changes to these combustion characteristics can significantly influence the formation of NO_x [20]. Current aviation gas turbine research focuses on lowering the combustion temperature and simultaneously improving the mixing of the H_2 fuel and compressed air by designing new fuel nozzles focusing on either lean premix combustion systems [21] or reducing the scale of the fuel nozzles [22] (micro-mix burners) to improve pre-combustion hydrogen – air fuel mixtures. Both methods substantially reduce NOx emissions from gas turbine based hydrogen combustion compared to kerosene combustion.

In order to evaluate the technical and economic potential of hydrogen fuel in fast marine transport a design study is being conducted based around a high-speed long-haul feeder container ship. The study involves establishing the hydrogen fuel consumption and subsequent financial requirements satisfying this fuel demand on three ocean crossing sea routes for the container feeder ship. Hydrogen fuel supply is envisaged to be supplied by dedicated hydrogen marine terminals located in each end port of each ocean route. The financial expenditure, created by the hydrogen fuel consumption, capital investment of the containerships and hydrogen marine fuel terminals, is to be matched by transport income. Subsequently, minimum transport unit pricing may be established for both zero profit and zero net present value conditions to identify market positioning of a potential hydrogen fuelled fast marine container transport service. The naval architecture of the design is in itself advanced [23, 24] as the ship design involves a dynamically foil-assisted catamaran (FAC) combining both foil lift and buoyancy lift into one ship concept to improve transport efficiency beyond those of current in-service high-speed ships [25]. The 175 m vessel is designed to carry 600 TEU (Twenty feet Equivalent container Unit) at speeds up to 64 knots (118.5 km/hr) over a range 5300 nautical miles (≈ 10,000 km). Propulsion will be provided by four aero-derivative gas turbines driving water jets and the hydrogen will be carried as a cryogenic liquid. This type of vessel is intended to meet the demand for transport of time-sensitive products, subject to Just-In-Time (JIT) supply chain management, on both Pacific and Atlantic trade routes.

2. FAST MARINE CONTAINER TRANSPORT

Consumer product life cycle times have significantly reduced in the nineties and early 2000 compared to the seventies [26]. Technological advances have partially driven this life cycle time reduction in conjunction with market competition between consumer product manufacturers and the advent of exterior product design. For example, in the seventies one manufacturer produced only one version of a typical consumer product. Currently, multiple versions of the same product are now available from a wide range of manufacturers. For consumer product manufactures this has meant that time available to design and produce these products has reduced significantly. Consequently, consumer product companies changed their production systems and internal mechanisms to meet these new market conditions, culminating in Just-In-Time management schemes and lean production setups. The marine container transport sector is a crucial linking mechanism for many consumer product manufacturers with their market place. The current marine container transport industry is an highly evolved and efficient transport industry [27], but further efficiency gains in conjunction with a further reduction in unit transport costs are sought via economies of scale. Subsequently, the current and near future containership designs have container capacities ranging from 9,600 20' TEU currently to 12,000 - 15,000 TEU for near future designs. The increase in containership size will influence other transport links within the marine container transport chain, such as the increased amount of container moves required to empty such a large containership. Consequently, it can be argued that the actual door-to-door delivery times within the marine transport industry will actually increase, rather then speed up in the near future. This is in sharp contrast with the requirements of consumer product manufacturers aiming to bring their goods quicker to market. The fast marine container transport system presented here aims to provide an alternative to the current marine containerships in both speed and delivery time. The high-speed FAC containership, subject of this design study, is intended to operate between conventional marine container transport and aviation transport, aiming to provide transport cost competition primarily with aviation and transport time competition with conventional marine container ships. Hydrogen fuelling of high-speed containerships allows this competition to take place. The existence of the middle cargo transport market between conventional shipping and aviation door-to-door delivery times on inter-continental crossings has been identified previously [28-32]. Additionally, the smaller container capacity of the FAC container ship in combination with its high speed allows for more operational and scheduling flexibility on long-haul sea routes for container shippers.

Figure 1: Rendering of LH_2 fuelled high-speed FAC containership.

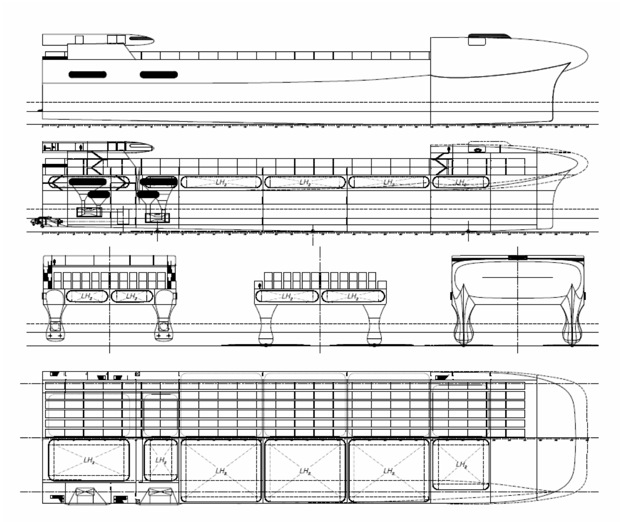

Figure 2: Cross-sections of the FAC containership.

Figure 1 and Figure 2 provide an exterior view and cross-sections of the high-speed FAC containership respectively, while Table 1 provides the ship's main dimensions, speed, machinery details and hydrogen fuel storage capacity. As indicated previously, the LH_2 fuelling is fundamental to the feasibility of the proposed FAC, the high speed and high transport efficiency also depend upon the advanced naval architecture of the design which employs hydrofoils located at the keels of the catamaran demi-hulls to generate hydrodynamic lift (See vertical cross-section in Figure 2). This lift (magnitude ≈ 3000 tonnes) reduces wetted area (which limits speed) and increases payload capacity and hence contributes to a high transport efficiency. Hydrodynamic resistance depends on the ship speed squared and the wetted area (S_w) of the hull(s) and other immersed surfaces. In the case of high-speed ships, particularly catamarans, this is often the primary resistance component. For a given installed power, ship speed can ultimately only be increased by reducing wetted area. In the proposed design the hydrofoils produce a vertical elevation of 2.95m at the design speed of 64 knots, reducing the draught from a static value of 7.20m to 4.25m (Figure 2 shows these two waterlines in the profile views). This leads to a reduction in wetted area of 2020m^2, ≈39% of the static wetted area, which has a significant impact on the propulsion power required and consequently on the technical and economic feasibility of the design. A secondary benefit of the hydrofoils are their effect on ship motion behaviour when compared with catamarans without foils [33]. Earlier research [23] indicated that at the proposed speeds for certain wave conditions the ship motions would be too excessive for human comfort without the hydrofoil damping effect.

Ship particulars	Units	Value
Length overall / Length waterline	[m]	175.50 / 164.18
Beam (container deck) / Beam (foils)	[m]	42.50 / 62.15
Depth (WT deck) / Depth (Top of superstructure)	[m]	18.30 / 29.05
Draught (service speed) / Draught (floating)	[m]	4.25 / 7.20
Machinery	[MW]	4 x GE LM Sprint 6000 turbines 196.8 (4 x 49.2)
Container capacity / Payload max weight	[TEU] / [tonnes]	600 / 3000
LH_2 fuel capacity	[m^3] / [tonnes]	14,214.3 / 1001.0
Service speed	[Knots] / [km/hr]	64.0 / 118.5
Range	[N. miles] / [km]	5300 / 9815.6
Crew		18

Table 1: High-speed LH_2 container feeder ship particulars.

Route no.	Start Port	End Port	Distance		Time	Departure freq.[a]	LH_2 fuel load [a]
			[N. Miles]	[km]	[hours]	[dep./4wks]	[tonnes]
1	Yokohama	Tacoma	4274	7915	66.78	9	911.2
2	Philadelphia	Cherbourg	3265	6047	51.02	12	696.1
3	Yokohama	Long Beach	4838	8960	75.59	8	1031.4
a:	Applies to one ship only						

Table 2: Investigated ocean transport routes

The main dimensions and layout of the FAC are influenced by the requirement to accommodate 600 TEU and the LH_2 fuel in a configuration that provides the desired sea-keeping properties (i.e. stability, speed, manoeuvrability, ability to cope with a range of sea states). Hydrodynamic considerations determine optimum catamaran hull-spacing [34] and ship/wave interference effects influence resistance. In the proposed design the container layout is 25 TEU in length and 12 TEU in beam resulting in the specification detailed in Table 1 for the ship design previously presented in Figure 1 and Figure 2. In order to minimise ship weight, and provide a high strength-to-weight ratio, the vessel is designed to be constructed principally of welded aluminium alloy. Similarly, it is anticipated that the container units themselves would be of aluminium.

Propulsion for the FAC is delivered by four 2.5m diameter waterjets each driven by its own gas turbine. This type of propulsion is needed because conventional propellers become impractical at such high ship speeds [35]. Two aero-derivative gas turbines, suitably modified for hydrogen operation, and two waterjets are located in each demi-hull, see the general arrangement in Figure 2. For reasons of safety and redundancy, each turbine occupies a separate engine room, arranged in tandem along the demi-hull, and is linked to its respective aft-mounted waterjet by a drive shaft connected via a gearbox located between the engine rooms. The aft turbine is positioned higher than the forward turbine allowing the two outgoing shafts from the gearbox to pass beneath this turbine. The design is based around LM6000 Sprint gas turbines manufactured by General Electric [16]. These have a maximum output of 49.2 MW per unit and for marine propulsion are supplied in self-contained power modules intended for 'drop in' installation. It is anticipated that auxiliary power for the ship will provided by smaller turbine/generator sets, fuelled by boil-off gas (often referred to as Auxiliary Power Units (APU).

The Specific Fuel Consumption (SFC) of the four LM6000 gas turbines used for propulsion can be estimated from experimental data on similar hydrogen fuelled turbines [18]. This indicates that a modest increase in thermal efficiency of about 2% might be expected when burning hydrogen rather than liquid hydrocarbon fuels. Assuming stoichiometric combustion of hydrogen having a calorific value of 120,650 kJ/kg and a quoted thermal efficiency for the turbines of 42.7% [16], with further enhancement of 2% to reflect the improved performance when fuelled with hydrogen, the fuel consumption rate per turbine is calculated as 0.8614 kg/s for an output of 46.45MW, the required power per turbine needed to drive the ship at its 64 knots service speed. Three potential long-haul ocean crossing routes have been selected to test the commercial viability of the hydrogen fuelled FAC containership, which is discussed in Section 4 of this paper. The three routes represent a North and South Pacific ocean crossing in addition to a North Atlantic crossing and are indicated in Table 2. Combining the established SFC figure for the utilized gas turbines with the projected sea time spent at each route enables the minimum fuel load for each route to be calculated. A 10% reserve must be added to satisfy the requirements of ship design codes. These minimum fuel loads are also indicated in Table 2 in addition to the departure frequency per ship in a four week period on each route. The information presented in this table forms the basis of the scale of the hydrogen production plant based in each port supplying these ships.

Whilst provision of fuel storage volume is much less of a problem in ships than most other forms of transport, placement and integration of fuel tanks is still an important design consideration, irrespective of fuel type, particularly where the quantities needed for trans-oceanic range at high ship speeds are involved. One of the advantages of the proposed catamaran ship configuration is that the cross-body structure linking the demi-hulls lends itself to the storage of large volumes of LH_2 in cryogenic tanks. For operation on trans-Pacific routes (the longest anticipated) at the design speed of 64 knots a fuel capacity of approximately 14.2×10^3 m^3 LH_2 is needed. In the proposed design this is divided between twelve tanks accommodated in a 5m high deck space in the cross-body.

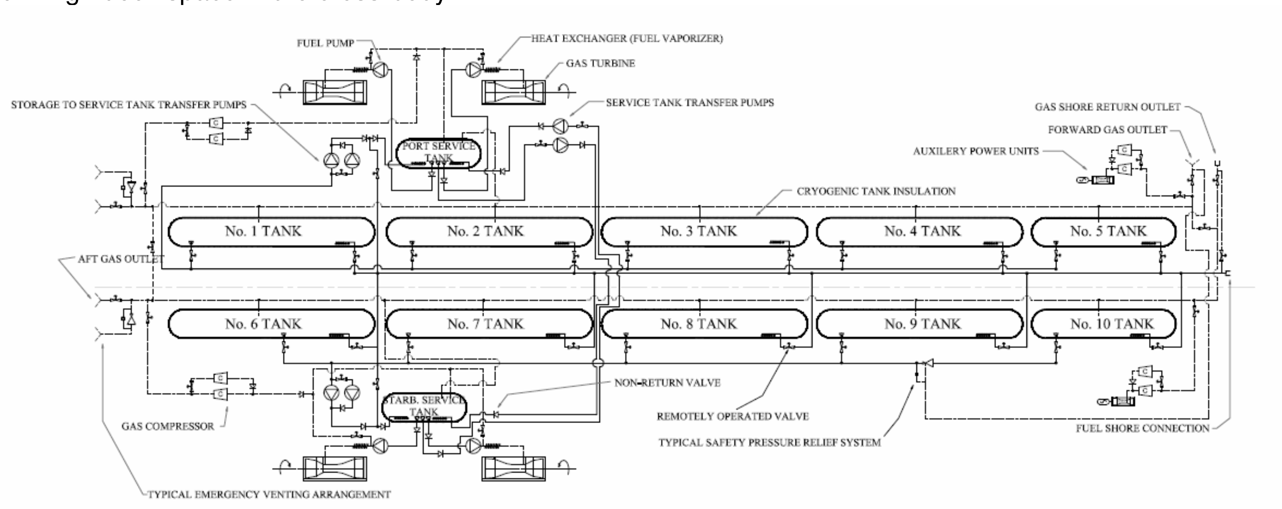

Figure 3: System schematic of the LH_2 fuel system onboard the FAC containership.

A schematic of the fuel system is presented in Figure 3. There are ten main storage tanks located between the cross-body decks. In addition, there are two, smaller, service tanks each of which supplies the propulsion gas turbine units in one demi-hull. Liquid transfer lines run the full length of the ship allowing LH_2 to be pumped between tanks. The pumps and valves are arranged to enable transfer between any of the individual storage tanks and between the storage tanks and service tanks. Gaseous transfer lines, also running the full length of the ship, allow boil-off gas to be directed to empty (or partially empty) tanks and the propulsion and auxiliary power turbines as required. Compressors are used to boost gas line pressures to the level required for injection into the turbine combustion chambers. Duplicate liquid pumps and gas compressors are included in the system for reasons of safety and redundancy. During normal operation at sea the service tanks are kept at a constant fill level by pumping LH_2 from the storage tanks. Turbine driven pumps are used to transfer fuel from the service tanks to vaporizers and also provide gas injection pressure to the turbine combustion chambers. During refuelling operations in port a closed loop allows gaseous hydrogen (GH_2) displaced from the, still cold, tanks to be recovered for re-liquefaction. Similarly, any boil-off gas not required by the APU whilst in port is returned to the hydrogen marine terminal.

A potential pressure hazard due to the significant expansion ratio from liquid to vapour always exists when using cryogenic fluids [29]. In the case of hydrogen, at a pressure of 1 bar the volume increase from saturated liquid to saturated vapour (i.e. at its boiling point of 20.4K) is a little over 50 but if the vapour is then allowed to warm to ambient temperatures the volume increase is of the order 845. It is therefore vital that pressure relief and venting systems are fitted to protect every part of the system in which a volume of LH_2 could become trapped. A typical system would combine pressure relief valves, to vent small overpressures, and a bursting disc as the ultimate safety device. By way of example, Figure 3 shows such a combination protecting each side of the fuel system (adjacent to tanks 1 an 6 respectively) but the detailed design includes overpressure protection at numerous points. The liquid to gas expansion ratio of hydrogen mentioned previously also increases the potential of a significant pressure build up inside the fuel tank containment space onboard the ship in case of a significant tank failure with serious consequences for the ship structural integrity. The LH_2 fuel tank containment space should therefore be fitted with an emergency ventilation system as indicated by a recent safety study by the American Bureau of Shipping (ABS) for fuel cells onboard ships for auxiliary power [6].

The design of the on-board LH_2 storage tanks is crucial to the viability of the overall system. The tank shells are fabricated from aluminium alloy [36] which unlike certain steels does not exhibit low temperature embrittlement and is therefore quite suitable for use at LH_2 temperatures. Usual cryogenic practice is to employ vacuum insulated storage Dewars but these are neither necessary nor desirable in this application being relatively heavy, fragile and expensive. In the majority of applications involving cryogens minimising boil-off due to heat in-leak is a major concern. However, in this application there is a need to vaporize the LH_2 at a significant rate. In principle, the level of insulation required need only be such that the rate of boil-off is equal to the consumption of the turbines. This would also obviate the need for separate vaporizers. In practice, the size of the gas lines required would become impractically large, control and balancing of individual tanks difficult and the energy consumed in re-liquefying boil-off whilst refuelling and loading significant. Conveniently, LH_2 boil-off can be maintained at a manageable rate without resort to vacuum insulation. A dual layer of 75mm closed cell polyurethane foam (density 35.24 kg/m^3, thermal conductivity ≈0.02 W/mK) separated by Mylar/Aluminium foil/Dacron vapour barriers provide the required level of insulation which is robust, light-weight and inexpensive. A similar solution was proposed in the LH_2 aircraft study [1] and structural foams (or in some instances Balsa wood) is commonly employed to insulate the tanks aboard LNG carriers (where the boil-off is again used to fuel the propulsion system). The tank material used here is 5083 aluminium alloy. The tanks are designed to operate at minimal over-pressure with relief valves set to operate at 2 bar absolute. Wall thickness varies from 6 mm to 10 mm and the shells are reinforced with stiffening ribs. The aluminium itself (conductivity ≈ 109 W/mK) offers minimal thermal resistance and assuming a temperature differential of approximately 280 K between ambient and the LH_2 the effective surface transfer coefficient of the insulation and wall is of the order 10 W/m^2.

The vapour barriers are crucial to the safety of the whole ship and must also form part of the insulation on all cold pipelines. The hazard is one of air liquefaction [37] and oxygen enrichment. Gaseous air comprises approximately of 21% oxygen and 79% nitrogen but the equilibrium composition at its dew point of approximately 81 K (-192^{o}C) is 50% - 50%. It follows that air will condense on any exposed surface below this temperature which will be the case for most of the LH_2 and GH_2 pipelines in addition to the storage tanks. Even assuming no leakage of hydrogen, liquid oxygen in contact with oil, combustible waste and even many materials not normally considered combustible can create a fire and/or explosion hazard and must be prevented at all cost. These potential hazards in using hydrogen clearly state the requirement for sensors measuring the hydrogen content in areas containing the fuel tanks. In addition, oxygen sensors are needed to monitor for both oxygen enrichment due to air liquefaction in the event of insulation failure or an asphyxiation hazard in the event of oxygen displacement. Such sensors need to form part of the ships integrated safety system.

Design and operations modelling of the FAC are based upon the needs of two trans-Pacific routes, Tacoma-Yokohama and Long Beach-Yokohama, and one trans-Atlantic route, Philadelphia-Cherbourg, each chosen because of their strategic and economic significance. The route lengths and estimated voyage times at the design speed of 64 knots are given in Table 2. Each route employs two FAC ships, sailing simultaneously in opposite direction, serviced by a dedicated container terminal combined with a hydrogen marine fuel terminal in each port. Turn-around operations for each ship when berthed in the terminal involves refuelling and the cargo unloading/loading cycle. It is estimated that these operations can be completed within eight hours. Given this route information and unit fuel load data for each refuelling cycle, the operating profile of each combined container terminal/hydrogen marine terminal and each FAC containership can be established over a four-week period. The departure frequencies for the three routes considered are 9, 12 and 8 respectively in a 4-week (nominal month) period. The corresponding annual container flows in each direction are 140,700, 187,200 and 124,800 TEU respectively, while the annual fuel consumption by two ships on routes 1 to 3 are 213,208, 217,189 and 214,532 tonnes LH_2. This ship fuel demand information can now function as input for the hydrogen marine fuel terminal capacity and its input and output demand cycle, described in Section 3 of this paper.

3. HYDROGEN PORT-SIDE INFRASTRUCTURE

The main components of the onshore hydrogen marine fuel terminal are the Steam Methane Reformation plant (SMR) plant, in which GH_2 is produced from Natural Gas (NG) feedstock, and the cryogenic plant in which the GH_2 is liquefied before being delivered to storage tanks. Both processes are described in detail by [38]. The main plant input is, of course, NG assumed to be primarily methane but in addition grid electricity is required to drive the liquefaction system, the fuel delivery pumps/compressors and associated systems. A representative electrical energy consumption for the liquefaction process is 8.88 kWh/kg LH_2 [39]. The additional electricity used for LH_2 pumping, either between tanks or from shore-to-ship, and boil-off gas compression is negligible by comparison. It is well know that the SMR process generates CO_2 as a by-product at a rate of 10.66 CO_2 kg/kg H_2 [40] in creating hydrogen fuel. The CO_2 emissions associated with liquefaction are approximately 2.13 kg/kg LH_2, based on unit emissions of 0.24 kg CO_2 per kWh for grid electricity [41] and the unit energy consumption for large scale hydrogen liquefaction, mentioned previously. The total CO_2 emissions associated with the reformation and liquefaction process are therefore of the order 12.79 kg/kg LH_2 and it is this figure that may be used to establish total emissions of the hydrogen marine fuel terminals in case no CO_2 sequestration of the marine fuel terminals is planned. However, CO_2 sequestration could potentially provide this form of hydrogen marine fuel production as a zero carbon emission method and subsequently provide carbon free marine container transport.

The capacities of the hydrogen marine fuel terminals must be such that sufficient LH_2 can be produced and stored whilst the vessels are at sea to ensure that turnaround time in port is determined by cargo handling considerations rather than any limitation on fuel availability or production rate. The passage times vary for the three routes under consideration but are, of course, directly related to the lengths of the routes which in turn determine the quantity of fuel consumed. As a result, whilst the available production time varies from approximately 59 hours (route 1) to 84 hours (route 3) the capacities of the plants required to service the proposed routes are all similar at ≈12 tonnes/hour as shown in Table 3. The table also lists the volumetric outputs of the SMR plant (GH_2) and liquefier (LH_2) which are in the ratio of 845:1 corresponding to the expansion ratio of hydrogen from saturated liquid at 1 bar to gas at normal temperature & pressure [42]. The corresponding NG input to the SMR is determined from the knowledge that 70% of the NG is reformed to GH_2 whilst 30% is consumed in providing the thermal input to the SMR process.

Route no.	**Production time**	**LH_2 production requirement**	**Liquefaction plant capacity**		**SMR GH_2 output capacity**	**NG SMR input flow [b]**
[-]	[hours]	[m^3]	[m^3/hr]	[tonnes/hr][a]	[m^3/hr]	[MBTU/hr]
1	74.78	12,938.8	173.1	12.192	146,300.0	2138.82
2	59.02	9,885.2	167.6	11.801	141,600.0	2070.10
3	83.59	14,646.4	175.7	12.376	148,500.0	2170.98

a: Density of liquid hydrogen used here is 70.42 kg/m3
b: The efficiency of the SMR process used here is 70%.

Table 3: Hydrogen fuel plant capacities determined from ship fuel demand cycle for the three target routes.

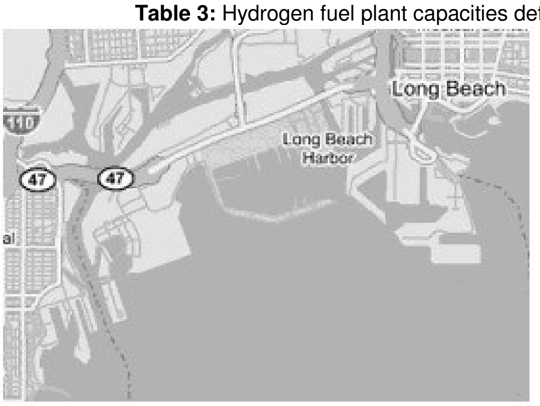

Figure 4: Long Beach (USA) existing port layout.

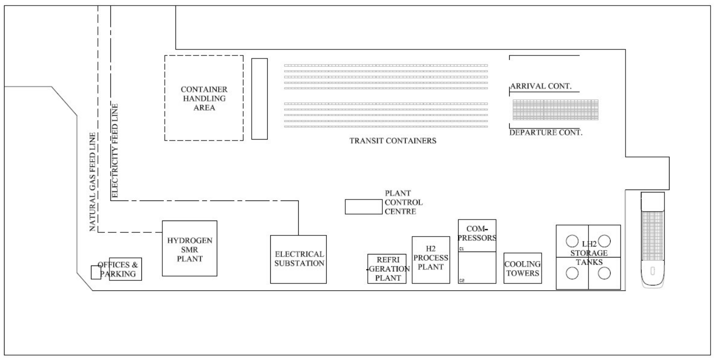

Figure 5: H_2 plant layout on existing port island of Long Beach port.

Considering route 3 (Long Beach – Yokohama) by way of example, the existing Long Beach port layout is shown in Figure 4 and a possible configuration for the hydrogen terminal appears in Figure 5. The island indicated in the middle-right of Figure 4, currently in use as a container terminal, would be an ideal location for the new terminal being accessible, yet sufficiently isolated to satisfy safety requirements, and offering the required space. While the hydrogen SMR plant has a relatively small footprint, the hydrogen liquefaction plant and storage tanks occupy significant space. The footprint requirements for the liquefaction plant are based upon the study into a large hydrogen facility at San Francisco airport [1] but scaled to reflect the fact that this study was based upon a capacity of 1000 tonnes/day rather than the 297 tonnes/day required for the fast ship facility. The SMR footprint is scaled from a contemporary plant operated by the BOC Group [43].

Various other hydrogen fuel plant layouts are possible, including the option of locating parts of the fuel plant and LH_2 storage tanks underground, but the proposed layout reflects the desire that at this early stage the facility should be kept as simple as possible and capital costs minimised. The scale and design of the facility might also change significantly if it were decided to use the opportunity to develop an infrastructure to serve markets other than the fast ship and immediate port operations. Further research and detailed engineering design will be needed to fully investigate, and exploit, the potential of any new port hydrogen facility.

4. ECONOMIC ASPECTS

Economic evaluation of the hydrogen fuelled high-speed FAC containership designs, presented in Section 2 of this paper, are discussed here on the three long-haul ocean routes, indicated in Table 2. The economic evaluation aims to identify the market position within the marine container transport industry of the hydrogen fuelled FAC containerships. Two economic tools are utilized in the evaluation, zero profit and zero Net Present Value (NPV) analysis. Although it is not expected that a potential shipping company utilizing these type of high-speed ships and marine fuel terminals would operate within either a zero profit or zero NPV situation, the identified unit transport costs from these two these two artificial economic situations allows comparison with other conventional forms of transport. Such a comparison would provide some indication into the commercial viability of the presented hydrogen fuelled ship designs, but also on hydrogen marine fuel in general. In the evaluation, both initial capital investment and operational running costs are identified. Finally, identified unit transport costs from the analysis will be compared with other hydrocarbon fuelled high-speed containership design projects and conventional container shipping.

Investment type [-]	**No. of** [-]	**Unit costs** [M. €]	**Total costs** [M. €]
LH_2 ship.	2	94.97	189.93
Terminals	2	20.00	40.00
H_2 SMR plant	2	112.69	225.38
LH_2 plant & site storage	2	9.97	19.95
Aluminium containers	1	117.00	117.00
Total			592.25

Table 4: Capital investment Route 3.

Route	**Transport rate Zero Profit***		**Transport rate Zero NPV***	
	[€/TEU]	[€/kg]	[€/TEU]	[€/kg]
1	2,505.29	3,069.23	0.501	0.614
2	1,928.18	2,353.58	0.386	0.471
3	2,823.35	3,460.22	0.565	0.692
Including linear depreciation of invested capital.				

Table 5: Identified transport rates for break-even operation.

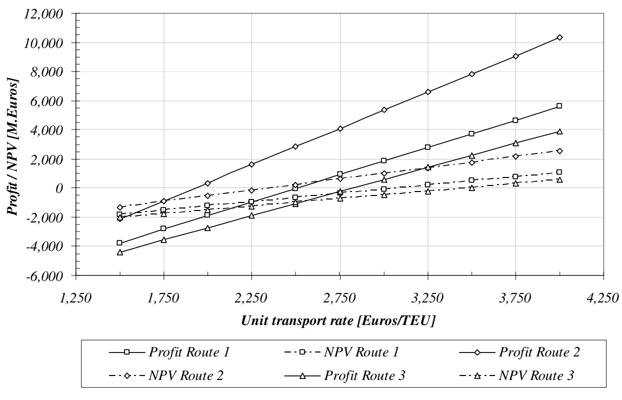

Figure 6: Economic evaluation results routes 1 to 3.

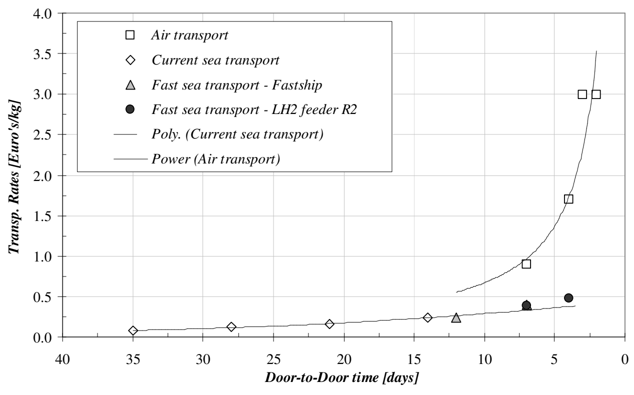

Figure 7: North Atlantic unit transport costs by mass.

Capital cost for the ships is difficult to estimate because of the novelty and complexity of the design. However an indication can be gained by comparing published contract values for similar sized fast catamarans, such as the HSS Stena 1500 [44] and applying coefficient based analysis. The coefficients are based on the fraction between the main dimensions & ship speed over the installed propulsion power. Such analysis indicates a capital cost of 85.6M.€ per FAC containership. A 15% contingency has been added to reflect the novelty of the H_2 FAC giving a final figure of 95M.€. Linear depreciation of the ships, and other capital costs, has been included in the economic model. The residual value expected after a 25-year service life is 20% of initial investment.

Previous research [45, 39] has indicated that H_2 fuel plant capital costs and H_2 unit cost depend on the capacity of the SMR and liquefaction plants. In this application, this is determined by the refuelling requirements of each ship which is in turn route dependent.. These LH_2 fuel quantities are 911.2, 696.1 and

1031.4 tonnes for routes 1 to 3 respectively, indicated in Table 2. Combining fuel load data with ship departure frequency leads to the required block period fuel capacity per terminal. The average production rate across all the routes is 145.5x10^3 m^3/hr H_2 gas which is liquefied to yield 12.1x10^3 kg/hr LH_2 fuel. Utilizing investment data from this previous research of 8.04 €/GJ and 0.09 €/kg for the unit capital costs of H_2 SMR and liquefaction respectively, the costs for the fuel plant are obtained. The longest route, 3, requires the maximum fuel plant investment, as indicated in Table 4, but the investment required for routes 1 and 2 is of similar magnitude. Provision of the dedicated terminals and aluminium containers also require investment. Container terminal investment is small as only horizontal transport is envisaged for ship loading, additionally, terminal holding capacity is small; 2500 TEU. Approximate unit costs for the TEU and FEU aluminium containers are 16x10^3€ & 23x10^3€ . Total investment is therefore 589.0, 582.3 and 592.3 M.€ for routes 1 to 3, respectively.

H_2 fuel costs are critical to economic viability as they are a significant fraction of total costs. Other factors to be considered include: salaries, container moves, insurance, maintenance & repair and dry-docking. The cost of H_2 fuel is influenced by the scale of production; smaller H_2 production units having higher unit costs. The unit cost of H_2 fuel used in this study comprises the cost of SMR and liquefaction. The NG price used is 5.213 €/MBTU giving SMR unit H_2 gas price of 0.9098 €/kg. Research [39] indicates a unit H_2 liquefaction cost of 0.5366 €/kg for production rates indicated in Table 3. The total unit cost for LH_2 production is therefore 1.4464 €/kg. Using this value the block period fuel costs can be determined. The LH_2 consumed, for instance, on route 3 is 8,251.2 tonnes per block/ship, leading to a block fuel cost of 11.9M.€. The fuel costs therefore represents 88% of annual operating costs. Additionally, capital depreciation is equal to 5% of operating costs.

The economic evaluation results are presented in Figure 6, Figure 7 and Table 5. Figure 6 and Table 5 show the results for both zero profit and NPV based on a unit transport cost per TEU. Zero profit analysis was utilized previously [31] to establish unit transportation costs for Fastship, a high-speed sea transport chain concept on route 2. Fastship zero profit unit costs are 1,735 €/TEU, whilst for a conventional containership this unit cost is 939 €/TEU. Table 5 indicates that the proposed H_2 transport chain cost would be 1,928 €/TEU for the same route. These results indicate that there is competitive potential for the H_2 high-speed ship on this route. The zero NPV analysis (discount rate 10%) enables calculation of the minimum unit transport cost needed to recover investment over the lifespan of the ships (25 years). These unit transport costs are unsurprisingly significantly higher. Figure 7 shows the unit cost per unit mass transported allowing comparison with other fast transport modes, such as aircraft. Plotting the unit rates in Figure 7 shows that the H_2 unit mass transport rates are significantly lower than aviation rates for similar door-to-door transit times.

5. CONCLUSIONS

The results of this study show that a hydrogen fuelled high-speed container ship is, in principle, technically and economically viable. Current research indicates that aero-derivative gas turbines can be successfully modified for hydrogen fuelling. Experience already exists with both gas turbines and cryogens (LNG) in a marine environment. Combing these technologies with hydrogen technology from industrial and aerospace fields is primarily a matter of technology transfer. The development of a hydrogen economy is a high priority for many Governments and international agencies because of concerns about fossil fuel reserves and pollution. The proposed H_2 FAC provides the opportunity to demonstrate the potential of hydrogen in the marine environment whilst offering an environmentally and commercially attractive alternative to air transportation for time sensitive products.

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More information on both researchers can be found at: http://www.soton.ac.uk/~ijsv/ for I. Veldhuis and http://www.soton.ac.uk/~howard/ for H. Stone, while information on the EngD centre at University of Southampton may be found at: http://www.soton.ac.uk/~geotech/EngD/

NOMENCLATURE & ABREVIATIONS

ABS	American Bureau of Shipping
APU	Auxiliary Power Unit
CO_2	Carbon Dioxide
FAC	Foil Assisted Catamaran
FEU	Forty feet Equivalent container Unit
GH_2	Gaseous Hydrogen
H_2	Hydrogen
ICE	Internal Combustion Engine
JIT	Just In Time
LH_2	Liquid Hydrogen
LNG	Liquefied Natural Gas
NG	Natural Gas
NO_x	Nitrogen Oxides
NPV	Net Present Value
SFC	Specific Fuel Consumption
SMR	Steam Methane Reformation
SO_x	Sulphur oxides
SO_2	Sulphur dioxide
Sw	Wetted area of ship's hull
TEU	Twenty feet Equivalent container Unit

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