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Project to Build a Prototype Hydrogen-Powered Hybrid Electric Tug

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SYNOPSIS

Harbour ship-docking tugs have been identified as a prime candidate for a hybrid propulsion system owing to the highly variable power utilisation of the main engines. Alternate power generation systems and alternate fuels have the potential to reduce fuel consumption and exhaust emissions. Engine data has been logged from conventionally powered ship-docking tugs. The engine data forms the basis for selection of an optimal power generation system resulting in the proposed Hybrid Electric Tug. The Hybrid Electric Tug has an electrical propulsion drive system powered by three sources: diesel generator, fuel cells, and battery system. The primary power generation mode will be zero-emission, fuel cell/battery hybrid to perform the tug's light duties that comprise 80 per cent of its operating hours. The remaining 20 per cent of the tug's operational hours will function as diesel generator/fuel cell/battery hybrid or diesel generator/battery hybrid to complete heavy duty ship-docking tasks or high speed transits. The challenges associated with marine application of hydrogen fuel systems are discussed. The Hybrid Electric Tug is estimated to reduce emissions by 67 per cent compared to conventional diesel-powered vessels.

1. INTRODUCTION

Ship-docking tugs have been developed in very distinct steps over the past 150 years. The class started with wooden, steam-driven side paddle-wheel tugs, and then changed slowly to a standard steel-hulled, steam-driven, single propeller vessel. Next, the industry standard for many years became a steel-hulled, diesel-driven, twin propeller vessel. Some 25 years ago, a huge step forward was made in efficiency, manoeuvrability and safety for ship-docking vessels with the introduction of azimuthing drives (Z-drives and Voith cycloidal units). Vancouver naval architects Robert Allan Ltd was one of the primary firms to perfect the design of the modern ship-docking tug. This class of tug is well developed and is now universally utilised in major ports around the world, handling all classes of deep-sea ships. The modern marine diesel, both medium and high-speed, is of course highly developed and efficient with its emissions meeting all modern environmental requirements and standards. The next big step forward is destined to be in the area of alternate fuels and power sources to satisfy the demands for ports and governments for reduced emissions and visual pollution.

A ship-docking tug leads a relatively sedate life. Most of its working day will be spent either at dock (shut down or idling), running errands around the port (delivering pilots, yarding barges), or standing by and escorting a deep-sea ship. Only for less than 5 per cent of the working day, when actually handling the deep-sea ship, will the tug be required to supply anything near full power. In a standard diesel ship-docking tug, this lower utilisation of power means that the main engines will be operating in a very inefficient manner. This leads to poor overall fuel consumption figures, poor emission control and increased engine maintenance. The fact that a ship-docking tug is a very powerful vessel that is required to use full power for less than 5 per cent of its working day, is leading naval architects to consider alternate, more efficient, powering options.

The authors have identified an opportunity to improve the operational design of ship-docking tugs. The improvement is based on appropriately matching the distinctive operational power requirement of a typical harbour tug with suitable power generation modes. The proposed concept design involves a fuel-cell and battery system operating in parallel for low-power operation, and then combined together with a significant boost from a single diesel generator for infrequent high-power operations.

Figure 1: **Seaspan Falcon** *performing ship-assist duties.*

2. DUTY PROFILE

Power and emissions data from two ship-docking tugs were recorded over 30 days of monitoring. The tugs, ***Seaspan Hawk*** and ***Seaspan Falcon***, were instrumented and monitored to collect data on the power duty profile and exhaust emissions. *Figure 1* shows ***Seaspan Falcon*** undocking the 70,000-tonne DWT oil products tanker ***Fedor***. *Figure 2* shows the power profile for a typical workday of ***Seaspan Hawk.*** It can be seen that the docking tug operates at less than 10 per cent engine load for 50 per cent of the day. The engines exceed 55 per cent engine load for only 4.3 per cent of the day, while 90 per cent engine load is exceeded for only 2 per cent of the day.

This light-duty profile of ship-docking tugs is well known, but it is still surprising when faced with the actual numbers. Analysis of the data indicates the following distinct operational modes shown in *Table 1.*

Item	Mode	Description	Engine Load
1	Idle	Engine idle at 650 rpm, clutch disengaged	5%
2	Idle On	Engine idle at 650 rpm, clutch engaged	16%
3	Easy Bollard	Engine at low speed from 900 rpm to 1,200 rpm with clutch engaged	25% to 35%
4	Half Bollard	Hold ship against dock or pull ship away from dock at intermediate engine speed 1,300 to 1,400 rpm	40% to 55%
5	Full Bollard	Full power at 1,750 rpm	90% to 100%
6	Transit	In transit with engine speed varying from 1,300 rpm to 1,750 rpm depending on urgency	35% to 75%

Table 1: Ship docking tug operational modes.

3. HYBRID CONCEPT

It was observed during the engine monitoring programme that the engines were very lightly loaded for a large percentage of the total operating hours. The engines are producing less than 35 per cent power nearly 80 per cent of the time. The remainder of the time the tug is used with short bursts of power at distinct levels of some 50 per cent, 75 per cent and >90 per cent power.

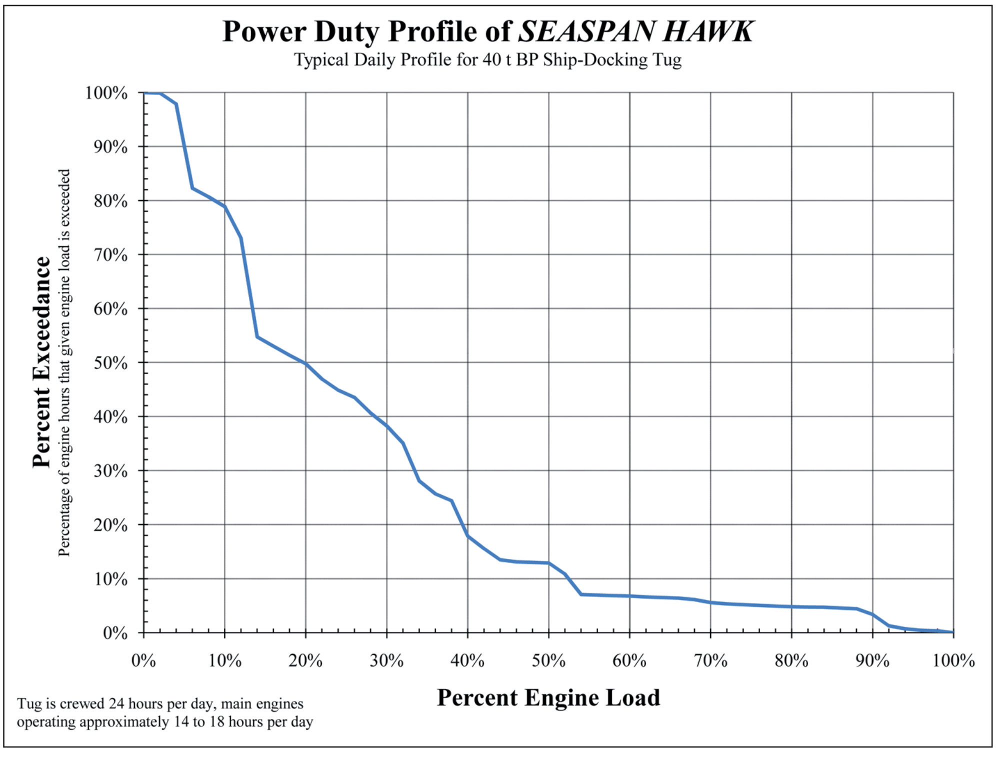

Figure 2: Typical Power Duty Profile for a ship-docking tug

The primary goal of this Hybrid Electric Tug is to provide a zero-emission operating mode that meets the low-level power requirements for the majority of the tug's duties. It is the lower power levels (<35 per cent engine load) that account for 80 per cent of engine hours on a conventional tug, but that also produce the worst emission levels per kilowatt. The low power hours on conventional diesel engines are also the cause of numerous maintenance issues. Hybrid propulsion system modes are shown in *Table 2, above.*

Item	Mode	Description	Power Level
A	Zero-Emission	Fuel Cell + Battery Hybrid	0% to 35%
B	Low Emission	Diesel Generator + Fuel Cell + Battery Hybrid	25% to 100%
C	Diesel Electric Hybrid	Diesel Generator + Battery Hybrid (limited endurance at 100% power)	25% to 100%
D	Diesel Electric	Diesel Generator	0% to 50%

Table 2: Hybrid propulsion system modes.

The Zero-Emission Mode A is designed to provide sufficient power for operational modes: Idle, Idle On, Easy Bollard, and Transit at economical cruising speed of about 9kn. The fuel cells provide continuous output of 600kW (17 per cent power), but combined with the batteries this mode can provide 1,250kW (35 per cent power level) for more than one hour. When the tug is only required to stand by with propulsion system idle then the fuel cells can continue to run at full power, charging the batteries for the tug's next task.

Modes B and C provide the power for Half Bollard, Full Bollard, and Full Transit Speed. The tug can operate at 100 per cent power for more than half-an-hour in Mode B and about 20 minutes in Mode C. The tug can operate continuously at 67 per cent power in Mode B and 50 per cent power in Mode C.

The Diesel-Electric Mode D can be used for long-distance voyages when hydrogen refuelling may not be available. The tug should be able to maintain a continuous cruising speed of at least 11kn in the straight Diesel-Electric Mode without battery assist.

4. GENERAL ARRANGEMENT DESIGN

The proposed Hybrid Electric Tug is based on a 24m hull design developed by Capilano Maritime Design Ltd. The general arrangement is shown in *Figure 3 (see end of paper)*. The tug is set up as a shift boat with a two-man crew. Two crew cabins/offices are located on the main deck level. Also on the main deck are the galley, lounge, and washroom with toilet and shower. Above the main deck the vessel appears virtually identical to a conventional ship-docking tug. It is below the main deck where the layout is considerably different. The Principal Particulars are listed in *Table 3.*

A 55-tonne BP was selected to provide a good, useful tug capable of handling nearly all ship-docking duties in a modern harbour. The same design could be increased to 70 tonnes BP with slight modifications to the hull, propulsion drives, and battery capacity. The diesel generator and fuel cell systems would not be altered for the 70-tonne version.

Principal Particulars:	
Length moulded	24.6 m
Beam moulded	10.0 m
Depth of Hull	4.65 m
Draft (including nozzle)	4.75 m
Bollard Pull	55 tonnes
Power Total	3600 kWe
Diesel Generator	1825 kWe
Hydrogen Fuel Cell Generators	600 kWe
Battery Power	1175–3000 kWe
Capacities:	
Marine Diesel Oil	35 m^3
Batteries	1000 kW - hour
Hydrogen (Liquid)	1,200 kg

Table 3: The Capilano Maritime design Hybrid tug.

5. ELECTRICAL SYSTEM

The key to the next generation of hybrids is an all-electrical propulsion system, which provides maximum flexibility for selection of various power sources and fuel types to minimise emissions and improve fuel efficiency. With an electrical drive system, power may be generated from different sources including diesel generator, batteries, fuel cell, gas turbine, etc. The power generation choices can also be combined on a single vessel, as they are on the proposed tug to provide maximum flexibility in a choice of different performance characteristics, emission profiles and fuel types. Electrical power generators can be easily upgraded or replaced to take advantage of new technologies. The one constant is the electrically driven Z-Drive or cycloidal thrusters.

The electrical system provides power for all systems on the tug including propulsion, hotel loads, and auxiliary deck equipment such as the main hawser winch and anchor windlass. Power generators can be brought on in steps to match the power demands of the various operating modes. The fuel cell system comprises four 150kWe units, which can be energised in steps of 0, 150, 300, 450, and 600kWe generating capacity. The diesel generator provides a large step up in generating capacity of 1,825kWe to handle major ship-docking duties. The numerous generators supported by completely independent auxiliary systems provide significant redundancy while also allowing the opportunity to optimise fuel efficiency and emissions.

The AC diesel generator and the DC fuel cell generators are connected via the DC common bus and DC control centre to charge the batteries, which in turn run the AC propulsion motors and other AC loads through inverters in the Variable Frequency Drives. The simplified diagram of the electrical propulsion system is shown in *Figure 4*.

The battery system provides the short-term intermittent power to temporarily boost the power available from the diesel generator and/or fuel cells and drive the large propulsion motors at their maximum rating. The batteries are an energy storage device providing mobile power on demand. The batteries store energy generated by the diesel generator, hydrogen fuel cells, and/or the grid. The batteries can then release that energy at a later time to amplify the power available from the power generators and they can also be used selectively to minimise total emissions if so desired at any particular time or location.

One of the greatest advantages of a large battery system is that it allows the operator to store inexpensive shore power onboard the vessel to use as propulsion or auxiliary power when needed. Industrial electricity rates in British Columbia are approximately $0.08 per kWh thanks to substantial hydro-electric generation capacity in the province. The production of electricity from an onboard diesel generator is approximately $0.35 per kWh so obviously the use of shore-charged battery power is a big advantage.

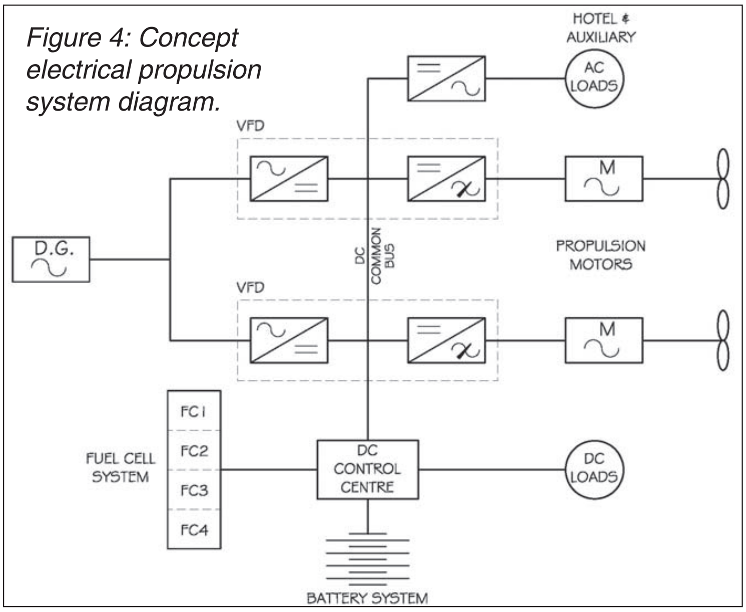

Figure 4: Concept electrical propulsion system diagram.

6. BATTERY TECHNOLOGY

Battery technology is changing very fast with the rapid development of various hybrid vehicles such as passenger cars, buses, and rail locomotives. A list of the major battery types and some of their primary attributes are listed below:

Sodium Sulphur Battery

1. NGK/TEPCO (Japan);
2. Specific Energy Density: 91Wh/kg;
3. High operating temperature;
4. Very long shelf life.

Sodium Chloroaluminate Battery (ZEBRA Battery)

1. MES-DEA SA (Switzerland);
2. Specific Energy Density: 100Wh/kg;
3. Cycle Life: 1,500 cycles at 80 per cent Depth of Discharge (DOD);
4. 270 degrees C – 350 degrees C operating temperature;
5. Very long shelf life.

Sodium Metal Halide Battery

1. GE Technology (USA);
2. Specific Energy Density: approximately 100;
3. Charge and discharge rate: unknown;
4. Unknown price, but understand it will be very competitive;
5. Unknown performance.

Lithium Ion Battery (Lithium NMC chemistry)

1. Corvus Energy (Canada) & Dow Kokam (USA);
2. Specific Energy Density: 103 Wh/kg;
3. Cycle Life: > 3,000 cycles at 100 per cent DOD;
4. Expensive;
5. Very high charge and discharge rates (10 degrees C).

Lithium Ion Battery (Lithium Iron Phosphate chemistry)

1. Mastervolt (The Netherlands);
2. Specific Energy Density: 90Wh/kg;
3. Cycle Life: 2,000 at 80 per cent DOD;
4. Expensive.

Nickel-Metal Hydride Battery

1. Various manufacturers (Sanyo, Panasonic etc);
2. Specific Energy Density: 70 Wh/kg;
3. Medium price.

Lead Acid Battery

1. Various manufacturers (etc);
2. Specific Energy Density: 25Wh/kg (one hour discharge);
3. Cycle Life: 300 at 80 DOD;
4. Lowest price.

The sodium, or molten salt, batteries provide high energy density comparable with the lithium ion batteries, but at lower cost. The sodium batteries are manufactured from abundant and readily available materials so future cost of these batteries should remain stable. The molten salt batteries are sealed zero-maintenance batteries.

Other advantages are:

- Long life – 10-year calendar life and nearly unlimited shelf life;
- Safety – passed all major vehicle safety tests, including collision, fire, submerged in water, over-charged, and over-discharged;
- Sodium batteries have been in production for more than 10 years.

However, the sodium batteries also have some disadvantages:

- Low power density – It is not possible to rapidly charge or discharge the batteries so it would be necessary to have a significantly larger total battery capacity in order to generate the same amount of peak power as a Li-Ion battery system. A minimum 2,000kWh capacity battery system would be required to provide maximum continuous power capability of 3,000kW. This may end up being a space constraint on a compact tug.

- High operating temperature – Sodium batteries have approximately 300 degrees C operating temperature. When the batteries are not in use for extended periods of time (more than four hours) it is essential to keep them warm. A 2,000kWh battery system would require 7kW to keep itself at temperature and ready for immediate use. The batteries reject heat when in operation so space cooling is required. This can be somewhat alleviated by placing the batteries in a hold with side shell and bottom in direct contact with cool seawater. The batteries have a long shelf life, but once brought up to operating temperature, they cannot be cooled down again without affecting the cycle life.

Lithium Ion batteries have high energy density and high power density. This means the battery system will be much lighter and take up half as much space as sodium batteries of equivalent power output. A 1,000kWh battery system will easily produce 3,000kW or more, while some of the better Li-Ion chemistries have very long life with greater than 3,000 deep discharge (100 per cent) cycle life. High power density combined with long cycle life results in fewer batteries having to be replaced in the lifetime of the vessel. The Li-Ion batteries appear to be the technically superior choice. However, the greatest disadvantage is the cost. Current Li-Ion batteries prices are in the range of $1,500 to $1,750/kWh. It is forecast that large-scale production for the automotive industry could drive the cost down to $350/kWh. In contrast, the forecast for large-scale production of the Zebra sodium batteries is $130/kWh. However, the ship-docking tug application requires at least twice as many kWh sodium batteries in comparison to Li-Ion batteries owing to the high power requirement so the initial cost of the two battery types becomes much closer. The Li-Ion batteries have a longer cycle life so replacement cost is less, but there is some concern that Li-Ion battery prices may increase as production volumes ramp up for hybrid passenger cars because of the scarcity of lithium.

The Hybrid Electric Tug is based on 1,000kWh capacity Li-Ion battery system from Corvus Energy which provides the best technical performance of all battery systems readily available today.

7. HYDROGEN FUEL CELL SYSTEM

Fuel Cells

The fuel cells proposed for the Hybrid Electric Tug are proton-exchange-membrane (PEM) type FC velocity-HD6 from Ballard Power Systems. The HD6 has a maximum continuous power output of 150kWe. There are indications that if the fuel cells are employed in a hybrid combination with batteries in a marine application (excellent seawater cooling) that the maximum rating might be increased to nearly 200kWe. It is planned to install four of these units for a total fuel cell output of 600kWe. The fuel cells output DC voltage between 550v to 800v with a maximum current of 300A. Physical dimensions of each 150kWe HD6 unit are as follows:

Weight:	500kg
Length:	1,270mm
Width:	870mm
Height:	505mm

Fuel cells emit only water vapour, eliminating air pollutants such as nitrogen oxides, sulphur-oxides and particulate matter (PM). The use of hydrogen by-product that is currently available and untapped in some ports can also significantly reduce greenhouse gas emissions on a 'well-to-tail pipe' basis, when compared to conventional technologies. Fuel cells are also very quiet in operation, significantly reducing noise and vibration on board the tug.

Unique aspects of fuel cell installations include the auxiliary systems for cooling water and compressed air supply.

Cooling System

One of the great advantages of using fuel cells in a marine application is access to an immense heat source and sink provided by the ocean. Maintaining internal temperatures is the key to proper fuel cell function. The Ballard HD6 fuel cells have an advanced control system to maintain a high degree of temperature control. The control system communicates with variable speed cooling pumps allocated for each fuel cell. These cooling pumps draw cool water from the tug's seawater box coolers. This variable flow of cooling water circulates through each fuel cell as needed.

The cooling system becomes dual purpose when the vessel is fuelled using liquid hydrogen. In this case, the heat removed from the fuel cells combined with the comparably warm ocean temperature is used to draw cryogenic hydrogen out of the storage tank, a process similar to the familiar home barbeque system. On a moist, cool day you may see frost developing on the outside of the propane tank. This is because the tank is drawing heat from the atmosphere in order to vaporise the gas in the bottle. In the case of liquid hydrogen, the tank is insulated so another heat source is required to vaporise the liquid.

Land-based liquid hydrogen installations utilise multiple expensive and large (more than10m high) liquid-to-air heat exchangers. *Figure 5* shows BC Transit's cryogenic liquid hydrogen tank installation at Whistler, BC. The large air-to-liquid heat exchanger (hydrogen vaporiser) can be seen to the right of the hydrogen tanks in the background. In contrast, the tug utilises a liquid-to-liquid hydrogen vaporiser that is a fraction of the size of the land-based equivalent. The liquid-to-liquid vaporiser is only approximately 0.5m(length) x 0.4m(width) x 0.5m(height) in size due to the much higher efficiencies of the liquid-to-liquid heat transfer using the 'warm' Pacific Ocean.

Figure 5: Fuel cell bus and liquid hydrogen tank at Whistler, BC.

Reaction Air Supply System

At full output, the four hydrogen fuel cells on the tug require 640 litres per second of atmospheric air to react with the hydrogen. This air must be supplied at 1.2 bar requiring significant input power for air blower systems. The air supply also needs to be clean and the parasitic power demand minimised. Installation on board a tug affords greater advantages towards these goals than are available to land-based vehicles. A commercial package-type blower system can be used because of the ample physical space available on board the vessel. These highly advanced and engineered packages from large global manufacturers reduce power requirements and provide built-in air scrubbers to ensure clean reactions within the fuel cell. Having a globally standardised system also makes for a very serviceable installation.

The Ballard HD6 fuel cells are equipped with air/water separators for the air leaving the fuel cell after reaction. Condensate is drained through the hull of the vessel below the waterline. The rest of the moist air is directed to an exhaust that leads above the main deck and is connected at the lower end to the same overboard condensate drain for collection of water that condenses on the way up the exhaust.

Hydrogen Storage

The four HD6 fuel cells consume a combined total of 30kg/h of hydrogen at a full output of 600kWe. It was decided that an endurance of about 40 hours at full power should provide sufficient capacity to limit refuelling to about once per week. This results in a storage requirement of 1,200 kg of hydrogen.

Compressed hydrogen gas can be stored at extremely high pressures in specialised cylinders. Cylinder pressures in excess of 700 bar are utilised for most efficient storage. Hydrogen density at this pressure is about 35kg/m^3. However, the cylinder diameters are quite small and have very thick walls in order to withstand such high pressure. Consequently, the overall bulk storage density is somewhat low and cylinder weight quite substantial. The high cylinder pressure also generates safety concerns in the event of a collision with another vessel or a fire on board the tug. Compressed gas is the most economical with regard to capital cost of the on board and shore-based storage and fuel transfer equipment. However, mobile fuel delivery can be challenging owing to the low pressure of the tanker trucks. It would take four tanker-trucks to deliver 1,200kg of compressed hydrogen, thus providing many logistical problems for hydrogen refuelling. It is much more practical to take the tug to a central hydrogen storage facility rather than deliver the fuel to the tug via tanker truck. Unfortunately, this would tie the operator to a limited source of nearby hydrogen gas.

Cryogenic liquid hydrogen is stored at -253 degrees C at 10 bar. The density is better than compressed gas, but is still very light at 70kg/m^3 (by comparison, diesel fuel is 850kg/m^3). Advanced tank designs with excellent insulation keep the hydrogen cool without need for refrigeration for up to two weeks. The tanks are essentially thermoses under low pressure to improve storage density. The liquid hydrogen slowly boils off to the outside environment after some two weeks of storage. Fuel delivery becomes more feasible as one tanker truck can easily transport 1,200kg of liquid hydrogen, providing a commercial advantage as the tug operator can purchase hydrogen from a variety of suppliers and have it delivered to his site by cryogenic tanker-truck.

Hydrogen can be chemically bound and stored as a solid compound. Solid-hydride storage materials release hydrogen gas under suitable conditions of temperature and hydrogen pressure (generally 2 to 5 bar). Hydrogen density improves to about 100 kg/m^3 in the solid form, but the overriding disadvantage of the solid system is installation and replacement cost. The capital cost is well beyond the realms of feasibility for a commercial vessel and is currently only relevant for specialised military applications.

8. CAPITAL AND OPERATING COSTS

The proposed Hybrid Electric Tug with hydrogen fuel cells would be a demonstration vessel at this stage in the application of fuel cell and advanced battery systems in a marine environment. The cost of the first demonstration vessel would certainly far exceed the cost of an equivalent conventional diesel-powered tug. The base price for a conventional 55-tonne BP, 24m diesel-powered ship-docking tug is estimated to be about $12m in the North American market today. The cost to produce the first demonstration vessel Hybrid Electric Tug is estimated to be $23m-$25m, but it is believed that this cost can be reduced to $16m-$18m after several vessels of this class have been built and capital cost of fuel cells and advanced batteries has been reduced due to mass production.

Government funding is available to support the higher cost of the new technology.

Operating cost can be lower, especially if shore power is used extensively to recharge the battery system in between ship-docking jobs. However, this will require an upgrade to shore power systems to enable fast recharge at the dock (say 200kW-500kW capacity).

Overall lifecycle costs could be estimated to be lower for the Hybrid Electric Tug depending on future rates for diesel fuel and shore power.

9. EMISSION REDUCTION

The principal components of emission from marine vessels are mono-nitrogen oxides (NOx), carbon monoxide (CO), hydrocarbons (HC) and particulate matter (PM).

Based on our preliminary study, the Hybrid Electric Tug can reduce these emissions by up to 67 per cent compared to a modern, conventionally powered equivalent vessel. More particularly, since all energy produced at a low power mode is produced by fuel cell or draws from batteries, only the energy produced at high power modes contributes to emissions; within a 24-hour operational day, where an estimated 5,000kWh of energy is consumed by the tug, 3,340kWh is produced at a low (emissions-free) power mode, and 1,660kWh is produced at a high power mode. In addition, while emission reductions are principally tied to the reduced overall duty cycle of the diesel engine, further emission reductions are likely when considering the efficient operational range maintained by the diesel engine during active cycles.

The calculated emissions for the proposed hybrid electric tug are as follows:

- Mass of NOx emissions over operational day: 23.2kg (down from 70kg for a conventional tug);
- Mass of CO emissions over operational day: 1.74kg (down from 5.24kg);
- Mass of HC emissions over operational day:

0.088kg (down from 0.266kg);
- Mass of PM emissions over operational day: 0.17kg (down from 0.50kg).

Emission calculations are based on the following baseline data:

- Baseline mass of NOx per unit of energy consumed: 14.0g/kWh;
- Baseline mass of CO per unit of energy consumed: 1.05g/kWh;
- Baseline mass of HC per unit of energy consumed: 0.0533g/kWh;
- Baseline mass of PM per unit of energy consumed: 0.103g/kWh.

9. CONCLUSION

- A hybrid tug can be considered as a vessel with a varied number of power sources. It is capable of selecting the most efficient combination of power sources for the particular function that the tug is performing.

- This combination of available power sources has to fit comfortably within the hull of a standard ship-docking tug. Full power has to be quickly available upon the request of the captains and the pilots.

- The overwhelming motivation for hybrid tug development is the great reduction in emissions achieved. As stated previously, the tugs will perform their docking duties and be operated in exactly the same manner as conventional tugs. The requirements for the reduction in emissions within a port are being driven by port and federal agencies, as well as the surrounding cities' ever-increasing environmental requirements.

ACKNOWLEDGEMENTS

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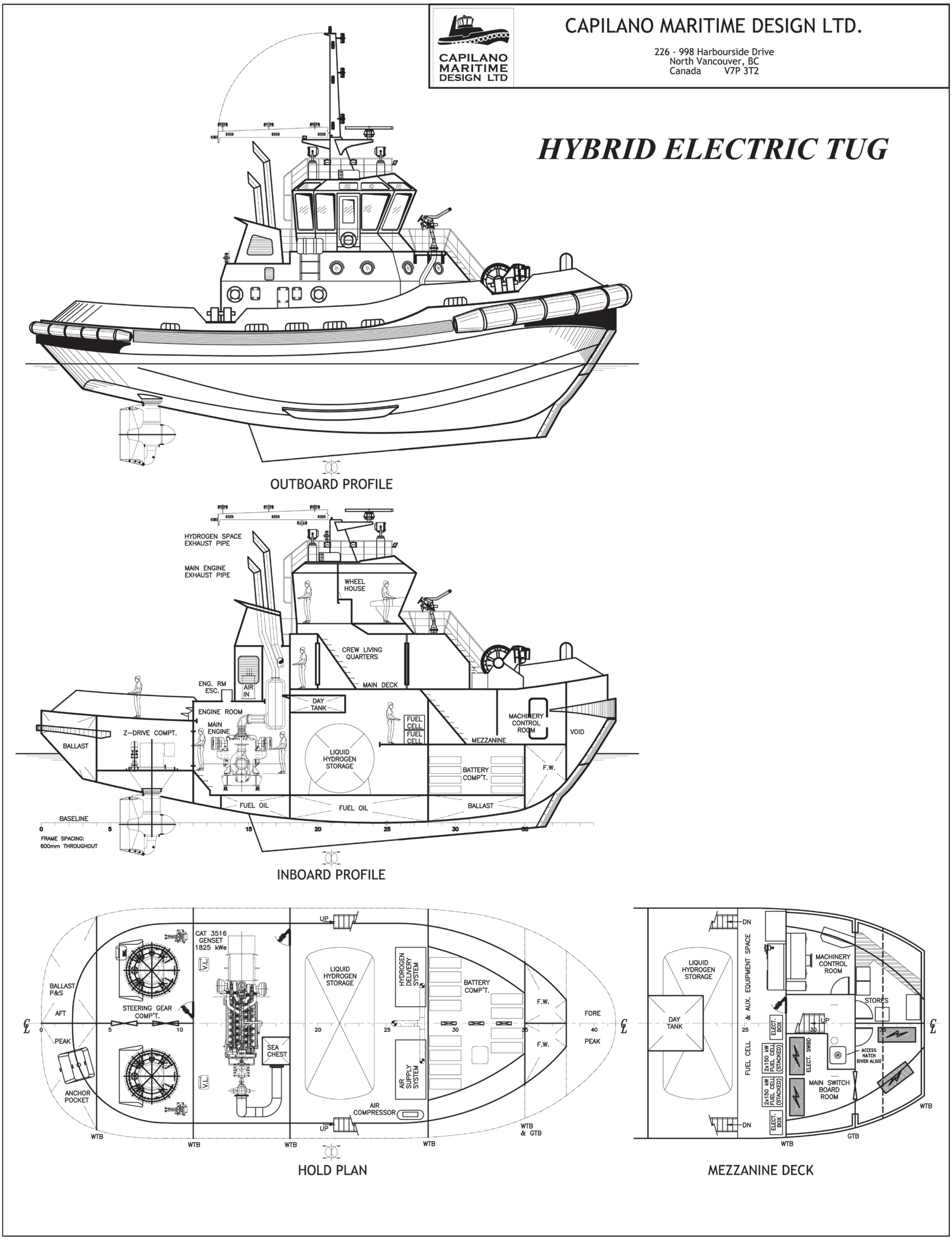

Figure 3: Capilano Maritime Design Ltd's Hybrid Electric Tug – General Arrangement.