In 1970, the phrase “hydrogen economy” was introduced by John Bockris. It referred to a world where hydrogen could be used as a transportation fuel, provide stationary power generation, and serve as an energy buffer for renewable forms of energy such as solar and wind. Hydrogen is the chemical element with the lowest atomic weight and can be readily combined with other elements to form a variety of molecules. As the chemical energy inputs into a fuel cell, hydrogen can combine with oxygen to create water while generating electricity and heat (see Figure 1).

The energy efficiency of a fuel cell is generally between 40% and 60% (see Figure 2).

Although the fuel cell was invented in 1838, the first practical use came in the 1950s and 1960s as NASA applied the technology to powering spacecraft and satellites. Fuel cells have no moving parts and are therefore very reliable and require minimal maintenance. Recently, fuel cells have been applied to stand-by power generation, transportation (automobiles, buses, forklifts), military applications, and portable power systems. The largest fuel cell plant is a 59-megawatt facility in South Korea. In marine applications, the German Type 212 submarine uses two fuel cells of 120 kilowatts each.

In 2015, Seattle-based Elliott Bay Design Group (EBDG) was selected by Sandia National Laboratories (Sandia) as part of a team to look at the feasibility of hydrogen fuel cells for a commercial marine application. Sandia chose a challenging scenario: Is it technically and economically feasible to operate a high speed passenger vessel in San Francisco Bay using hydrogen powered fuel cells and producing zero emissions? The Sandia team worked closely with the U.S. Coast Guard and the American Bureau of Shipping to evaluate the safety regulations for small passenger ferries and gas-fueled vessels. Sandia, along with EBDG, also looked at commercially available technology to see if there were “off the shelf” components that could be used. EBDG developed a vessel design (see Figure 3) that met the performance requirements. This then provided the basis for estimating capital and operating costs. A copy of the final report may be found at: http://energy.sandia.gov/transportation-energy/hydrogen market-transformation/maritime-fuel-cells/sf-breeze/

Some lessons learned from that project:

- If significant quantities of hydrogen are required, storing the hydrogen as a cryogenic liquid is more space efficient. Also, the combination of fuel and storage tank weighs less than a compressed hydrogen system and has lower capital cost.

- Refueling frequency is a critical design decision. Carrying a minimal amount of fuel reduces weight and space requirements, which for a high speed vessel means reduced propulsion requirements, that in turn further reduces the fuel storage requirements.

- The set of safety regulations developed for LNG as a cryogenic fuel can be readily adapted for use with liquid hydrogen.

- The weight and space requirements for the fuel storage, the fuel cells, and the electrical propulsion equipment meant that the carrying capacity was only 150 passengers.
DEAR PVA MEMBERS,

As many of you know, in 2013 my father Jim Murray and longtime friend Stuart Reeves reopened what was previously known as Freeport Shipbuilding under the new name Gulfstream Shipbuilding. Upon reopening they were able to rehire 75% of their previous workforce and all upper level management. This in itself speaks to the strong culture and professionalism that my father and Stuart brought to ownership. Today I am proud to announce I have rejoined the Gulfstream team.

In 2004, I left Freeport Shipbuilding to start my own passenger boat business. My company SunQuest Cruises and SunVenture Cruises currently operates a 125’ dining/entertainment yacht and a 45’ eco-excursion boat. I truly understand the challenges you face as an operator on a day-to-day basis. My understanding of these challenges, and my knowledge in building a functional passenger vessel, is what I bring to Gulfstream.

If you are thinking of a new construction project or a refurbish, please don’t hesitate to contact me. Thanks and continue to prosper.

Sincerely,

Gulfstream Shipbuilding, Inc.
James Murray II, Sales Manager

P.S. Thank you all for your thoughts and prayers during my father’s passing. He was a beautiful person who had a passion for boatbuilding and a love for family.
Figure 3 - Concept Design of a 35 knot, 150 passenger Hydrogen Fuel Cell Ferry (Source: EBDG)

instead of 300 passengers that would be found on an equivalent diesel-driven vessel.

- The combination of high capital cost, expensive fuel (currently), and low carrying capacity resulted in a vessel that was technically feasible but not economically viable.

In order to further assess the possibilities of a hydrogen-fueled ferry, EBDG applied the technology to a conventional car ferry. EBDG selected a vessel that was previously designed for Pierce County, WA, that has reliable data readily available on capital and operating costs (see Figure 5). This allowed EBDG to benchmark performance and financial assumptions as the design was modified for hydrogen fuel cells.

The reference vessel has the following characteristics (see Table 1).

The U.S. Coast Guard does not allow gas fuels to be stored underneath accommodation spaces due to the risk of a gas leak creating an explosive condition. Therefore, the fuel storage was placed on the open deck adjacent to the passenger spaces. Since hydrogen is significantly lighter than air, any leaking hydrogen rapidly moves up and away from potential ignition sources. The liquid hydrogen is converted back into a gas state in a cold box adjacent to the fuel storage tank. The gas fuel is then carried in double-walled piping in a dedicated, well-ventilated trunk down to the fuel cells located in the hull under the main deck. The fuel cells are arranged in racks similar to lithium ion batteries. The fuel cell room is also well-ventilated and monitored to detect any gas leaks and to prevent the accumulation of gas.

Since the ferry is double-ended, the powering is split approximately 80 percent to the pushing propeller and 20% to the pulling propeller. This means that the total propulsive requirements are approximately 830 kW. If we assume a 10 percent conversion loss for the electrical motors and controllers, plus add the shipboard electrical consumption of 105 kW, the total elec-

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Table 1. Vessel Characteristics.

<table>
<thead>
<tr>
<th>ITEM</th>
<th>ENGLISH UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length Overall:</td>
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<tr>
<td>Beam:</td>
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</tr>
<tr>
<td>Depth:</td>
<td>16.5 ft</td>
</tr>
<tr>
<td>Design Draft:</td>
<td>10.25 ft</td>
</tr>
<tr>
<td>Lightship Weight:</td>
<td>733 LT</td>
</tr>
<tr>
<td>Full Load Displacement:</td>
<td>996 LT</td>
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<tr>
<td>Car Capacity:</td>
<td>54 vehicles</td>
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<tr>
<td>Passenger Capacity</td>
<td>325</td>
</tr>
<tr>
<td>Crew Size:</td>
<td>5</td>
</tr>
<tr>
<td>Main Propulsion</td>
<td>2 x 1050 hp</td>
</tr>
<tr>
<td>Electrical Capacity</td>
<td>2 x 110 eKW</td>
</tr>
</tbody>
</table>
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Figure 5. 120 kW Fuel Cell Rack (Source: Hydrogenics)

The capital cost of the fuel cell ferry is approximately $7.5 million greater than the reference vessel due to the electric propulsion equipment, the fuel cells, and the cryogenic tank. This cost difference will shrink as demand for fuel cell technology increases but fuel cells are competing with a technology (geared diesel engines) that is mature, with many competing vendors, and a large base of applications. The key advantages of fuel cells driving electric motors are extremely low maintenance and, of paramount importance, the zero emissions.

The current cost of LH2 is roughly $6.35/kg to $7.40/kg depending upon the annual demand. This is significantly greater than current marine diesel oil at $0.48/kg. (Based on New York Harbor Ultra-Low Sulfur No. 2 Diesel Spot Price of $1.564 per gallon as on June 1, 2017). Note that the diesel fuel price does not include the cost of delivery to the vessel whereas the LH2 price is inclusive of trucking.) After accounting for the energy density difference (a kg of LH2 has 2.9 times the energy content of a kg of diesel) and the efficiency difference (a fuel cell is somewhat more efficient than a diesel engine at converting chemical energy into electricity) the fuel costs for hydrogen for a ferry operating 350 days per year are approximately three times the costs for a diesel fueled vessel.

In conclusion, this investigation demonstrated that using hydrogen fuel cells to power a conventional ferry did not result in any loss in capacity for the vessel to remove the propulsion diesels and the diesel generator sets and then added the weights of the cryogenic storage tank, the cold box, the fuel cells, the electrical conversion equipment, and the electric motors. EBDG also deducted the weight of the diesel fuel and added the weight of the LH2. The resulting vessel had a larger light ship weight than the reference vessel (774 Long Tons versus 733 Long Tons) but a lesser Full Load Displacement (966 Long Tons versus 996 Long Tons) due to the decreased fuel weight.

The reference vessel has sufficient fuel for 35 days of operation, due to the client’s desire for reserves in the event of a major earthquake. The fuel cell version cannot carry large quantities of liquid hydrogen (LH2) since LH2 has much less energy density than diesel fuel. EBDG sized the LH2 storage tank to suit a resupply every four days with a 20 percent margin from a standard tank truck with a capacity of 3,200 kg of LH2.

EBDG adjusted the weight estimate of electrical requirements when underway are approximately 1,020 kW. Allowing for some reserves for increased speed to make-up schedule, EBDG assumed that 10 fuel cell units of 120 kW each plus one unit in reserve would form the basic power plant.

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for carrying either vehicles or passengers. Nor was there a reduction in performance of the vessel, with the sole exception of the quantity of fuel reserves. Currently the fuel cell ferry is burdened with both greater capital cost and higher fuel cost. However, the cost difference between a conventional ferry and a fuel cell ferry will decrease as the hydrogen economy becomes reality. If the United States moves to a cap and trade system for emissions, there will be additional economic incentives to operate zero emission vessels. Look for hydrogen-powered vessels on your waterfront sometime in the next 10 to 20 years.

About the Author
John W. Waterhouse, PE, PMP is EBDG’s Vice President, Chief Concept Engineer and resident passenger vessel expert. With 30+ years of experience in naval architecture and marine engineering, he has made significant contributions to the passenger vessel industry through innovative design and engineering achievement. EBDG, which is headquartered in Seattle and has offices in New Orleans and Ketchikan, AK, provides naval architecture, marine engineering and production support services to maritime industry. For more information, please visit www.ebdg.com.