ON-DEMAND HYDROGEN GENERATING SYSTEM DEMONSTRATION CONCEPT DEVELOPMENT, PHASE I: TASK 5.0: Final Report

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I. INTRODUCTION

The air quality in many United States ports is already at or in excess of EPA limits of harmful pollutants. Engine exhaust emissions of NO_x, SO_x, HC and particulate, as well as greenhouse gases, have reached levels high enough to significantly hamper civilian and military port and industrial commerce and development. The Port of Houston, for example, faces a potential total shutdown as a result of extremely poor air quality. Further, California's major ports have a number of important programs, such as dredging the Port of Oakland's harbor, expanding runways at the San Francisco International Airport, introducing new fast ferry services, and sighting new electric power generating stations. All of these projects are being held in abeyance pending the development of plans and techniques to minimize their anticipated impact on air quality.

To that end, hydrogen fuel generation, based on non-petroleum fuels, offers a non-toxic, renewable, recyclable, and clean burning energy source for fuel cells, reciprocating engines and combustion turbine engines. The potential for this technology to reduce engine exhaust emissions is significant, given that the emission streams from the combustion (oxidation) of pure hydrogen are heat and water vapor. The proposed technology under review in this project will directly support CCDoTT goals by providing an option to obtain "zero emissions" from fuel cells. The technology originates with New Jersey-based Millennium Cell Corporation, which has developed a chemical process that solves the problems associated with generating, storing, and transporting hydrogen by extracting pure hydrogen gas from safe, environment-friendly raw materials. Millennium Cell's proprietary process combines sodium borohydride with water to create a non-toxic, non-flammable solution that produces hydrogen on demand, that is, only when the solution is in contact with a metal catalyst. When the sodium borohydride solution and catalyst are separated the solution stops producing hydrogen. After being processed by the catalyst, the spent fuel source goes to a waste tank, from which it can be recycled into new fuel or discharged safely into the ocean.

High hydrogen content, cleaner burning fossil fuels have long been a prime factor in reducing emissions from and extending the operating life of conventional fossil fuel fired prime movers such as diesel engines and combustion turbines. Additionally, the primary limitation for reducing the size and weight and increasing the output and durability of fuel cells has been the requirement of systems and equipment, called reformers, to extract pure hydrogen from conventional liquid and gaseous petroleum fuels. The proposed demonstration of a fuel cell, diesel engine or combustion turbine, powered by an on-demand hydrogen generating system that utilizes commonly occurring non-petroleum based constituents to generate hydrogen will eliminate all environmentally harmful effluent streams produced by these prime movers now operated on petroleum-based fuels.

Continuous operation on pure hydrogen also offers the potential for significant extension of fuel cell durability and operating life. This technology has potential for continued development in CCDoTT's Agile Port and High Speed Sealift program sectors by virtue of its reduced emission/effluent stream and the fact that it does not depend on petroleum hydrocarbon fuel sources. For High Speed Sealift, the application of Hydrogen On Demand ™ (HOD) technology for high-speed vessel propulsion systems using seawater as a primary ingredient in the hydrogen generation process is obvious. By way of eliminating weight and space penalties associated with the handling and reforming (in the case of fuel cells) of large volumes of liquid petroleum fuels, HOD technology could avail more ship volume and deadweight capacity for cargo and passenger transport.

The Phase I portion of this program has been segmented into the following discrete tasks.

Task 1.0: Literature Survey
Task 2.0: Existing Technology Review
Task 3.0: Regulatory Code Review
Task 4.0: Concept Design Development
Task 5.0: Final Report

1.0 LITERATURE SURVEY

1.1 Objective

Task 1.0 of Phase I comprises a broad literature search focused on identifying meaningful propulsion applications for pure hydrogen fuel, specifically among reciprocating internal combustion engines, combustion turbines and fuel cells. The results of this literature search, summarized in this report, will be utilized to develop a system concept design that integrates the HOD system in a marine fuel cell, diesel engine or gas turbine application.

1.2 Procedure

The technical literature search utilized the following methods:

1. Search of Seaworthy's technical library, including relevant documents from the Millennium Cell Corporation.
2. Searches of the Worldwide Web via the Internet.
3. Searches at the reference section of the U.S. Coast Guard Academy library.
4. Review of various government agency and industry-supported technical society. Respective document sources include the U.S. Maritime Administration (MARAD), the U.S. Coast Guard, the U.S. Department of Energy (DOE), the American Bureau of Shipping (ABS), the International Association for Hydrogen Energy, the Society of Automotive Engineers (SAE), the Society of Naval Architects and Marine Engineers (SNAME) and the online services of a variety of engineering libraries.

The information obtained from all sources was reviewed, including numerous candidate protocols for applicability.

1.3 Search Results

The search identified 95 relevant documents that addressed the application results, benefits and limitations of pure hydrogen fuel in reciprocating internal combustion engines, combustion turbines and fuel cells. A listing of reviewed documents, that were determined to apply directly to this program, follows.

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1.4 Discussion

As a result of the superior combustion and limited pollution characteristics of pure hydrogen fuel, engineers and scientists have generated abundant literature on its use as fuel in power and propulsion plants for decades. The literature suggests that hydrogen fuel can work well in both reciprocating and turbine engines. Until now, hydrogen's use has been limited by the hazards of storage and transportation. Moreover, to store hydrogen with sufficient density for use as a transportation fuel, it must be refrigerated or pressurized into a liquid state, which is an inefficient, energy-consuming process, which, in decades past, has diminished hydrogen's attractiveness as a fuel source.

According to the literature, there are three major catalysts that will drive a future hydrogen economy beyond the petroleum age: global sustainability, energy efficiency, and reduction of greenhouse gas emissions. This conclusion is bolstered by hydrogen on demand technology, which can eliminate the costly cryogenic processes historically inherent to this fuel source. Moreover, if utilized with fuel cells, the HOD process will replace the petroleum-dependent hydrogen reformers presently required by that technology, thereby eliminating toxic byproducts and effluent streams. Yet, by some estimates, the capital cost of a proton exchange membrane (PEM) fuel cell stack ranges from $6,000 to $12,000 per kilowatt. While this is significantly higher than the cost of internal combustion engines, it's approximately 90% to 95% less than their cost in 1991. One source suggests the cost of PEM fuel cells will continue to decline to where they are competitive with internal combustion engines over the next five to ten years.

As for conventional reciprocating engines and combustion turbines, the literature suggests that both can be converted for use with hydrogen fuel. Again, the only HC and CO emissions from a hydrogen-fueled engine are produced by lube oil consumption, which is typically low for this class of diesel engine. For the hydrogen-fueled reciprocating engine, it is felt that a natural gas-fueled engine could be modified to operate on lean hydrogen air mixtures. The consensus is that engine controls and fuel systems would need modification along with the addition of a turbocharger and aftercooler to provided adequate operation on hydrogen. Effort would need to focus on limiting pre-ignition and knock. Hydrogen use in turbines and jet engines is similar to use of conventional jet fuel, according to the International Association for Hydrogen Energy. The use of hydrogen avoids the problems of sediments and corrosion on turbine blades, which prolongs life and reduces maintenance. Gas inlet temperatures can be pushed beyond normal gas turbine temperatures of 800 °C, thus increasing overall thermal efficiency. The only pollutants resulting from the use of hydrogen in turbines and jet engines are nitrogen oxides.

2.0 REVIEW OF EXISTING TECHNOLOGY

2.1 Objective

The objective of Task 2.0 is to review relevant published technical literature to identify the current state of hydrogen fuel technology in transportation applications. This assessment will form the basis for Task 4.0, the concept design of the HOD system aboard a passenger ferry vessel. The information will also allow planners and managers in both civilian and military organizations to consider and take advantage of the benefits offered by this technology when utilized in other marine/maritime applications.

2.2 Hydrogen As A Fuel Source

Hydrogen is the most abundant and simplest element found in the universe. Under atmospheric conditions, hydrogen is a colorless, odorless, tasteless gas. It normally occurs as a diatomic molecule, or two hydrogen atoms bound together by shared electrons. Because hydrogen is chemically active, it is rarely found in its elemental condition. In most cases it is bonded with other elements, forming other molecules, such as oxygen in water and carbon in methane. Hydrogen bound in water and other organic matter comprises 70 percent of the earth's surface.

Hydrogen also has the highest energy content, by mass, of any known fuel, 61,000 BTU/lbm, HHV. In a liquid state (-423°F), it occupies 1/700 as much space as it does as a gas at atmospheric pressure. When hydrogen is burned with pure oxygen (or used in a fuel cell) the only byproducts are heat and water vapor. When burned in air, which is almost 70 percent nitrogen, some oxides of nitrogen (NO_X) are formed. Hydrogen combustion nevertheless causes far less air pollution than any other fossil fuel in use today. This importance of this is evident in the following statistics.

- Air pollution from transportation is estimated to account for more than 70 percent of all air pollution in densely populated urban areas, according to the U.S. Department of Energy (DOE).

- Transportation accounted for more than 68 percent of the 19.3 mmbbls/day of oil consumed in 2000, according to DOE estimates. Less than half of that oil was produced domestically.

The clean burning qualities and abundance of hydrogen is well established, but its production for use as a clean fuel is very costly. As a result, most alternative-fuel applications in industry and transportation have thus far used natural gas and propane. Natural gas occurs widely and benefits from a well-established infrastructure for its transportation and use. Natural gas is also attractive because it requires little processing and burns cleaner than coal or liquid petroleum fuels, yet not as clean as pure hydrogen.

As fuel cells evolve and gain traction in the market for power supply and transportation, the demand for hydrogen will grow, and technology for producing, storing, and transporting hydrogen is expected to improve, as it must, if hydrogen is to succeed as a viable alternative fuel. Each year, the world uses about $400x10^9$ m^3 of hydrogen, with 20 percent being consumed in the United States. Most hydrogen use is "captive," which means it is utilized in the same refining facilities as where it is generated. Experts believe that worldwide hydrogen production must at least double to become a primary transportation fuel. There are presently only a few proven methods for producing pure hydrogen fuel.

2.3 Hydrogen Fuel Production Methods

If hydrogen fuel is to be adopted by the U.S. transportation sector, its availability and production costs will have to approximate those of gasoline and distillate fuels. To match the *pre-tax* cost of gasoline at $0.855 per gallon ($6.71/mmBTU), hydrogen would have to be available at approximately $2.00/kg ($14.85/mmBTU), taking into account the superior thermal efficiency of a fuel cell (40 %). Reciprocating engines, with lower thermal efficiencies (ranging from 15 to 32 %), would require slightly cheaper hydrogen, for replacement of gasoline or diesel fuel. Moore and Raman co-authored a paper on the required infrastructure for hydrogen fuel cell transportation that clarifies the associated costs of introducing and maintaining a hydrogen fuel system for transportation. Their paper is based on the entire U.S. vehicle population, which consumes 350 million gallons of gasoline each day. Although this is a much broader market than a typical passenger ferry system, examining a broad-based transportation sector is essential for assessing the costs and energy requirements for producing and marketing pure hydrogen fuel.

Presently, there are four common methods for producing pure hydrogen, all of which strip hydrogen from conventional fossil fuels in a process called reforming. All methods also require some amount of energy input into the system.

- Steam reforming of methane (SMR) — The most common production method in which natural gas is steam heated to 850°C over a nickel catalyst bed, which yields a mixture of CO and H_2. The mixture is then cooled and catalyzed with steam again to yield pure hydrogen and CO_2. Therefore, this source of hydrogen does not eliminate the production of CO_2, a greenhouse gas. It simply relocates CO_2 production to upstream of the end user.
- Partial oxidation of heavy oil — This is a large-scale production method, yielding up to $50x10^6$ standard cubic feet per day (SCF/D), using heavy oil (low value) refinery byproducts. The heavy oil byproduct is reacted with oxygen at high temperature to yield CO and H_2, which are cooled to obtain pure hydrogen.
- Electrolysis of water — This process produces small quantities of hydrogen from water, but requires an inexpensive source of electricity. It can be implemented locally, on a household basis, but the cost is up to twice as high as the methods mentioned above.
- Methanol reformation —This process takes advantage of methanol's benign shipping and storage properties for localized hydrogen production where natural gas feedstock is not available. Reformation with water occurs at 250 to 300°C. Its cost is governed by methanol prices. As in natural gas reforming, there is also a CO_2 yield.

The economic comparison of each production method follows in Table 2.1.

Hydrogen Fuel Production Process	Output (tonnes/day)	Investment ($1000)	Product Cost ($/lbm)	Product Cost ($/mmBTU)*
Remote Reformer and Liquefier	27	63,000	1.52	24.87
Remote Reformer and Liquefier	270	259,000	1.07	17.45
Remote Reformer and Pipeline	27	82,000	1.32	21.61
Remote Reformer and Pipeline	270	667,000	1.12	18.34
On-Site Natural Gas Reformer	2.7	9,600	1.62	26.51
Partial Oxidation of Oil	2.7	12,500	1.80	29.40
Electrolysis of Water	3 kg/day	13.5-23.1	3.16	51.75
Methanol Reformation	2.7	6,800	1.71	27.92

*All prices are pre-tax estimates. All energy values are based on the higher heating value, HHV.

Table 2.1: Comparative Hydrogen Production Costs

Sources: Moore, R.B., Raman, V., Hydrogen Infrastructure for Fuel Cell Transportation, Int'l Journal of Hydrogen Energy 23 (1998) 617-620.

The cost and energy balance above depends on the following assumptions for developing pure hydrogen fuels.

- Natural gas is $2/mmBTU at a remote, large-scale facilities (270 tonne/day).
- Natural gas is $3/mmBTU at a regional, medium scale facility (27 tonne/day).
- Natural gas is $4/mmBTU at a local, small-scale facility (2.7 tonne/day).
- Electric power is $0.07/kWh for a home electrolysis unit; $0.05/kWh for continuous usage at on-site, regional and remote plants; and $0.03/kWh at all locations during off-peak periods.
- Methanol at a market price of $0.18/liter.
- Heavy oil at a market price of $0.09/liter.

Millennium Cell's Hydrogen on Demand (HOD) system introduces another possibility for hydrogen production, a solution that is independent of fossil fuels. HOD is a localized process that uses on-board storage of sodium borohydride, $NaBH_4$, mixed with water. The solution reacts with a metal catalyst to yield pure hydrogen gas and a byproduct, $NaBO_2$, which can be recycled back to $NaBH_4$ feed stock. Sodium borohydride is nonflammable and easily transferred for on-board storage — like a conventional liquid fuel. While $NaBH_4$ is available today, it is relatively expensive due to lack of a production infrastructure, when compared to the hydrogen reforming technologies described previously.

The present cost of $NaBH_4$ is $7/dry pound, which equates to $468/mmBTU for finished hydrogen. Researchers at Millennium Cell, Inc., project that this cost can be reduced to $17.37/mmBTU with the construction of a large processing plant (2,500 tons of $NaBH_4$ output per day, enough to power 900,000 fuel cell vehicles). The total installed capital cost of such a plant is estimated to be $200 million. Millennium Cell's estimated fuel cost of $17.37/mmBTU is competitive with the most economically produced hydrogen cost of $17.45/mmBTU, based on steam reformation of natural gas at a large-scale plant, vs. $6.71/mmBTU for gasoline and $6.68/mmBTU for number 2 diesel fuel.

Although the price of $NaBH_4$ is presently high, if production plants are developed the fuel cost should drop to the range of other hydrogen production methods. Furthermore, there are some notable advantages offered by the HOD process when compared to other hydrogen reformation technologies.

- The feedstock byproduct is 100 percent recyclable with water.
- The HOD process yields no greenhouse gases such as CO and CO_2, unlike all other fossil fuel-based reforming methods.
- The feedstock has superior hydrogen-storage efficiency (see Table 2.2, below).
- The feedstock is stored and processed at low pressure, is stable at room temperature, and is completely non-flammable.
- Hydrogen generation rates are fully controllable, based on engine or fuel cell demand, and may be stopped immediately.
- The feedstock is easily transported, stored, and transferred to vehicles equipped with the HOD system.

Extensive production plant development is expected to occur if an appreciable market for $NaBH_4$ is developed with a hydrogen economy. All other production methods would also require significant expansion for a change to hydrogen fuel by as little as one percent of the U.S. vehicle market. While the projected cost of hydrogen fuel is higher than gasoline per million BTU, it would also be somewhat offset by the superior efficiency of fuel cell-powered vehicles. Fuel cells are 40 percent thermally efficient. Presently, most engine-powered vehicles are 15 to 20 percent thermally efficient. The current hydrogen production technologies, such as steam-reformation of natural gas, are potentially feasible on a large scale, but do not eliminate the production of CO_2.

2.4 Hydrogen Fuel Distribution and Refueling

Currently, hydrogen-refueling stations are almost non-existent, except for some experimental applications such as the hydrogen-fueled passenger bus program in Chicago, Ill., consisting of three buses. An industrial gas vendor supplies liquid hydrogen to the Chicago bus facility. The most economical means of producing hydrogen for an application such as this is steam reformation of natural gas and transport via a pipeline or in cryogenic tractor-trailers. Because hydrogen pipelines in the United States are nonexistent, with the exception of a small system on the Gulf coast, hydrogen producers generally liquefy immediately upon production and ship hydrogen over the road in tanker trailers. In the case of the Chicago bus refueling-terminal, the liquid hydrogen, when needed, is vaporized through a heat exchanger and then compressed into a series of lightweight, composite cylinders fixed on top of each bus. It takes about two hours to refuel all three buses, one at a time.

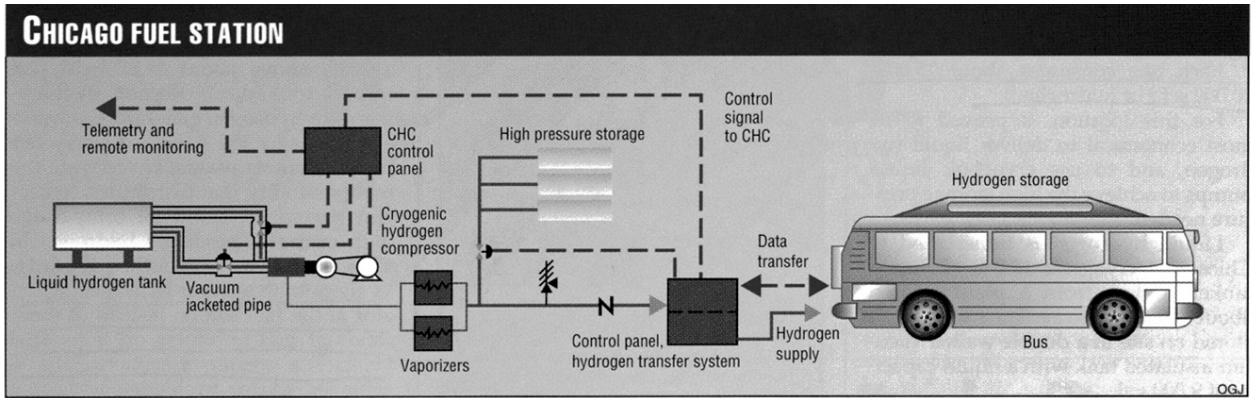


Figure 2.1: Chicago PEM Fuel Cell Passenger Bus Hydrogen Refueling Terminal

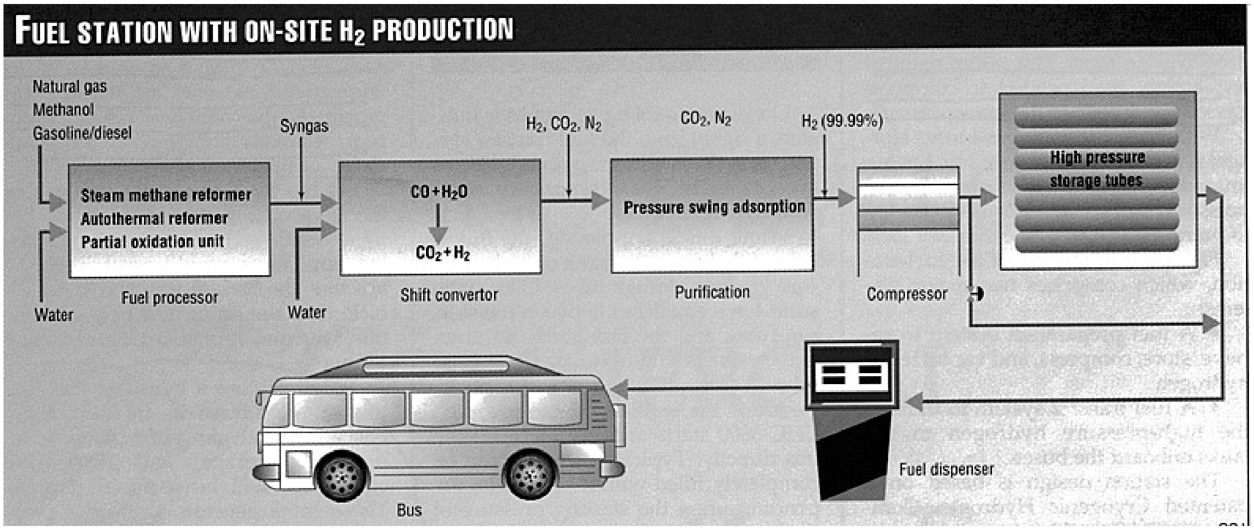
Source: Raman, Venki, "Chicago Develops Commercial Hydrogen Bus Fleet," Oil and Gas Journal, July 12, 1999.

To gain acceptance, centralized hydrogen production facilities must optimize economies of scale. For now, cryogenic shipping of liquid hydrogen is the most efficient way to transport hydrogen in small quantities. In the long term, a network of dedicated pipelines connecting remote large-scale production facilities to urban population centers will further reduce the cost per million BTU.

There are several ways to refuel vehicles with conventionally reformed pure hydrogen.

- Compressed gas stations that recharge vehicle-mounted gas cylinders, as in the Chicago bus system.
- Replace with pre-filled compressed hydrogen cylinders that enable empty cylinders to be traded for full ones.
- Liquid hydrogen cylinders with cryogenic forwarding systems have superior energy storage capabilities when compared to compressed gas.

Figure 2.2 depicts a hydrogen refueling system, based on the Chicago bus system, with localized hydrogen reforming. Table 2.2, below that, depicts storage densities for the most common on-board storage methods for hydrogen fuel.



Note: The type of fuel processor selected depends on the type of fuel feed stock.

Figure 2.2: On-Site Hydrogen Reforming and Refueling Station for a Hydrogen-Fueled Passenger Bus System

Source: Raman, Venki, "Chicago Develops Commercial Hydrogen Bus Fleet," Oil and Gas Journal, July 12, 1999.

Five (5) Kilograms of Hydrogen (0.673 mmBTU)	
Storage Method	Required Storage Volume
Compressed Gas Bottles (5000 psig)	180 Liters
Liquid Cryogenic (0 psig)	71 Liters
In 35 wt% $NaBH_4$ Solution (0 psig)	65 Liters

Note: The $NaBH_4$ Solution (in water) is the feedstock for the Millennium Cell Hydrogen on Demand system.

Table 2.2: Required Storage Volumes for 5 kg of Hydrogen

Source: Amendola, S., et al, A Safe Portable Hydrogen Gas Generator Using Aqueous Borohydride Solution and Ru Catalyst, Int'l Journal of Hydrogen Energy 25 (2000) 969-975.

In conclusion, there are several methods of producing, storing, transferring, and using hydrogen, Earth's most abundant element, and industry's cleanest-burning fuel. Although hydrogen is also very dense in energy (61,100 Btu/lbm), it is important to note that its production is, in all cases, an energy consumer. The costs of this energy required for production are already built into the price estimates presented in Table 2.1. However, from an environmental standpoint, it worth noting the following about conventional methods of reforming hydrogen.

- To net 61,000 Btu/lbm hydrogen fuel, energy must be consumed in the process.
- Production of high temperature steam, required for natural gas and methanol reformation into hydrogen, is a large energy consumer.
- Electricity required for the electrolysis of water must come from a power plant, most of which burn fossil fuels, with all their attendant emissions.
- Hydrogen combustion yields no oxides of carbon (CO, CO_2). Obtaining pure hydrogen from fossil fuels, however, must yield oxides of carbon in the same amount as combustion of fossil fuels. The CO and CO_2 emissions simply occur upstream of the end user, where reforming occurs.
- In contrast, Millennium Cell's Hydrogen on Demand process yields zero emissions of CO or CO_2 at any point in the system. The spent $NaBH_4$ feedstock is also 100 percent recyclable. Energy, on some scale, must be consumed however by the production of the feed stock, $NaBH_4$, and its recycling.

The most effective means of mitigating the energy loss in the production of hydrogen fuel is to implement economies of scale. Large steam generating systems are more efficient than small plants. If steam reformation of natural gas is used to reform hydrogen, the most cost-effective plants will operate on a large scale, using vast amounts of high-efficiency steam to reform large amounts of hydrogen. Similarly, if Millennium Cell's HOD system is implemented, the best, most efficient producers of $NaBH_4$ feedstock will operate large-scale mining, purifying, and recycling facilities. Just as in the generation of electricity, hydrogen production — or hydrogen feedstock production — is best effected on a large, efficient, scale and distributed to end users, as opposed to local, household-sized reformers.

2.5 Engine Applications

2.5.1 Internal Combustion Engines

Internal combustion engines have been the integral prime mover in transportation since vehicles were mechanized more than a century ago. Such engines have been optimized to burn liquid hydrocarbon fuels. Yet despite decades of engine tuning and advances in material science, the overall thermal efficiency of the average automobile engine is just 15 to 20 percent. A large portion of the available thermal energy is lost to the engine cooling system and to the exhaust stream out the tailpipe. Other energy losses arise from the friction of the running gear and through each piston's functioning as an air pump on the intake, compression and exhaust strokes of the typical engine.

Electronic fuel injection has improved engine efficiency by accurately controlling the metering and timing of fuel injection into each engine cylinder. This ensures that more of the fuel is burned per injection event, as opposed to earlier engines that relied on carburetors to perform the fuel/air mixing function for all cylinders in common. Carburetor fuel metering is an imperfect process that inevitably over feeds cylinders during load transients. The unburned hydrocarbons exit the tailpipe as major air pollutants. However, even sophisticated engines with the ideal injection systems will pollute the atmosphere as long as they burn petroleum-based hydrocarbon fuels. During hydrocarbon combustion, carbon disassociates from the hydrogen and forms carbon monoxide (CO), which is toxic, and/or carbon dioxide (CO_2), the most abundantly produced transportation greenhouse gas.

Hydrogen burns cleanly because it has no carbons attached that disassociate to form CO and CO_2. As a result, scientists and engineers have experimented intermittently for many decades with the combustion of pure hydrogen, H_2. With the present commercialization of the fuel cell, the uncertain future of the crude oil supply, and the regulatory thrust toward lower emission vehicles, interest and experimentation with hydrogen combustion has dramatically increased.

Hydrogen is generally considered more thermally efficient than gasoline for internal combustion applications, mainly because it burns more completely and allows use of higher compression ratios. Because of its wide explosive range in air (4 to 75 percent, by volume), hydrogen can burn in lean as well as rich air mixtures. As a result, hydrogen improves fuel economy in stop-and-go traffic and eliminates smoke, soot and odor from vehicle exhaust. Moreover, the small amount of $NO_{X,}$ formed when H_2 is burned in air, can be further minimized by reducing the fuel/air ratio or by scrubbing the exhaust.

Reciprocating internal combustion engines can be divided into two groups, the compression ignition (Diesel cycle) engine and the spark ignition (Otto cycle) engine. Hydrogen combustion in each of these types of engines has been experimented with over the years, with a greater focus on the spark ignition engine.

2.5.2 Compression Ignition (CI) Reciprocating Engines

Hydrogen-fueled compression ignition engines are sparsely mentioned in the technical literature. The auto-ignition temperature of diesel fuel, the predominant CI-engine fuel, is 251°C. The auto-ignition temperature of natural gas, the predominant alternative fuel in internal combustion engines, is 540°C. As a result, engines that burn natural gas require some form of ignition assistance, usually in the form of a spark plug. Meanwhile, the auto-ignition temperature of hydrogen is even higher at 585°C. A CI engine capable of auto-igniting hydrogen would require an exponentially higher compression ratio than exists among conventional Diesel-cycle engines. A fuel injection system to overcome that cylinder pressure as the piston nears top dead center (TDC) would be extremely complex. As a result, virtually all hydrogen-fueled engines to date have been of the spark ignition (SI) type.

It is also worth noting that a number of commercial engine manufacturers have developed compression ignition engines that burn natural gas, despite the fuel's high auto-ignition temperature. These engines typically inject a small burst of diesel fuel at top dead center (TDC). The diesel fuel auto-ignites and detonates the natural gas charges already present in the cylinder. This combustion process, while cleaner than conventional all-diesel fueled engines, still produces measurable amounts of CO, CO_2, SO_X and NO_X from the burst of diesel fuel.

2.5.3 Spark Ignition (SI) Reciprocating Engines

A variety of SI engines have been modified experimentally to burn pure hydrogen fuel. This work has shown numerous pros and cons for the use of hydrogen as a fuel, some of which are addressed below.

- Most engines are fairly easily modified to burn hydrogen.
- The wide flammability range of hydrogen, which spans a hydrogen concentration of 4 to 75 percent by volume in air, enables the engines to run at a very lean fuel/air ratio. A lean mixture lowers the combustion temperature and therefore limits NO_X production.
- Fuel storage systems must be modified to overcome the low volumetric energy density of hydrogen by using high-pressure compressed hydrogen or cryogenic liquid hydrogen (LH2).

For all the promise of hydrogen-fueled SI engines, there are also a number of challenges that must be overcome to successfully modify SI engines. Because hydrogen has low volumetric energy, a unit volume of hydrogen and air at stoichiometry has only 85 percent of the calorific value of the gasoline-air mixture. A hydrogen-fueled engine is estimated to be 15 percent less powerful than an equivalent-sized gasoline engine from the outset. Power output from an external-mixture type hydrogen engine, using a common intake manifold for fuel and air, is typically even lower because of backfire and pre-ignition. Moreover, carbureted/intake-port-fueled engines permit gaseous hydrogen to displace part of the intake charge air, reducing ignition pressure. This loss, added to the losses of irregular combustion, translate to 20 percent less power developed by a carbureted or intake-port-fueled engine, as opposed to direct cylinder injection.

Hydrogen can be independently injected -- instead of aspirated with intake air -- at bottom dead center (BDC) at the start of the compression stroke, but pre-ignition and power loss still occur. Therefore, the most effective method incorporates hydrogen injection under high pressure as the compression stroke nears TDC. The HP injection process prevents backfiring, pre-ignition and the attendant power loss. In many cases, the fuel/air mixing is the greatest challenge to effective HP direct injection because the duration of the injection and mixing event is so brief before combustion occurs. Thermal efficiency, therefore, does not greatly improve with HP direct injection over LP intake-port injection, but all other aspects of engine operation do improve, especially power output and smooth combustion.

Another potential concern associated with hydrogen combustion in SI engines is lubricating oil contamination. The very low density of hydrogen gas allows it to blow by the piston rings on the compression stroke and enter the crankcase. Under these conditions, it appears that the oil rapidly loses its lubrication qualities and undergoes a dramatic increase in viscosity at operating temperature, in effect "hardening" the oil. One possible solution to this problem would be forced ventilation of the crankcase, followed by oil mist separation. Another solution would be to develop lubricating oil with deterioration-resistant properties when in contact with hydrogen.

Figure 2.3, below, depicts a typical SI engine combustion chamber and fuel injection system. This particular design utilized electronic pickups on the flywheel and output shaft to regulate the injector and air-inlet throttle valve for better engine control during speed and load changes. Injection controls of this type improve engine performance in terms of power output, thermal efficiency and emissions.

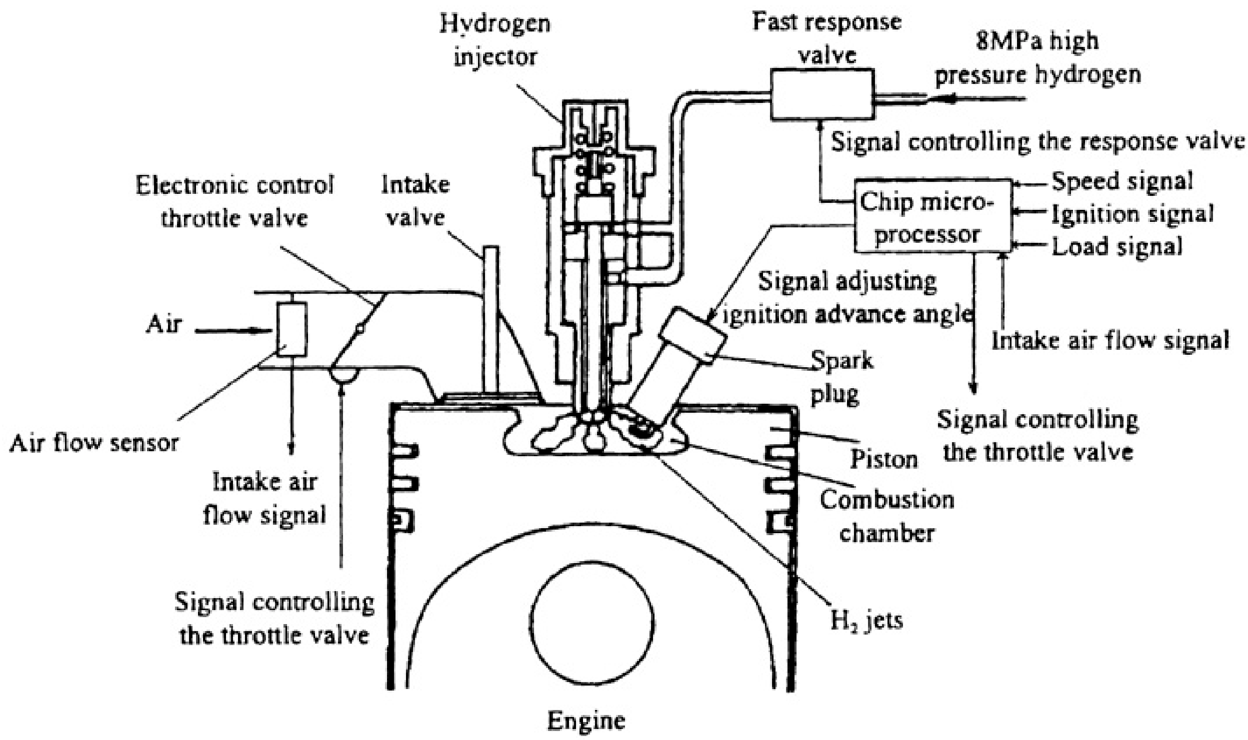
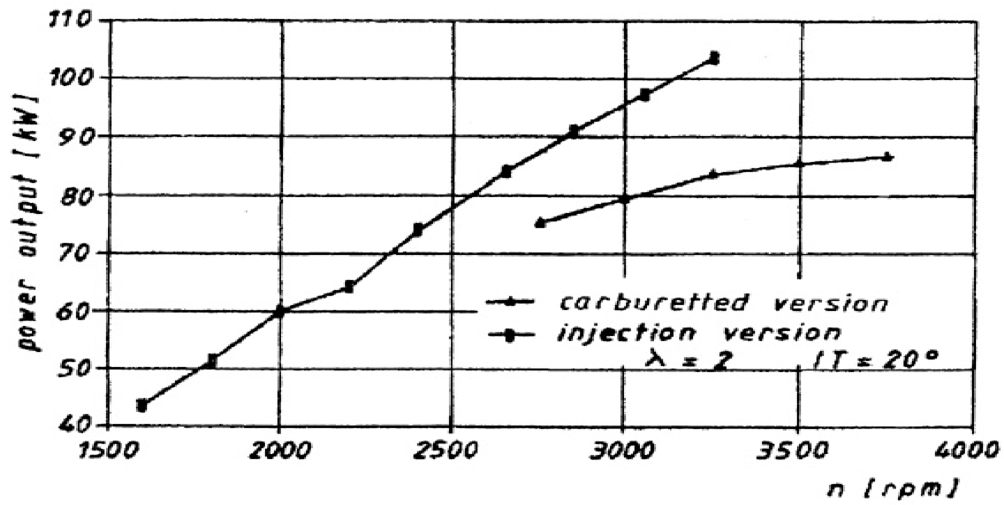


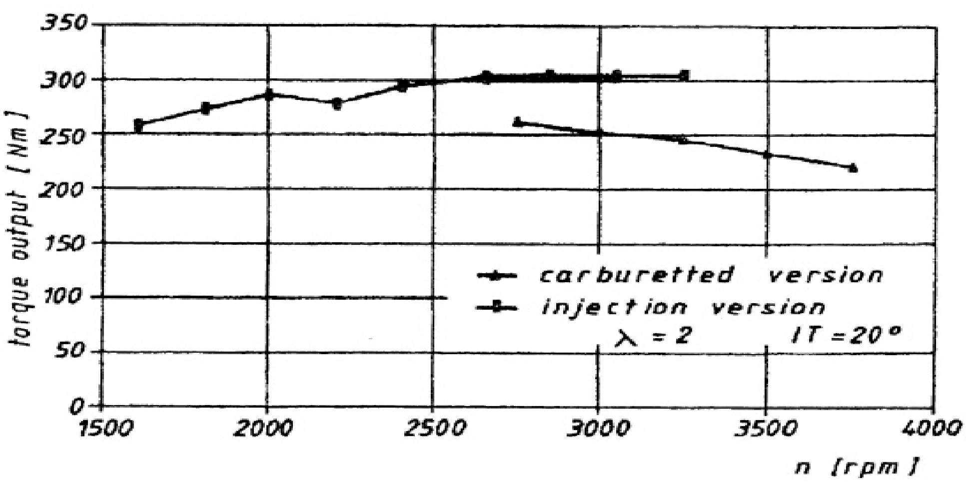
Figure 2.3: Schematic Diagram of a Hydrogen-Fueled SI Engine Combustion System

Source: Guo, L.S., Lu, H.B., Li, J.D. A Hydrogen Injection System with Solenoid Valves for a Four-Cylinder Hydrogen-Fuelled Engine, Int'l Journal of Hydrogen Energy 24 (1999) 377-382.

Figure 2.4, below, depicts the superior power and torque performance characteristics of hydrogen-fueled SI engines with direct injection fuel systems, vice the carburetor and intake manifold approach.



Power output.



Torque output.

Figure 2.4: Performance Characteristics of Direct-Injection vs. Carburetor in a GM 454 Big Block SI Engine Modified for Hydrogen Fuel

Source: Verhelst, S., Sierens, R., Aspects Concerning the Optimisation of a Hydrogen Fueled Engine, Int'l Journal of Hydrogen Energy, 26 (2001) 981-985.

Figures 2.5 and 2.6, below, depict two variations of existing fuel injectors utilizing compressed hydrogen fuel in a SI engine.

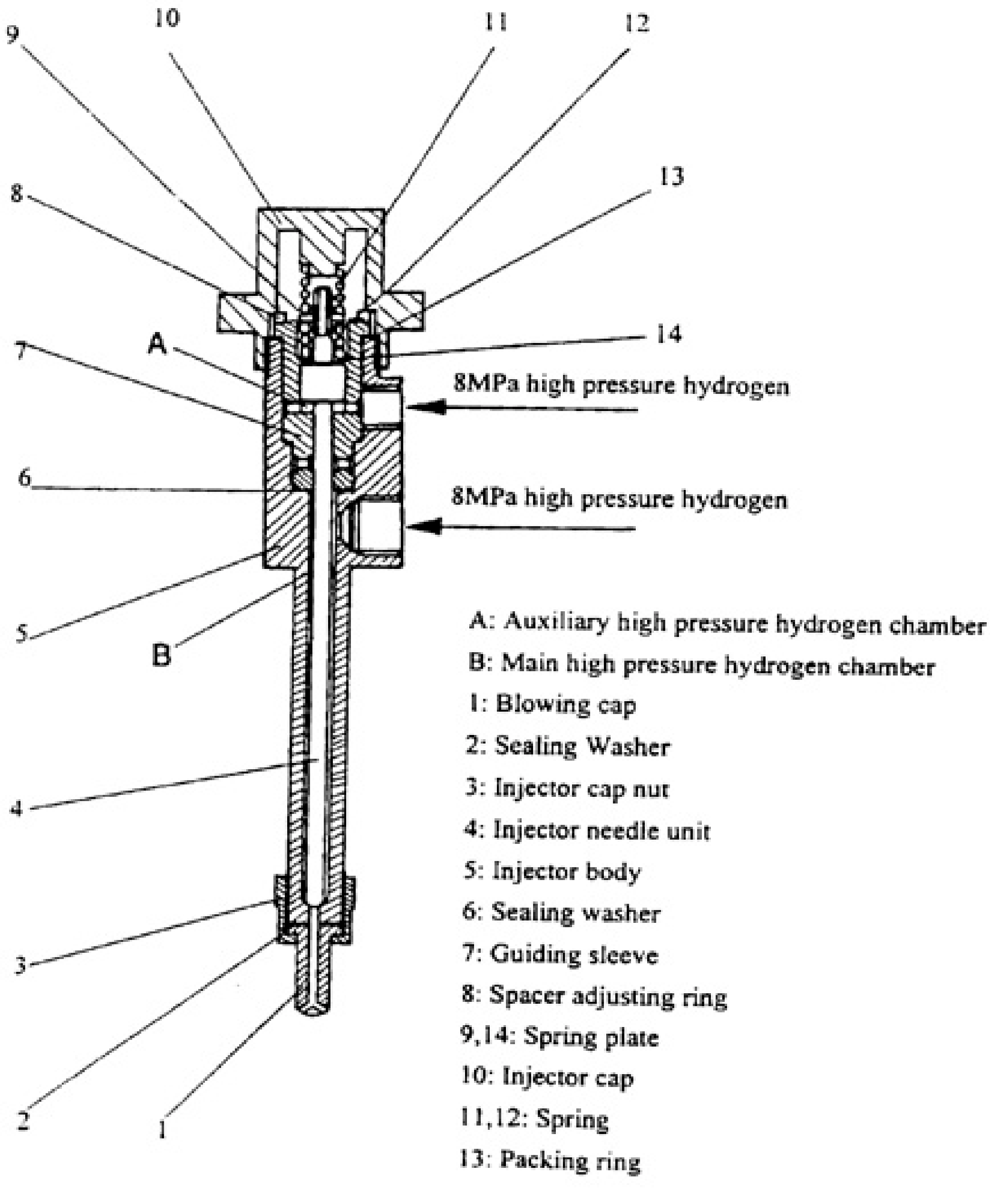


Figure 2.5: Sectional Drawing of an In-Cylinder Hydrogen Injector

Source: Guo, L.S., Lu, H.B., Li, J.D. A Hydrogen Injection System with Solenoid Valves for a Four-Cylinder Hydrogen-Fuelled Engine, Int'l Journal of Hydrogen Energy 24 (1999) 377-382

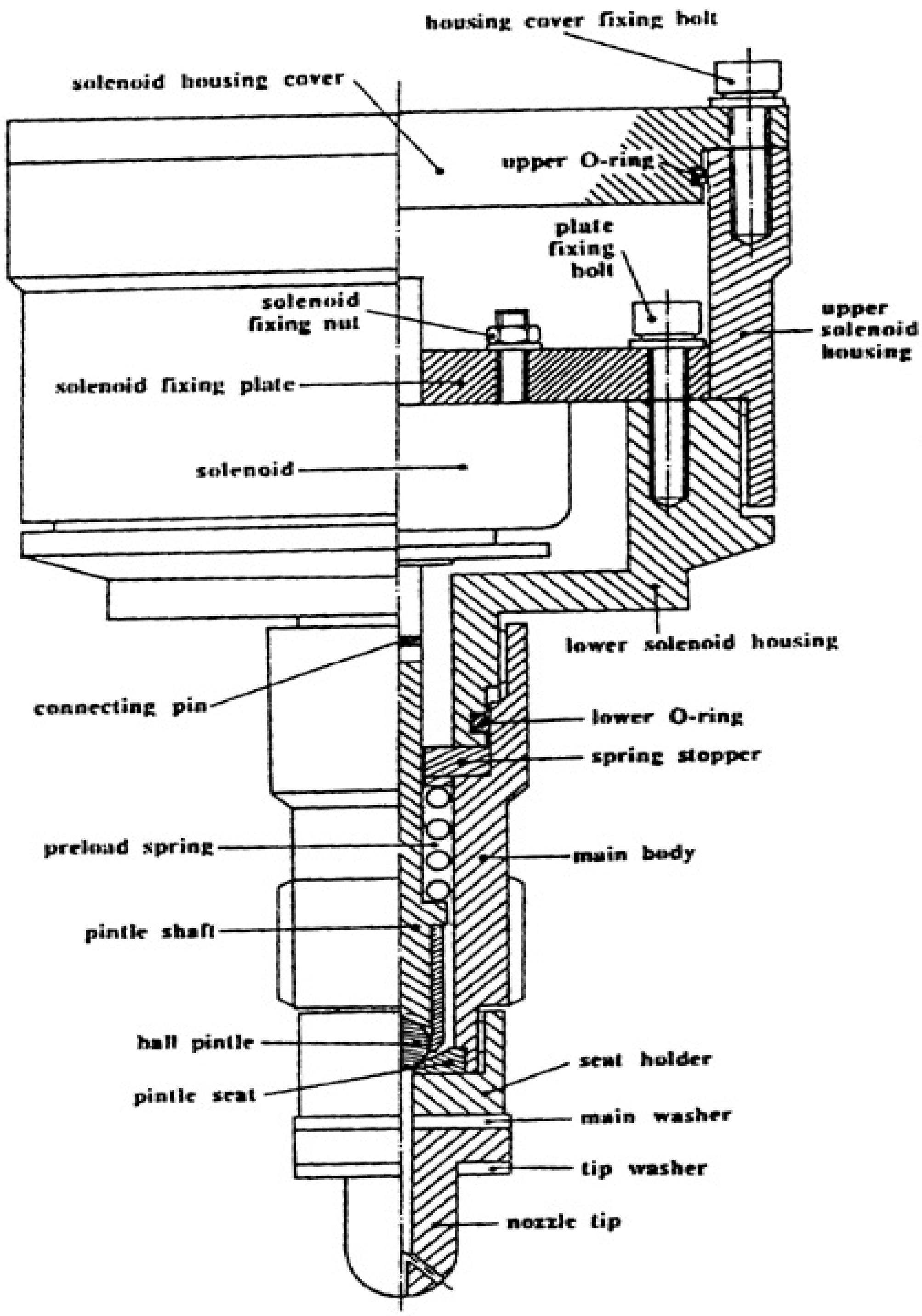


Figure 2.6: Sectional Drawing of an In-Cylinder Hydrogen Injector

Source: Yi, H.S., Lee, S.J., Kim, E.S., Performance Evaluation and Emission Characteristics of In-Cylinder Injection Type Hydrogen Fueled Engine, Int'l Journal of Hydrogen Energy, 21 (1996) 617-624.

2.6 On-Board Hydrogen Storage and Forwarding Systems

Some engines have performed well on cryogenic LH_2 because the fuel, which originates at -423°F at 2 bar, cools the combustion process enough to reduce NO_X and engine knock, due to the over-rapid rise of combustion pressures. NO_X is a (mostly) unavoidable byproduct of combustion in air. Cold H_2 also displaces less air than ambient H_2 resulting in increased power output. Therefore, cryogenic hydrogen is helpful because it cools the mixture to reduce emissions without the power loss that detracts from other methods such as water injection and exhaust gas recirculation. Yet LH_2 fuel systems have many problems of their own, which offset the storage density advantage. For example, they require heavily insulated storage and delivery piping, as well as a non-cavitating pump to boost the fuel to a required injection pressure. The cryogenic storage and forwarding system for LH_2 is not yet technically available for mass production.

The most commercially developed hydrogen fuel system, for both storage and combustion is similar to natural gas fuel systems. High-pressure hydrogen gas is stored in composite cylinders and regulated through supply piping to a direct injection system on the engine. Figure 2.7 depicts a typical fuel storage and forwarding system for an inline four-cylinder SI hydrogen test engine. A commercially produced SI engine of this type would forego the exhaust analyzers and flow meters shown in the bottom of the figure.

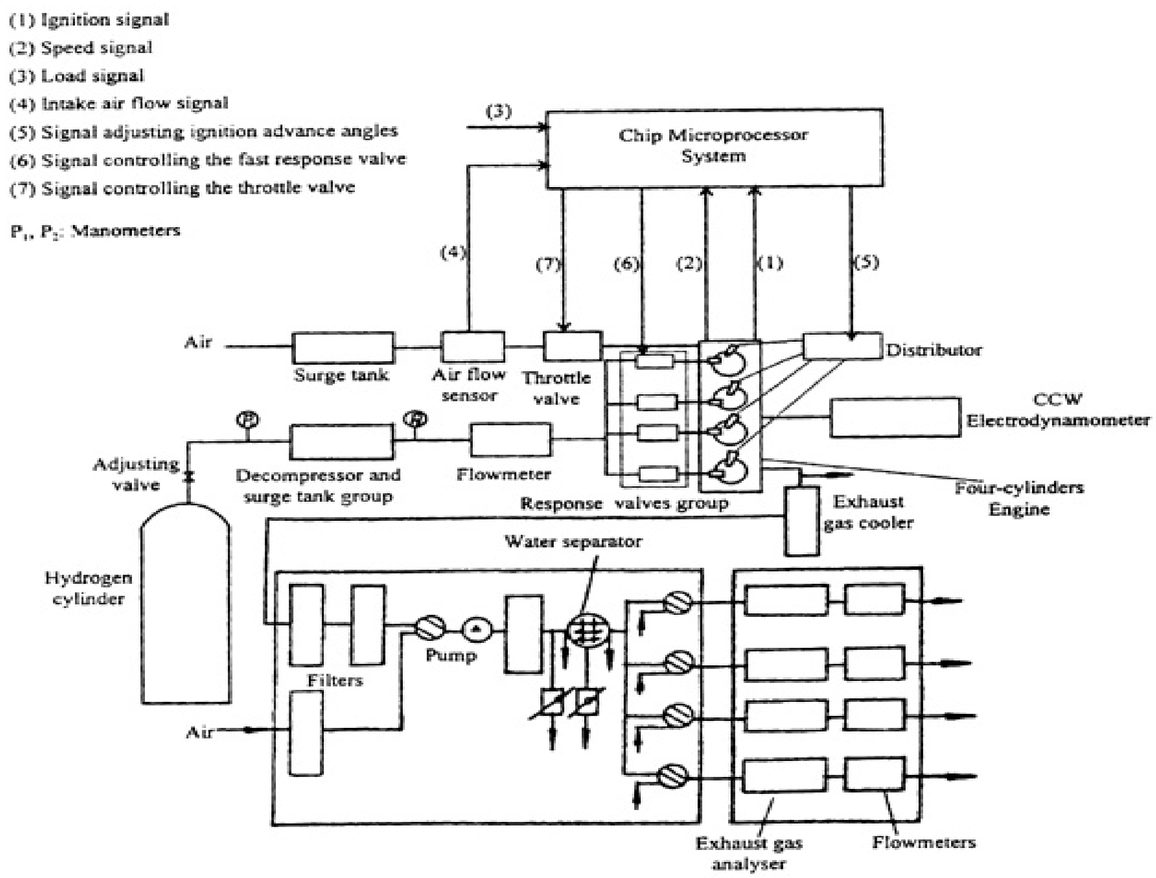


Figure 2.7: Hydrogen Storage and Forwarding System for a Four-Cylinder SI, Compressed-Hydrogen-Fueled Test Engine

Source: Guo, L.S., Lu, H.B., Li, J.D. A Hydrogen Injection System with Solenoid Valves for a Four-Cylinder Hydrogen-Fuelled Engine, Int'l Journal of Hydrogen Energy 24 (1999) 377-382

High Pressure injection requires precision fine-tuning, in terms of timing and metering. It must also be capable of handling a range of hydrogen pressures (3 to 120 bar). In test situations thus far, the most common fuel forwarding system comprises compressed hydrogen in bottles (or from the HOD system), a pressure regulator, and a common rail system that supplies injectors at constant pressure. Injectors are carefully designed to prevent leakage through the tip by the high-pressure gas. Without a cost-efficient hydrogen infrastructure, relative to gasoline, hydrogen-fueled SI engines have not progressed beyond experimental development to commercial production. Hydrogen-fueled SI engines have been demonstrated to be a potentially viable concept once a hydrogen production, distribution and storage infrastructure is put in place.

2.7 Combustion Turbines

Combustion (gas) turbines are commonly operated on gaseous fuels, such as compressed natural gas. The transition to hydrogen fuel presents few technical barriers at this time, none of them substantial. Conversion of a natural gas engine to operate on hydrogen would require modification to the fuel delivery system and combustor section of the turbine itself. The compressor and power turbine stages would be mostly unaffected by the change. Further development of this technology awaits commercialization of a hydrogen fuel supply system.

As prime movers in ships, ferries, aircraft, etc., gas turbines burn liquid fuel for its superior volumetric energy density and ease of storage and transfer. There is also an extensive amount of application experience for gas-burning combustion turbines, most of which comes from the utility industry. As a result, the transition to pure hydrogen fuel should be relatively straight forward, as the majority of combustion turbine utility plants worldwide are fueled by compressed natural gas. In the past five years alone, hundreds of new gas turbine units have been built and put on-line around the United States, nearly all of which are fueled directly by high pressure natural gas pipelines. Another notable source of hydrogen experience is with experimental aircraft of the U.S. air and space program, which began testing jet engines with liquid hydrogen fuel as early as 1943 at Ohio State University. These early experiments were a force behind NASA's adoption of the LH_2/LO_2-fueled rocket programs. Research engineers have added results from a variety of hydrogen-fueled test engines to this body of knowledge.

As with the reciprocating engines discussed in Section 2.5, pure hydrogen fuel in a combustion turbine is ideal in terms of emissions, sparing the exhaust stream of soot, CO, CO_2 and acid rain-causing sulfur dioxide, SO_2. Oxides of nitrogen (NO_X) remain a problem, however, because high combustion temperatures and the presence of nitrogen in air cause NOX. NO_X forms tropospheric ozone, or smog. The rate of NO_X generation varies exponentially with flame temperature and linearly with the amount of time that the gases are exposed to the flame zone.

This is also known as reaction zone dwell time. It is important to limit these two factors that account for NO_X in the combustion turbine exhaust stream.

Compared to other fuels, hydrogen also offers other distinct advantages when burned in a combustion turbine. The flammability range of hydrogen is 14-times greater than the range of kerosene. Therefore, the fuel/air ratio can be throttled for much leaner combustion than kerosene could ever sustain. This reduces the reaction zone temperature, which reduces NO_X formation exponentially. Hydrogen also has a much higher flame speed than kerosene. As a result, the reaction zone dwell time is shorter than combustion with other fuels, which limits the combustion gas's contact with the hot zone, and reduces NO_X formation linearly with exposure to the hot zone. Figure 2.8 depicts the relationship between combustion temperature and the formation of NO_X.

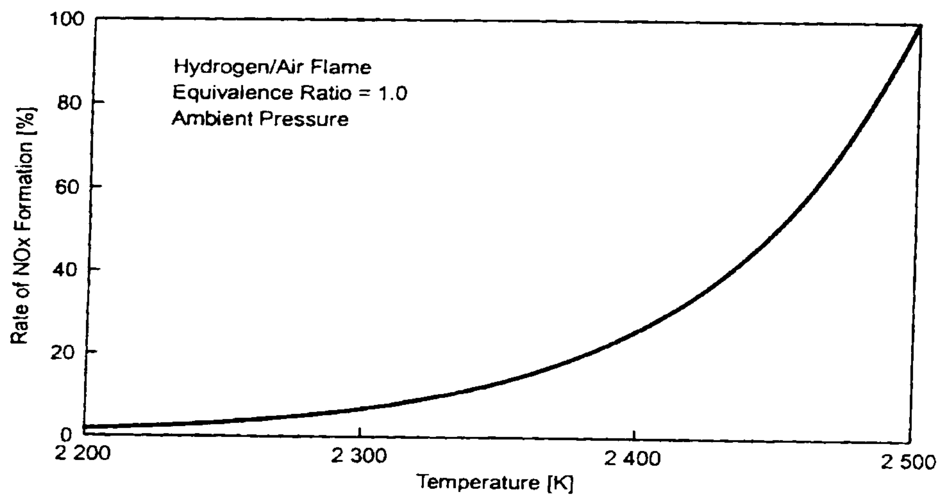


Figure 2.8: NO_X Formation as a Function of Temperature, Normalized at 2500 K

Source: Ziemann, J, et al, Low-NO_X Combustors for Hydrogen Fueled Aero Engine, Int'l Journal of Hydrogen Energy, 23 (1998) 281-288.

Table 2.3 compares the properties of hydrogen and natural gas fuels as demonstrated by analysis of a computer-simulated high output combustion turbine.

Parameter	Natural Gas Fuel	Hydrogen Fuel
Pressure Ratio	17	17.1
Turbine Entry Temperature (K)	1150	1550
Inlet Flow (kg/sec)	622	622
Power Output (MW)	250	261
Thermal Efficiency (%)	38.7	39.6
Exhaust Temperature (K)	857	852

Table 2.3: Simulated Performance for a Combustion Turbine Burning Natural Gas and Hydrogen Fuels

Source: Audus, H. and Jackson, A.J.B., CO2 Abatement by the Combustion of H2-Rich Fuels in Gas Turbines, IEA Greenhouse Gas R&D Programme.

This analysis was based on state-of-the-art technology developed by leading gas turbine manufacturers, specifically ABB-Alstom, Siemens-Westinghouse, and General Electric. As shown in Table 2.3, the hydrogen engine is 4 percent more powerful and 2 percent more efficient than the natural gas engine. The hydrogen-fueled engine also eliminates the production of CO and CO_2 gases in the exhaust stream.

Modifications to the combustors and fuel mixing system are the principal requirements for converting a natural gas combustion turbine to burn hydrogen fuel, as a result of the higher flame speed and shorter auto-ignition delay for hydrogen. The changes are not considered difficult from a design standpoint. A second consideration is fuel system sizing. Although hydrogen has almost three times more energy by mass than natural gas (61,000 Btu/lbm vs. 24,000 BTU/lbm), by volume that energy density is much lower. At standard temperature and pressure, hydrogen has 325 BTU/ft^3, compared to 1014 BTU/ft^3 for natural gas. As a result, gaseous hydrogen-fueled combustion turbines will require larger delivery piping, manifold, valves and nozzle sizes than natural gas-burning engines currently need. Compressing hydrogen to a greater operating pressure than natural gas, to increase its volumetric energy density, would mitigate the increased size requirements for delivery equipment.

Although hydrogen combustion turbines are not presently commercially produced, due to a lack of a hydrogen fuel infrastructure, manufacturers have expressed some development concerns and indicate the combustor, materials, cooling, control system and operability would require most of this effort. However, at this time, there appear to be no major technical barriers for hydrogen-fueled combustion turbines. While immediate efficiency gains could be obtained using hydrogen in place of natural gas, these would likely be offset by NO_X control considerations, such as a lean fuel/air mixture to limit the combustion temperature. With efficiency and power considered equal between the fuels, the most significant gain from hydrogen fuel combustion turbines is its nearly completely clean emissions profile.

2.8 Fuel Cells

Fuel cells are the most frequently referenced prime mover among hydrogen-fueled, near-zero emissions energy converters in the marketplace today. The fuel cell is an electro-chemical device that combines oxygen from the air with an independent hydrogen fuel source that yields heat, water and electricity. Like other hydrogen energy-converters discussed herein, there are no CO, CO_2 or SO_X pollutant emissions. Fuel cells also produce zero NO_X emissions, as a result of their combustion-free operation. Without combustion and moving parts, the fuel cell also operates in near silence, with almost no vibration. The hydrogen is converted directly to electricity, without any rotational mechanical energy or the load-related dynamics of a spinning generator. As a result, fuel cell thermal efficiency is relatively high, at up to 40 percent. Although there are many variations of fuel cell design and operating principles, the hydrogen proton-exchange-membrane (PEM) type appears to be attracting the most interest, particularly in larger transportation applications.

2.8.1 Operation

The PEM fuel cell comprises three stationary parts: a negative electrode that repels electrons, called an anode; a positive electrode that attracts electrons, called and cathode; and an electrolyte membrane located between the anode and the cathode. Hydrogen flows first into the anode, which is coated with platinum to separate the gas into protons (+) and electrons (-). The anode repulses the electrons, which also cannot pass through the electrolyte barrier in the center. The electrons are then diverted as an electric current through a circuit, to the cathode side of the fuel cell. Meanwhile, the electrolyte in the center permits passage of the protons simultaneously to the cathode side of the fuel cell. As air flows into the cathode side of the fuel cell, a second platinum coating helps the hydrogen protons and electrons combine with oxygen to produce pure water and heat.

In each fuel cell, the electric current of the hydrogen electrons flowing to the cathode is tapped for electric power output. The surface area of each cell determines the total current. The number of cells placed together in one "stack" determines the voltage. Multiplying the current by the voltage yields the total power output of the PEM fuel cell stack. The ancillary heat output is clean and, therefore, suitable for auxiliary applications.

2.8.2 Fuel Storage and Handling Requirements

The conventional hydrogen fuel systems required to support a PEM fuel cell application are similar to those required by the IC engine and combustion turbine applications discussed above. The fuel cell requires gaseous hydrogen fuel. As depicted previously in Figures 2.1 and 2.2, the fuel can originate as a liquid or gas, but must be vaporized before it enters the fuel cell. It can also be stored as a compressed gas in cylinders and regulated to the required feed pressure at the fuel cell.

Millennium Cell, Inc., has recently demonstrated its HOD system, supporting a PEM fuel cell, in partnership with Daimler Chrysler Inc., aboard the new Chrysler Natrium minivan. While conventional on-board hydrogen reforming systems require substantial passenger/cargo space, the HOD storage and forwarding system is compact enough to fit under the floorboards. Figure 2.9 depicts the Natrium van fitted with an on-board HOD system and PEM fuel cell.

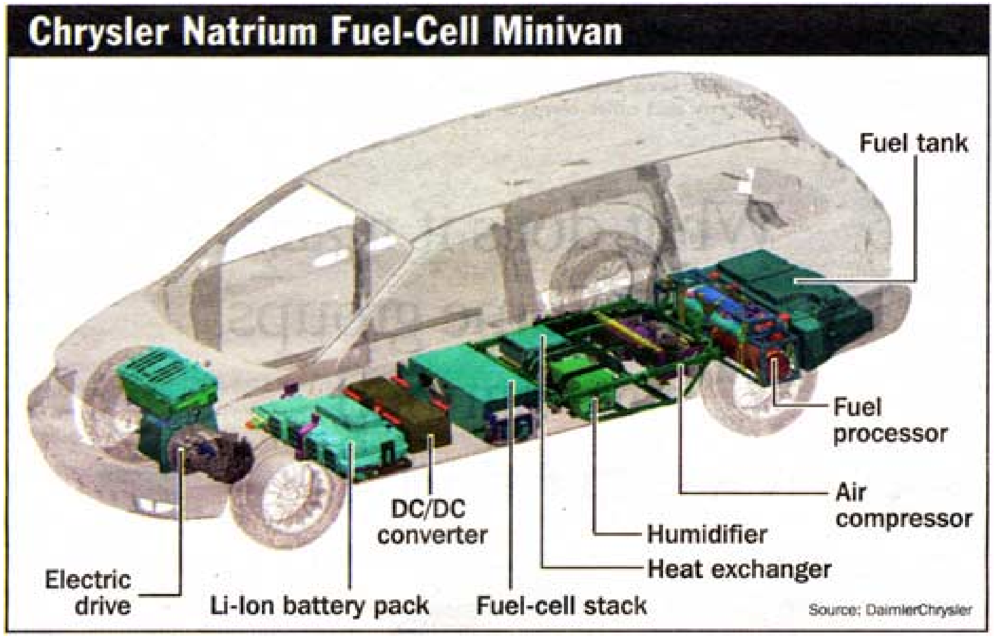


Figure 2.9: Millennium Cell Hydrogen on Demand System, Fitted in a Prototype Minivan.

Source: The Christian Science Monitor, "'Soap' may make clean fuel-cell cars feasible," January, 31, 2002, page 13.

2.8.3 Fuel Cell Applications

Numerous research facilities and manufacturers, including auto and engine makers, electrical engineering and energy firms, are developing PEM fuel cells and/or applications for them. In transportation, a significant number of fuel cell-powered city buses has been commissioned in the past five years and continues to operate in select markets. These buses take advantage of common overnight maintenance and storage cycles that allow for refueling with liquid or compressed hydrogen. The drivers of the Chicago fuel cell buses mentioned in Section 2.3 approved of the quiet and smooth operation of the buses. However, they also indicated that an improvement in throttle response is required to offset the increased weight of the fuel cell plant to make them comparable to conventional diesel engine-powered buses. Manufacturers plan for the next generation of fuel cell buses to have lighter weight prime movers. Elsewhere in transportation, most major automobile manufacturers are presently refining prototype PEM fuel cell vehicles, some since the early 1990s. In Japan, Toyota intends to market two types of fuel cell-powered vehicles in 2003.

The largest PEM fuel cells approach 300 kW output for heavy trucks and buses. Light truck and passenger car units are comparable to automotive ICE engines, in the power range of 60 to 100 kW. Although the PEM fuel cell has demonstrated clean, reliable power for years, obstacles to mass commercial production include the high cost of the internal platinum catalyst, as well as the unit overall. Costs are expected to drop dramatically with further research, development and marketing. Many researchers and developers estimate fuel cells will reach affordability in the next decade. Another obstacle has been the large size of the fuel cells per unit of power output. Power output in terms of engine size places the fuel cell third behind the combustion turbine, which is best for size, and the reciprocating engine. As the PEM cells become more compact, however, their superior thermal efficiency, emissions profile, and simple support systems could place them at an advantage over conventional prime movers.

2.9 Conclusions And Recommendations

2.9.1 Hydrogen Fuel Production Technology

The Hydrogen on Demand system developed by Millennium Cell, Inc., offers several distinct advantages over the four most common methods of reforming hydrogen, discussed in Section 2.3. The first issue is safety. The $NaBH_4$ feed stock, in solution with water, is completely stable, non-toxic and inert. It is stored at ambient pressure and temperature. The feedstock solution may be processed, transferred and stored without any risk of fire or explosion. The only flammable part of the fuel system is the relatively short segment of piping between the catalyst chamber and the fuel manifold of the prime mover. HOD hydrogen generation rates are fully controllable, based on prime mover demand, and can be stopped immediately at any time.

The second advantage is the environment-friendly nature of the HOD system. The $NaBH_4$ feedstock, once processed and stripped of hydrogen, is 100 percent recyclable and reusable. No fossil fuel, once reformed, can be recycled. An analysis of resources shows that reserves of the root molecule, B_2O_3, exist amply for the development of $NaBH_4$ feedstock. Also, the HOD system alone produces no greenhouse gases, either at the hydrogen end user or upstream of it, while all other reforming methods yield CO and CO_2, as part of their hydrogen production processes.

The third issue is utility. Although the production cost of $NaBH_4$ is currently higher than all other sources of reformed hydrogen, it is expected to decrease with the development of a broad hydrogen-fuel logistics system and subsequent expansion of mining for B_2O_3. The $NaBH_4$ feedstock also has superior hydrogen-storage efficiency, as shown in Table 2.2, surpassing even cryogenic liquid hydrogen in energy content per unit volume. It is also easily handled as an inert liquid and is readily catalyzed into pure hydrogen. Moreover, since this catalyzing process is exothermic, its heat yield can be used to compress the reformed hydrogen for high-pressure applications or as a source of energy for auxiliary heating demands

Millennium Cell's HOD technology, as well other currently utilized hydrogen reformation processes, requires continuing refinement to address production cost and overall energy balance issues in order to make hydrogen fuel competitive with current petroleum-based liquid fuels. However, the safety, storage, handling, energy density and environmental benefits associated with hydrogen fuel generated via the HOD process make it the reformation technology best suited for transportation applications.

2.9.2 Prime Movers

The three prime movers discussed in Sections 2.5, 2.7, and 2.8 can operate reliably on pure hydrogen fuel. Some require more modification than do others. The characteristics of each prime mover set the order in which they can be most readily adapted for hydrogen fuel operation in terms of safety, economics, and the environment.

The PEM fuel cell, despite its high ratio of size to power output, compared to the SI/CI engine and combustion turbines, is the power source best suited to operation on pure hydrogen fuel with minimum modification. With no moving parts, and no combustion, the fuel cell produces only electric power, heat, and pure water vapor. The heat and water vapor are clean and may be recovered for auxiliary heating loads. Unlike combustion turbines and reciprocating engines, which rely on combustion, the nitrogen in air is not oxidized in the fuel cell's power conversion process. As a result, a fuel cell produces zero NO_X, CO, CO_2 or SO_X emissions. It is a pollution-free, zero-emissions device. Operation is virtually silent and free of vibration. At forty-percent thermal efficiency, the fuel cell operates 25 to 50 percent more efficiently than conventional low-output hydrogen-fueled SI engines. Designed to operate on gaseous hydrogen, no modifications are required for fuel cell operation on this fuel.

Combustion turbines are commonly operated on compressed gaseous fuels and offer a much higher power density than a typical fuel cell. A combustion turbine is also less expensive per kilowatt output to purchase and operate than the PEM fuel cell. Certain drawbacks associated with hydrogen-fueled gas turbines exist, however. Although lower than when operated on other fuels, NOx emissions still occur with hydrogen combustion in a gas turbine. Moreover, because hydrogen has a considerably lower volumetric energy density than natural gas, the delivery piping, manifold and nozzles must either be increased in size, or the hydrogen must flow at a higher pressure to offset its lower energy density, compared to other fuels. While this increase may be of little concern in a utility plant, space considerations are at a premium in transportation applications. The combustion turbine also requires significant auxiliary support, such as vibration dampening, a lube oil system and coolers, extensive air-intake and exhaust ducting systems, combustor-transitions cooling systems, and sophisticated control logic.

Among reciprocating engines, the spark ignition (SI) type is the most viable hydrogen fuel option. The auto-ignition temperature of hydrogen is too high (twice as high as liquid distillate fuel), to make the compression ignition engine an attractive alternative. The SI engine is relatively inexpensive, used extensively in transportation applications, and offers engine-mounted auxiliary systems, e.g. lube oil pump, cooling water pump, and valve and spark timing gear to support its operation. The SI engine also suffers some significant drawbacks when compared to a fuel cell, in terms of operation, on hydrogen.   Pre-ignition and uncontrollable-backfire have been an issue with several hydrogen-fueled test engines. This problem has been overcome by incorporating sophisticated high-pressure injection systems and/or manifold aspiration with perfectly tuned valve and spark timing. Hydrogen is set apart from other gaseous fuels, such as propane and compressed natural gas, by its extremely rapid flame propagation rate. Complex SI engine control systems, governing valve and spark timing and fuel injection, have been successfully developed to address this characteristic, resulting in a more complex engine than a conventional SI design. SI engine thermal efficiency, when operating on hydrogen, is lower than that of a fuel cell. While SI engine operation on hydrogen produces no CO, CO_2, SO_X or particulate, it does produce NO_X, albeit at a lower level than when burning conventional liquid petroleum fuels.

Adaptation of hydrogen fuel-to-fuel cell operation is the least complicated of all of the prime movers investigated. However, fuel cell production costs and low power-density have together limited its application as a prime electrical power source to date. The cost of fuel cells is expected to decrease with expanded production. Of the two more commonly utilized prime movers considered herein, hydrogen fuel adaptation to the combustion turbine is more straightforward and considerably less complex than for SI (or CI) engines.

3.0 REGULATORY CODE REVIEW

3.1 Objective

The objective of Task 3.0 is to review relevant safety and operating codes and regulations that will govern shipboard hydrogen system design, construction and operation. This information then will be utilized in Task 4.0: Concept Design Development.

3.2 Codes and Standards

The U.S. codes, standards, guidelines and regulations for hydrogen fuel draw from a variety of technical sources to address requirements for the design and construction of facilities for the storage, transmission, transportation and use of gaseous and liquid hydrogen fuel. Currently, no codes, standards, guidelines or regulations exist for shipboard hydrogen fuel. The National Hydrogen Association, however, has recently formed working groups comprising industry leaders and scientists to update and/or create new standards and guidelines for all aspects of hydrogen use for both home and industry. One such subgroup, Working Group 7, is currently tasked with drafting standards and guidelines for maritime hydrogen fuel. It is expected that, once created, the new maritime standards and guidelines would form the basis of future amendments to the Code of Federal Regulations, specifically Title 46 (Shipping), Subchapter F, Marine Engineering. However, at this time there are no specific federal or international standards or guidelines regulating the shipboard storage and use of hydrogen fuel.

Although hydrogen in maritime applications is new, it has a long and safe history in other industries. The American National Standards Institute (ANSI) has adopted codes drafted by the American Society of Mechanical Engineers (ASME) in many cases. ANSI's mission is to enhance both the global competitiveness of U.S. business and the U.S. quality of life by promoting and facilitating voluntary consensus standards and conformity assessment systems, and safeguarding their integrity. Other contributing organizations include the National Fire Protection Association (NFPA) and the Compressed Gas Association, (CGA). Standards from such organizations are often adopted into law, applied within the U.S. Code of Federal Regulations. The groups have developed standards to address issues such as piping, storage, transmission and usage of hydrogen gas, often in the context of other similar gases and/or fluid streams. The existing standards are presently the best sources of safety and regulatory information for the conceptual design of a hydrogen-powered passenger ferry system. The following compilation of these sources is condensed from the Sourcebook for Hydrogen Applications, published by TISEC, Inc., of Montreal, Canada.

3.2.1 ANSI/ASME Codes and Standards

- ASME Boiler and Pressure Vessel Code (BPVC).

Section VIII, Division 1 of this code (1996) is commonly specified for the design, fabrication and testing of storage vessels, including those for gaseous and liquid hydrogen. Section IX (1996) is commonly specified for welding of these items.

3.2.2 Pressure Piping of Gaseous and Liquid Hydrogen.

- ASME/ANSI B31, Code for Pressure Piping. This code sets the engineering requirements for the safe design and construction of pressure piping systems. The code highlights areas requiring extra caution and consists of the following sections that specifically address hydrogen or other similar fuel gas piping systems. Other sections of this code that indirectly address fuel gas and/or hydrogen storage and transmission systems are also listed here.
- A13.1 — Scheme for the Identification of Piping Systems.
- B31.1 — Power Piping. The code specifies minimum requirements for the design, materials, fabrication and inspection of power and auxiliary service piping systems for industrial institutional plants, including boiler external piping. Parameters include fuel gas. Power piping, as defined in this book, includes pipe, flanges, bolting, gaskets, valves, relief devices, fittings, and pressure portions of other piping components. This code does not cover other piping specifically covered by other sections of ASME/ANSI B31, or pressure vessels covered by the BPVC.
- B31.3 — Process Piping (formerly Chemical Plant and Petroleum Refinery Piping). Considers piping design for petroleum refineries, chemical, pharmaceutical, textile, paper, semiconductor and cryogenic plants, and related plants and terminals. This code prescribes requirements for all fluids including raw, intermediate and finished

chemical, petroleum products, gas, steam, air and water; fluidized solids, refrigerants, and cryogenic fluids.

- B31.8 — Gas Transmission and Distribution Piping Systems. Covers the requirements for safe design and construction of pressure piping, as well as the safety aspects of operation and maintenance of gas transmission and distribution systems, including gas pipelines, gas compressor stations systems, gas metering and regulation stations, gas mains and service lines.

3.3 National Fire Protection Association

The National Fire Protection Association (NFPA) develops standards and codes to enhance fire safety. NFPA 50A (1994) and NFPA 50B(1994) have a narrow scope of application, covering bulk storage vessels from the fill connection to the point at which the hydrogen enters the distribution piping. The key feature of both standards is the Quantity-Distance (QD) requirements. QD's derive from the concept that effects of fire, explosion and detonation can be mitigated if the source of the hazard is kept far enough from people and other facilities. Separation distance provides flame-propagation control, that is, thermal radiation from fire does not create a situation in which fire from one source is propagated to another combustible material. Furthermore, the separation distance between a hydrogen system and people and other equipment reduces confinement, and permits hydrogen leaks and spills from one source to diffuse and dissipate without contacting an ignition source.

- NFPA 50A (1994) — Gaseous Hydrogen Systems at Consumer Sites. The standard does not apply to single systems containing less than $400ft^3$, unless there is more than one individual system, spaced less than five feet apart.
- NFPA 50B — Liquefied Hydrogen Systems at Consumer Sites. Covers the installation requirements for liquid hydrogen systems in which the hydrogen supply to the consumer premises originates outside the consumer premises and is delivered by mobile equipment. The standard does not apply to portable containers with a total content of 150L (39.7gal). Also addresses chemical plant and petroleum refinery piping, with materials meeting requirements of Chapter III for piping at an operating temperature less than 244K (-29°C, -20°F).

3.4 Code of Federal Regulations

3.4.1 Title 29 — Labor

As standards were developed, especially the QD requirements, many were folded into the Code of Federal Regulations, and compliance became mandatory. NFPA 50A(1994) and NFPA 50B(1994) for gaseous and liquid hydrogen storage were incorporated almost completely in 29 CFR 1910.103 (1996). The following sections of Title 29, Part 1910, Subpart H (1996), apply to hydrogen use. Parts 1900 through 1999 fall under the Occupational Safety and Health aspect of the Title 29.

1910.103	Hydrogen
1910.106	Flammable and Combustible Liquids
1910.114	Effective Dates
1910.115	Sources of Standards
1910.116	Standards Organizations
1910.117	Hazardous Waste Operations and Emergency Response

3.4.2 Title 46 — Shipping

There are presently no regulations in existence governing hydrogen fuel application for U. S. flag commercial shipping applications.

3.4.3 Title 49 — Transportation

Title 49 addresses transportation aspects of hydrogen, but without considering hydrogen as a fuel in transportation. 49 CFR, Subtitle B, Chapter I, Subchapters A, B, and C (1995) cover the regulations related to transportation equipment and to the transport of hydrogen. The outline below summarizes the pertinent subsections. The DOT is the enforcing agency.

- Hazard Classification for Gaseous and Liquid Hydrogen — Compressed and liquefied hydrogen are designated as a Hazard class, or Division, of 2.1 (Flammable Gas) in 49 CFR 172.101 (1995) and 49 CFR 173.2 (1995).

- 49 CFR 172.101 — addresses the quantity of compressed hydrogen, compressed methane, or liquefied hydrogen allowed in passenger aircraft or rail cars. All three are forbidden for transport in passenger aircraft or rail car. There is no mention of passenger vessels in these regulations.

3.5 Compressed Gas Association

The Compressed Gas Association pamphlet CGA P-1-1991 entitled "Safe Handling of Compressed Gases in Containers" classifies gases by hazard class. Classification is based on the chemical and physical hazards. Three gases grouped together by their principal hazards are acetylene, hydrogen, and methane. The limiting capacity for gas containers ($70m^3/2500ft^3$) stored inside industrial buildings at consumer sites is the same for all three gases.

Additionally, there is the CGA G-5.4 — Standard for Hydrogen Piping at a Consumer Location. This standard describes specifications and general principles recommended for piping systems for gaseous or liquid hydrogen on premises beginning at the point at which hydrogen enters the distribution piping at service pressure to the end use point of the hydrogen. The information in this code is general in nature, intended for use by designers, fabricators, installers, users and maintainers of hydrogen piping systems. It should also be of interest to fire and safety personnel, building inspectors, and other emergency workers. This code specifies that piping systems should be designed in accordance with ASME B31.3, Chemical Plant and Petroleum Refinery Piping.

3.6 Safety Review

The safety issues regarding both liquid and compressed gaseous hydrogen fuel are similar to those for other gaseous fuels. The principal risks are rupture of piping and pressure vessels and/or flammability and explosion. Hydrogen is a colorless, odorless, tasteless gas that is undetectable by the human senses. Hydrogen has been used successfully in industrial settings for decades, both in petro-chemical refining processes and as a cooling medium for enclosed electrical generators in large, stationary power plants. However, there is little, if any, experience available for hydrogen as a fuel gas in these settings. A comprehensive safety design review must consider process control/monitoring, hydrogen leak detection, and fire detection and suppression requirements.

3.6.1 Safety Design Review Process

A safety review should address potential safety risks in every step of the vessel (or facility) design process. An overview of this process is presented below.

- Concept Design Review — Indicate the type and magnitude of potential hazards. In the case of stored hydrogen aboard a passenger ferry, the risks are closest to compressed natural gas passenger buses, e.g. rupture of piping and pressure vessels and fire or explosion. In the case of Millennium Cell's Hydrogen on Demand system, these risks are greatly reduced by use of an inert, non-flammable fuel source, sodium borohydride. The concept design review should be base on applicable design codes, safety factors and safety criteria, such as ventilation and pressure relief systems. A preliminary hazards analysis should be initiated. Periodic safety reviews should be conducted throughout the design, test, manufacture and commissioning of the system.
- Emergency Procedures Review — Safety hazards should be assessed for all passengers and operating personnel, and emergency procedures should be developed accordingly in the earliest design stages.
- Preliminary Design Review — Calculations for structures and propulsion systems should adhere to applicable codes and regulations. A hazard analysis should be completed to include, failure modes and effects analysis, fault tree analysis, sneak circuit analysis, event tree analysis, and hazard operability study.
- Critical Design Review — The design is reviewed for conformance to design codes, required safety factors, and other safety criteria. Construction arrangements should demonstrate that hazards are effectively controlled.
- Design Certification Review — All project documentation, drawings, specifications, should be completed, reviewed and approved. All hazard analyses should be completed and action items from previous reviews should be completed.

- Emergency Readiness Review — The operational safety of personnel at or near hydrogen systems should be reviewed and the adequacy of emergency procedures should be periodically evaluated.

3.6.2 Process Control and Monitoring Systems

Hydrogen processes, like other fuels, require monitoring to ensure that they are within control limits. Process dynamics, the availability of trained operators and the criticality of response time will determine which aspects of a hydrogen fuel system will require manual and/or automatic control devices. Procedures must be in place to shutdown the hydrogen process immediately, once the process exceeds control limits.

Instrumentation and monitoring for hydrogen detection are required if hydrogen is used in an enclosed space, such as in the engine room of a vessel. The system should be fitted to effect the following: monitor and control operation, provide performance data, provide warnings/alarms for out-of-limits conditions, and indicate a hazardous condition. These conditions must be indicated early enough that the issue can be addressed and remedied, before a catastrophic casualty can occur. Moreover, the instrumentation should meet Class I, Division I/II, Group B requirements of the NFPA 70 (1993) when appropriate. Characteristics should include the following: compatibility with hydrogen and with all operating conditions it will encounter, such as temperature, pressure, and flow. Instrument and control (I&C) systems should also permit local and/or remote operation and monitoring of the hydrogen system. Appropriately fitted I&C systems must also possess adequate range, accuracy and response time.

The following criteria are significant considerations for the selection of a safe, reliable hydrogen I&C system.

- Hydrogen I&C systems fitted for the purpose of providing safety information should have redundant sensors, e.g. pressure transducers, thermocouples, and flow transmitters. Redundancy is also meant to include both local and remote indication of parameters.

- The operator should have a clear indication of the status of the hydrogen system, that is, data should be presented in a clear, logical order.
- Computer control and data acquisition systems should be continuously operated and regularly checked and calibrated to verify proper operation and indication with installed sensors.
- Calibration should be effected upon installation, and then periodically and routinely, on the computer, data acquisition system, transducers, sensors, and wiring.
- If a liquid hydrogen system is used, I&C equipment should be installed in manner that minimizes leakage of boil off gas.
- If the control console is remote, or out of view, from the main machinery space, a closed-circuit video monitoring system should be considered.

3.7 Hydrogen Leak Detection Systems

Hydrogen gas is colorless, odorless and tasteless, as are methane and propane. In commercial use, however, artificial odorants have been added to methane and propane to enable detection of leaks. In the case of hydrogen, means must be provided to detect its presence in all areas of the machinery spaces into which it could leak. In the case of larger installations, continuous automatic atmospheric sampling equipment is recommended. Such a hydrogen detection system must be compatible with other I&C systems, including systems for fire detection and suppression. Response of leak detection equipment from sampling to analysis to transmission and display of information should be as rapid as possible. Both portable and fixed hydrogen sensors should be installed in the space. Detection devices must not themselves be sources of ignition for hydrogen. Operating personnel should also have portable leak detection equipment at their disposal for entry into a space suspected to contain hydrogen gas.

The number and distribution of detection points, and the time allowed to secure the hydrogen supply system is determined by several factors including: possible leak flow rates, ventilation rates, and the volume of the space into which hydrogen could leak. The detection system should activate both audible and visual alarms and have the capability to trip the supply system off line in the even of a leak. The following are some considerations for the design of a hydrogen leak detection system.

- Sum all possible sources to be monitored, such as valves, flanges, connections, expansion joints, etc., and provide valid justification for other possible leak sources not included in this summary.
- Evaluate the designed response time of the leak detection system and determine if it will be suitable for the needs of the hydrogen system at hand.
- Provide for visual and audible alarming as conditions approach a danger level. The alarm set point should be adjusted to actuate while the hydrogen is still in a "safe" condition, and approaching a dangerous one.
- Develop a maintenance program to periodically clean and recalibrate portable and fixed detectors and validate acceptable performance of same.
- The atmospheric sampling equipment should detect hydrogen at 20 percent of its lower flammability limit (LFL), or 0.8 percent by volume, in air. (0.8% by volume in air = 20% of the LFL, 4% by volume in air).

3.8 Hydrogen Fire Detection Systems

The emissivity of a hydrogen fire is extremely low and the flame is nearly invisible. Therefore, means must be provided for the detection of a hydrogen fire in the machinery space. Although difficult to visually detect, the symptoms of a hydrogen fire, or its "signature," are reflected in changes in the surroundings due to the rapid heat build up and turbulence in the atmosphere. The following are requirements for a reliable fire detection system.

- The system should scan a large area of the space, covering considerable distances.
- The effects of lightning, sunlight and synthetic light sources must be allowed for in the selection of optical detectors.
- The system should comprise both fixed and portable detection equipment.
- The portable detectors must be available to operators (and firefighters) who enter a space thought to contain a hydrogen fire.

The following are some considerations, unique to a hydrogen fire that must be evaluated to ensure the design and implementation of a properly functioning, reliable fire detection system.

- Radiation from sunlight can overpower the visible spectrum of hydrogen flame, rendering it invisible in daylight.
- A large part of the radiation emitted from a hydrogen fire originates from heated water molecules in the surrounding air.
- Hydrogen fires emit radiation over a broad range of wavelengths and therefore do not exhibit well-defined peaks in the manner of a typical hydrocarbon fuel fire.
- Since detectors function at different parts of the spectrum, a detector with higher sensitivity at a smaller emission peak may surpass in effectiveness a lower sensitivity detector at a larger emission peak.
- The response time for the fire detection system must be at least as fast as the leak detection system to protect life and property.
- Currently, imaging systems are available to detect and determine the size, location and growth rate of an "invisible" hydrogen flame in daylight conditions.
- Fire detection equipment should meet the Class I, Division I/II, Group B requirements of the NFPA 70 (1993), as appropriate.
- At minimum, an optical flame detection system should, from a distance of at least 4.6m (15 feet), capably detect combustion of 5.0L/min (0.18 ft^3/min) of gaseous hydrogen at standard temperature and pressure (STP), flowing through a 1.66 mm (0.0625 in) orifice to produce 20 cm (8 in) high flame. Other sensors are available to detect flames at distances greater than 4.6 m (15 ft).

3.9 Hydrogen Fire Suppression Systems

The most common locations of shipboard fires are in the galley and in the engine room. Engine room fires are suppressed by a variety of methods, depending on the source of combustion. Most vessels use liquid distillate oil or heavy residual oil for propulsion and electrical power generation. Small fires are suppressed locally with semi-fixed foam extinguishers and/or permanent foam systems mounted beneath the deck plates that direct foam into the bilge, where fires often propagate while feeding on oily deposits. For larger fires, vessels employ a large smothering system consisting of carbon dioxide (CO_2) released into a closed space. In this case the space is evacuated of personnel; the ventilation is secured, and the CO_2 is discharged into the space, displacing oxygen and smothering the fire. The space remains secured for up to 24 hours, or more, until the hot spots have cooled sufficiently so that re-ignition by the introduction of air will not occur after the space is opened.

A hydrogen fuel system fire demands a unique response from operators in the area. A gaseous hydrogen fire can only be completely extinguished by securing the fuel source. Remote shut-off valves must be built into the system. However, isolation valves alone may not be effective in the event of a vessel collision, or similar casualty, that ruptures hydrogen fuel storage tanks/cylinders. While a fixed CO_2 system in a confined space could potentially smother a hydrogen fire by displacing the oxygen necessary for combustion, two significant dangers remain.

- A fixed CO_2 system will not act to secure the source of the hydrogen. This can create an increasingly hazardous combustible mixture as more and more unburned hydrogen fills the space. In this instance it is possible that the mixture could re-ignite and explode upon contact with any heat source after the CO_2 blanket has dissipated.
- Another concern is the escape of hydrogen from a "secured" space. Because hydrogen is a tiny, vaporous molecule that can escape through the smallest penetrations to adjacent spaces, efforts to contain the combustible atmosphere and/or fire would be ineffective without first securing the hydrogen fuel flow at its source.

Adjacent spaces must also be cooled with a water spray to minimize the spread of fire, until the hydrogen fuel source can be secured and the fire is extinguished. Hydrogen fuel tanks should be similarly sprayed and cooled to minimize the leak off rate. Ultimately, the best method of fire suppression with regard to hydrogen is fire prevention, by responding immediately to alarms from the leak detection system.

Another common practice at land-based hydrogen installations, contrary to conventional shipboard petroleum-based fuel fire scenarios, is not to secure the ventilation, but to *increase* it. The purpose of increased ventilation, upon detection of a leak is to dilute the hydrogen concentration to less that four percent, by volume, in air. The space should continue to be ventilated until well after the source of the leak is secured.

With regard to ventilation as a fire suppression technique, liquid hydrogen must be addressed in the same manner as compressed hydrogen gas because, upon leaking to atmosphere, the liquid hydrogen immediately boils off as a vapor. These two hydrogen fuel types, therefore, have identical flammability hazards as addressed above.

The Millennium Cell Hydrogen on Demand system, meanwhile, uses an inert, non-flammable solution of sodium borohydride as its hydrogen fuel source. In a fully operational propulsion plant utilizing the HOD system, no hydrogen exists in the machinery space until the feedstock is catalyzed in the reactor to form hydrogen at the fuel intake manifold of the prime mover. Even then, only enough hydrogen is provided to meet the load demand. When the demand for hydrogen ceases, production ceases. Having no bulk hydrogen fuel storage and transfer requirements on board to pose threat of fire, the Hydrogen on Demand system offers the most attractive fire safety characteristics for a hydrogen-fueled vessel.

4.0 CONCEPT DESIGN

4.1 Objective

The objective of Task 4.0 is to produce a marine Hydrogen on Demand (HOD)-fueled power system concept design based on recent technological advances in hydrogen fuel production, relevant safety codes and regulations and sound marine engineering practices. This information can then be utilized as the basis for the development of a marine HOD-fueled power system detail design as part of the Phase II system demonstration effort.

4.2 The NOAA 41-Foot Utility Boat

The National Oceanic and Atmospheric Agency (NOAA) has offered its 41-foot utility boat (UTB) class to serve as the basis for a concept design for a hydrogen-fueled propulsion system. One of these vessels presently serves as a mooring tender in the Florida Keys National Marine Sanctuary. As a steward of the oceans and atmosphere, NOAA intends to encourage the development of new, clean-engine technology for the protection of these natural resources. For the purposes of the CCDoTT research into hydrogen-fueled propulsion, the limited horsepower needs of the 41-foot UTB are well suited for an initial demonstration of hydrogen technology for marine propulsion.

The Florida Keys National Marine Sanctuary is part of a national network of thirteen underwater parks that encompass 18,000 square miles of select marine and Great Lakes waters from Lake Huron to American Samoa. The Florida sanctuary is home to the most extensive living coral reef in the United States (and third largest in the world), extending along the 126-mile island chain of the Florida Keys. The ecosystem's nursery, feeding and breeding grounds support a multi-million dollar commercial fishery that lands almost 20 million pounds seafood and marine products each year. The 2,800 square mile Florida Keys sanctuary is home to one of the most unique and diverse ecosystems in the nation. Vessel emissions from conventionally fueled wet exhaust systems and the potential spill risk of diesel fuel make gaseous hydrogen an attractive alternative fuel for NOAA support vessels in this area.

The NOAA 41-foot UTB class was built in the early 1980's for the U.S. Coast Guard. In later years the Coast Guard donated two of the UTB's to NOAA at the Florida Keys National Marine Sanctuary. Under NOAA control, the UTB is operated as a two or three crewmember workboat. Passengers are not carried. Vessel operators at NOAA have expressed concern about pollution from an aging pair of propulsion diesel engines onboard, specifically with engine lube oil leaks and exhaust gas emissions high in NOx, SOx, CO, CO_2, particulate matter and opacity. The vessel has a maximum speed of 26 knots, giving an endurance of 10.5 hours without refueling, in calm weather. At 18 knots, the UTB has a cruising range of 300 nautical miles (NM). The boat's full load displacement is 30,000 pounds, and 26,000 pounds without cargo. Other as-built particulars are listed in Table 4.1.

Figure 4.1 depicts the vessel's inboard profile, and Figure 4.2 shows the machinery space as presently configured.

Characteristic	Specification
Length, molded	40' 08"
Length (with rub rails)	41' 03 3/4"
Beam, molded	13' 05 1/4"
Beam, (with rub rails)	14' 01"
Freeboard, bow	4' 06"
Freeboard, amidship (frame 7)	3' 09"
Freeboard, stern	2' 09"
Draft (maximum)	4' 01"
Fixed height above waterline (top of radar antenna)	13' 02"
Unfixed height avove waterline (top of AM antenna)	26' 08"
Mast height (top of RDF antenna)	17' 00"
Displacement, full load	30,000 Pounds
Displacement, less cargo	26,000 Pounds
Crew	3
Passenger Capacity	20
Engines (2 per boat)	Cummins Diesel Model VT-903M
Brake horsepower / RPM	318 / 2000
Fuel	No.2 Diesel Oil
Fuel capacity	486.8 Gallons
Fuel capacity (95 % full)	463.0 Gallons
Fuel, usable	420.0 Gallons
Propellers, 2 ea.	4-Bladed, 26" Dia., 28" Pitch
Maximum speed	26 Knots
Endurance at maximum speed	10.5 Hours
Range at 18 knots	300 NM
Electric System	Charging System and Shore Power Connection

Table 4.1: 41' UTB As-Built Particulars

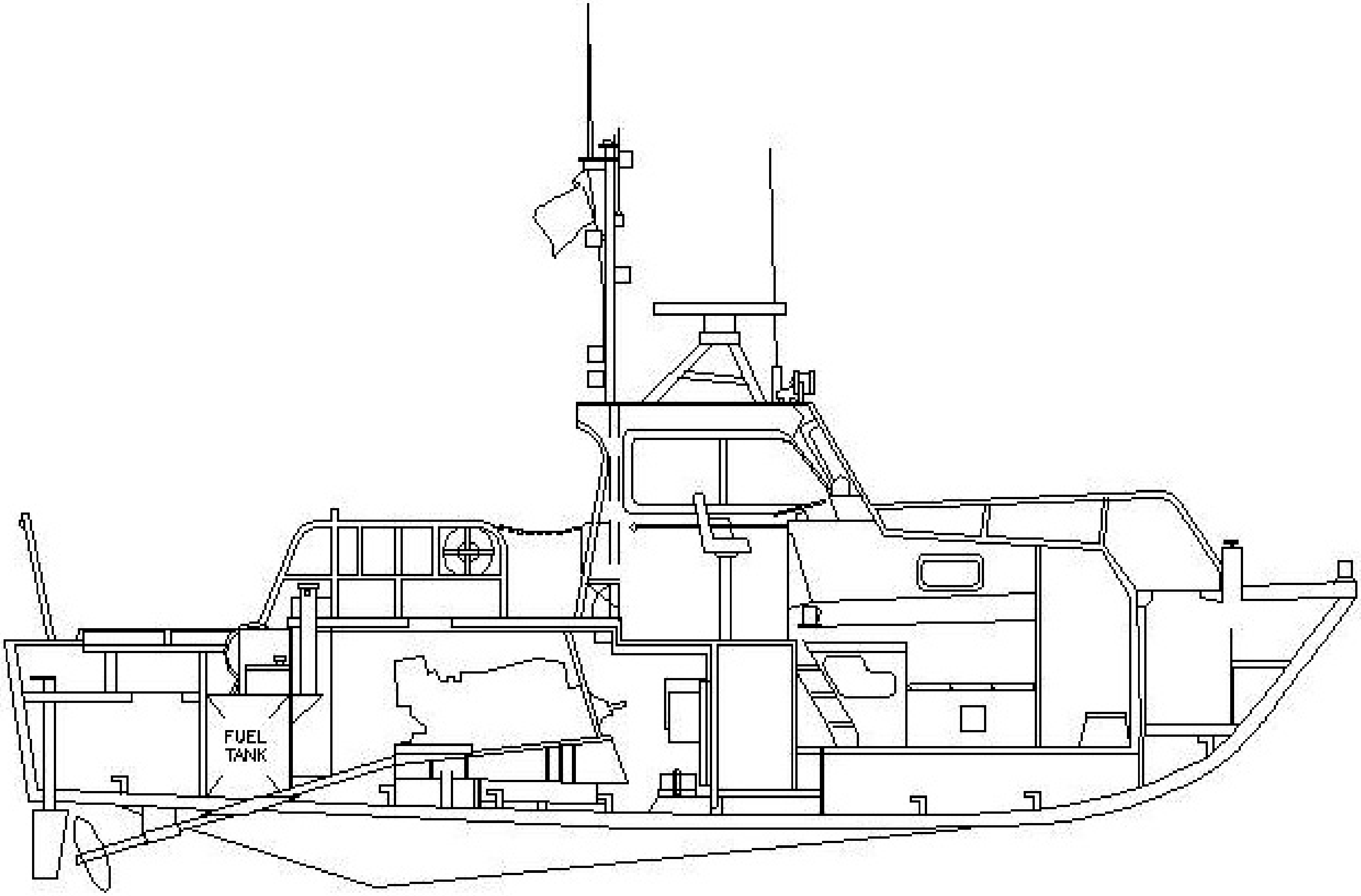
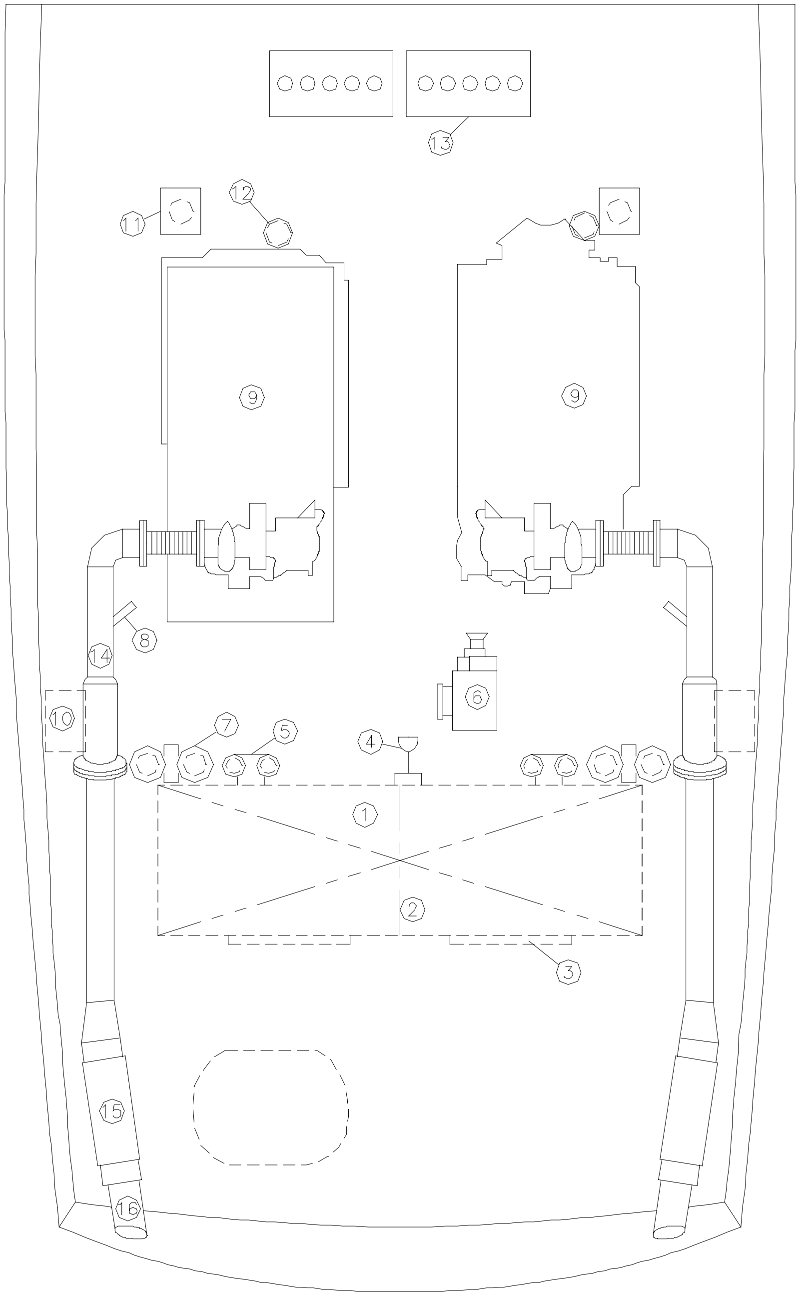


Figure 4.1:

41’ UTB As-Built Profile



Fuel Oil System
1. Fuel Tank (486 gal.)
2. Fuel Tank Baffle
3. Fuel Tank Inspection Plates
4. Priming and Stripping Pump
5. Fuel Oil Filter

Raw Water System
6. Sea Chest
7. Duplex Raw Water Strainer
8. Water Jacket Exhaust Injection

Main Engine
9. Main Engine
10. Air Intake Vent
11. Air Exhaust Vent
12. Lube Oil Filter
13. 12V Batteries
14. Exhaust Line
15. Neoprene Muffler
16. Tail Pipe

Note: The engine room extends from bulkhead 6 to bulkhead 10, below the main deck.

Figure 4.2: 41' UTB As-Built Machinery Arrangement

4.3 41' UTB HOD System and Engine Modifications

4.3.1 Engine Room Ventilation

The engine room extends from bulkhead 6 to bulkhead 10, below the main deck. The main engines and associated mechanical equipment are located here. The engine room ladder is fixed directly beneath the engine room scuttle, located on centerline between the main engine hatches on the weather deck. The engine room air vents comprise two pair of ducts. The air intake vent ducts are outboard of the engine exhaust lines at Frame 9 and extend into the engine room to a level below the main engine turbochargers. The intake vents use natural ventilation. Gaseous hydrogen fuel requires a greater amount of combustion air than what is necessary for IC engines burning liquid fuel. As a result, a supply fan for each engine will be installed to supply increased airflow to the machinery space.

The air exhaust vent ducts are immediately forward and outboard of the main engines at Frame 7. At main deck level, the ductwork is part of the aft pilothouse bulkhead, port and starboard side. The engine room ventilation exhaust system will be modified to include fans powered by sealed, brushless motors for intrinsic fire safety. The fans will be designed to energize and rapidly ventilate the space in the event that hydrogen was detected by the Mine Safety Appliance, Inc. (MSA) gas detection system. The precaution of venting a space known to contain hydrogen is in accordance with accepted fire safety practice, as described in the *Sourcebook for Hydrogen Applications* by Bain, et al.

4.3.2 Electrical Systems

The electrical system comprises a pair of 12V batteries on centerline along the forward engine room bulkhead (bulkhead 6). The batteries are wired in series to provide 24 VDC power to the vessel. The battery charger is mounted above on the bulkhead. A shore-tie transformer allows charging of the batteries alongside the pier from a shoreside 120 VAC power source. The main engine cutout switches are manually tripped to prevent accidental starting of engines undergoing maintenance. There are also four 24 VDC engine room lights fixed on the overhead.

The electrical system would be modified, as required, to increase the battery power and charging system to power two (2) engine room exhaust fans, one (1) fuel forwarding pump and one (1) fuel return pump (Section 4.3.3). The engine alarm system will also be modified to integrate hydrogen detection equipment, the MSA Ultima Gas Monitor. The Ultima monitor is designed for a 12 or 24 VDC power supply and outputs two alarm levels on a 4-20 mA scale. The monitor will be mounted to the overhead, where hydrogen, being lighter than air, is first detectable. The alarm signal will be designed to interrupt the power supply for spark to the engines, thus shutting them down, at 20 percent of the lower explosive limit (LEL) of hydrogen in air. When the engines trip, the $NaBH_4$ (fuel) forwarding pump, the $NaBO_2$ (fuel byproduct) return pump, and the HOD reactor will also trip, thus stopping the production of hydrogen.

The LEL of hydrogen is 4 percent by volume in air. At 20 percent LEL, the HOD/engine system will shut down and the space will be ventilated when a concentration of hydrogen in air of 0.8 percent is detected by the MSA gas detection system. In short, the HOD system will be secured and the space ventilated, automatically by the hydrogen detection system, when hydrogen is found to occur at one-fifth of the concentration that would be required for it to ignite.

The fans are sized to move 1,200 CFM of air from the engine room, which is equivalent to one air change per minute in an empty engine room. Accounting for machinery volume, actual air changes would occur approximately every 40 seconds. A conservative estimate of the fans' total electrical load is 1.1 kW. Drawing 46 amps on a 24 VDC system, the fans could operate for several hours on two marine-type batteries connected in series. This exhaust capacity is ample, considering the inert properties of the sodium borohydride fuel system.

Calculating fan power, assume:

- Mechanical Efficiency = 60%
- Motor Efficiency = 85 %
- Fan ΔP = 4” of water column
- Flow Rate = 1,200 CFM

P_{fan} = [(Flow Rate x ΔP) / (6356)(Mechanical Efficiency)] = [(1,200)(4”)/(6356)(0.6)]

= (1.25865 BHP) x (0.7457 kW/HP) = 0.94 kW

Load = P_{fan} / Motor Efficiency = (0.94 kW/.85) **= 1.1 kW**

Other new electrical loads include the $NaBH_4$ fuel supply pump and the $NaBO_2$ return pump draw of 154 Watts for a 4.8 GPM maximum combined output. Lights and navigation equipment are expected to draw an intermittent maximum of 1 kW. The total electrical load amounts to 2.3 kW. Considering the exhaust fans would energize only after the engines, fuel pumps, and some auxiliary equipment was tripped, the existing 3 kW belt-driven alternator would be more than ample for continuous charging of the batteries in support of a total DC electrical system after the HOD modification. For the purposes of reliability, the new arrangement would maintain the existing configuration of one belt-driven alternator fixed to each engine, consistent with the present arrangement.

Fuel pump electrical power demand is calculated below:

- 1,036 gallons $NaBH_4$, used in 6.4 hours (see Section 2.1.3) = 2.7 GPM supply
- Return flow, GPM = (0.75)(Supply Flow) = 2.1 GPM
- Delivery Head Pressure, H = (50 psig)(2.311 FT/psi) = 115.6 FT
- Specific Gravity of $NaBH_4$ and $NaBO_2$ Solutions = 1.03
- Pump Mechanical x Electrical Efficiency = 0.70

$\mathbf{P_{sup}} =$ [(GPM)(H)(Specific Gravity) / (3960)(Pump Efficiency)]

= [(2.7)(115.6)(1.03) / (3960)(0.7)] = (0.116 HP)(745.7 W/HP) **= 86.4 W**

$\mathbf{P_{ret}} =$ [(2.1)(115.6)(1.03) / (3960)(0.7)] = (0.090 HP)(745.7 W/HP) **= 67.3 W**

4.3.3 Fuel System

The present vessel arrangement has twin fuel tanks with a common center bulkhead fitted aft of the engine room between Bulkheads 10 and 11. The tanks run athwart ship, stopping short of the skin of the vessel, permitting passage of the engine exhaust piping on either side. The tanks hold a total of 486.8 gallons. Of that capacity, 420 gallons are accessible and usable by the fuel system. The (hand-cranked) fuel oil priming and stripping pump is on the centerline, just forward of bulkhead 10. Each fuel oil filter is also at Bulkhead 10, outboard of the priming and stripping pump, on the port and starboard sides. Each filter is inline with its tank and respective engine-driven diesel fuel pump.

The existing liquid distillate fuel system requires the most extensive modifications. It will be changed entirely to accommodate the Hydrogen On Demand (HOD) system and the $NaBH_4$ (sodium borohydride) fuel source. The $NaBH_4$ solution is less energy-dense by volume (BTU/GAL) than the marine gas oil (MGO) currently used aboard the vessel. More storage volume will therefore be required. The fuel source is completely inert, however, which permits a variety of storage locations. The amount of added fuel storage capacity is limited by how much additional weight can be added to the vessel without exceeding its full load displacement of 30,000 pounds. To permit an acceptable vessel endurance and range, fuel would be carried in lieu of the 4,000-lb passenger and cargo margin.

When calculating available margin for added fuel weight, consider the following:

- Specific Gravity of $NaBH_4$ is 1.03; DFM is 0.848. Weight of water is 8.3378 Lb/gal.
- Carry No Cargo/Passengers = + 4,000 Lb (credit)
- Use Lighter Engines (see Table 2.2) = + 2,060 Lb (credit)
- Eliminate 486 Gal of MGO = + 3,436 Lb (credit)*
- Add HOD Reactor System = - 600 Lb (penalty)

8,896 Lbs Available

*MGO = (7.07 lb/Gal)(486 Gal) = 3,436 Lbs

- **Margin for $NaBH_4$ Fuel Solution =** (8,896 Lbs) / (8.59 Lb/gal) **= 1,036 Gallons**

The added 550 gallons will be split forward and aft of the engine room to disperse the weight evenly on the vessel and maintain trim. The existing fuel tanks will be extended aft beyond Bulkhead 11 to add 275 gallons for a total of 761 gallons aft of the machinery space. An additional 275-gallon tank will be fitted forward of the machinery space, between Bulkhead 2 and Frame 5, beneath the passenger compartment deck plates. The tank design will be of the membrane-type, to include a bladder device that accepts a return stream of $NaBO_2$ (sodium metaborate) fuel byproduct, which is also inert. After processing the hydrogen gas, the $NaBO_2$ will amount to approximately 75 percent by volume of the original fuel source. The byproduct will flow back to the fuel tank bladder as a continuous stream when the HOD system is in operation. Figure 4.3 depicts the added $NaBH_4$ fuel tanks.

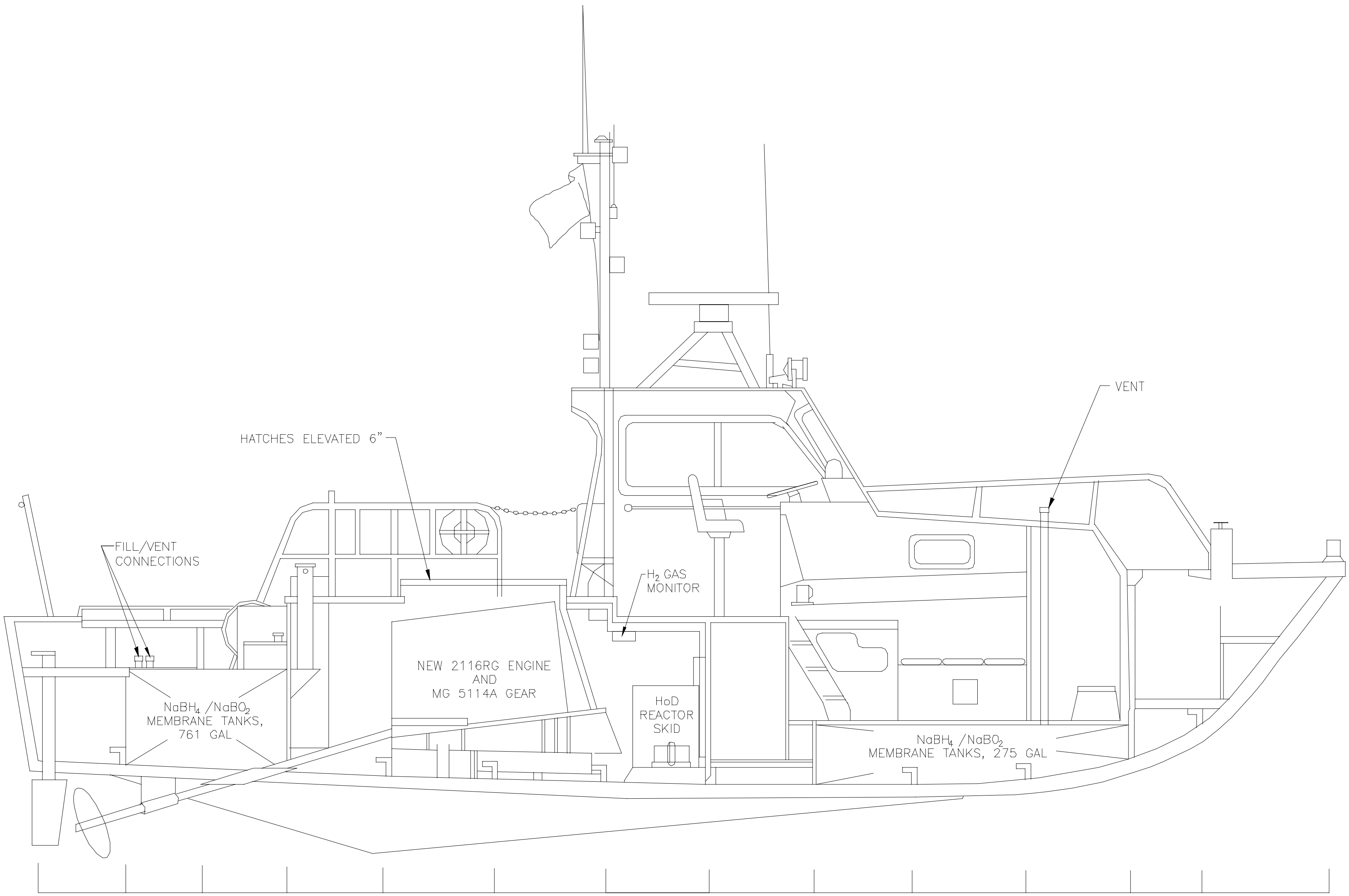
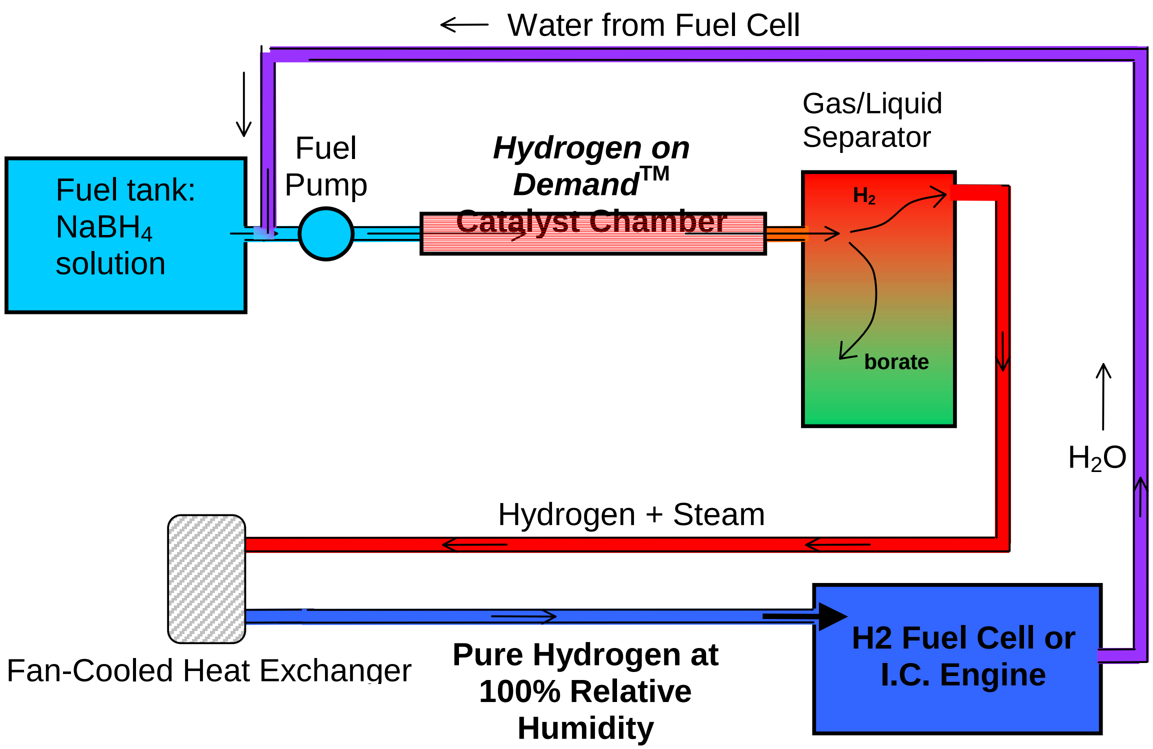


Figure 4.3: 41' UTB Profile After HOD System Modification

Arrangements will be made to pump the $NaBO_2$ ashore for transport to the factory to be recycled into $NaBH_4$ fuel stock. In this case, the $NaBO_2$ return pump will be used to pump the spent fuel byproduct ashore. The discharge piping to the $NaBO_2$ storage tank will be used instead as a suction line, by valving open a branch around the pump to the suction side. A simple configuration of valves will permit operation in this manner, using a second branch line off the pump discharge to send the $NaBO_2$ to a deck connection. Further consultation with Millennium Cell, Inc., in later design stages will determine what methods, if any, would be necessary to maintain the sodium metaborate byproduct in transferable, liquid solution. The fuel-priming pump would remain to prime the system as far as the fuel-forwarding pump that would be part of the HOD reactor.

The operation of the HOD system is straightforward. First, the $NaBH_4$ fuel pump directs fuel from the tank(s) into a Ruthenium catalyst chamber. The hydrogen and metaborate solution separate in a second chamber, which also acts as a small storage ballast for hydrogen gas. The humidified hydrogen is processed through a heat exchanger to achieve a specified dew point, and is then sent through a regulator to the main propulsion engines. In operation, the rate at which hydrogen gas is generated is directly proportional to the rate at which the $NaBH_4$ solution is pumped into the catalyst chamber, which is based on the engines' output power demand. This operational simplicity translates into relatively straightforward control strategies.

A HOD reactor to supply a 636 BHP propulsion plant has not yet been developed. A current model processes fuel for a maximum output of 100 BHP. To achieve 636 BHP, several reactors would have to be enlarged or clustered to an approximate size of 4'L x 2'W x 3'H. The $NaBH_4$ forwarding pump will be powered by a sealed, brushless, electric motor arranged as part of the HOD reactor skid. A return pump of the same type would also be included for restoring the $NaBO_2$ byproduct to its respective bladder tanks. Figure 4.4 shows a schematic arrangement for a representative HOD system.



Note: The sodium metaborate byproduct (in green) is pumped to a separate holding tank. Pump is not shown.

Figure 4.4: HOD Schematic with Internal Combustion Engine or Fuel Cell

4.3.4 HOD System Endurance

The UTB's existing full-power endurance with 420 gallons of DFM is 10.5 hours at 26 knots, for a range of 273 nautical miles. The HOD system would best be utilized with the most concentrated solution of sodium borohydride available. Assuming a mixture of 30 % by weight of $NaBH_4$ solution in water, there is a hydrogen yield of 0.55 Lbs/gal of solution. With 1,036 gallons of $NaBH_4$ solution onboard, the UTB's full-power endurance is 6.4 hours. The range is 166 NM. The calculation follows.

Assume:

- 1036 gallons of 30-wt% fuel solution on board.
- 0.55 Lb Hydrogen/gal at 30-wt% $NaBH_4$ solution.
- 61,100 BTU/Lb of hydrogen (higher heating value, HHV) = 33,605 BTU/gal $NaBH_4$.
- 318 BHP engine output (x 2).
- 8,550 BTU/HP-Hr heat rate, per engine, at 318 BHP output.
- 26 NM/Hr speed at full power

Supply = [(1036 gal $NaBH_4$)*(0.55 Lb H_2/gal)*(61,100 BTU/Lb H_2)] = **34,814,780 BTU**

Demand = [(318 BHP/Engine)*(2 Eng.)*(8550 BTU/BHP-Hr)] = **5,437,800 BTU/HR**

Endurance = Supply / Demand = (34,814,780 BTU) / (5,437,800 BTU/Hr) = **6.4 Hours**

Range = Speed x Endurance = (26 NM / Hr)(6.4 Hr) **= 166 Nautical Miles**

Based on the calculations above, for the HOD configuration to match the current full-power endurance and range of the UTB, the vessel would require an additional 667 gallons of $NaBH_4$ solution, weighing 5,727 Lbs. In practice, however, that added weight would increase the boat's full load displacement by 20 percent. This added weight would result in a lower maximum speed for the UTB as well as potential stability impacts and limitations. The estimate below assumes a constant fuel rate.

Additional Fuel Required:

Range Deficit = (Existing Range) – (HOD Range) = (273 NM) - (166 NM) **= 107 NM**

Endurance Deficit = (Range Deficit) / (speed) = (107 NM) / (26 NM/Hr) **= 4.12 Hours**

Energy Deficit = (Endurance Deficit) x (Fuel Demand) =

(4.12 Hr) x (5,437,800 BTU/Hr) **= 22,403,736 BTU**

Additional Fuel Required = (Energy Deficit) / (Fuel Heating Value) =

(22,403,736 BTU) / (33,605 BTU/gal) **= 667 gallons**

Added Weight = (Additional Fuel) x (Fuel Density) = (667 gal) x (8.59 Lb/gal) **= 5,727 Lbs**.

Since it is not practical to increase the UTB's full load displacement by 20 percent with added fuel reserves, reducing its speed can increase the vessel's range and endurance. The power to speed relationship can be assumed to be cubic. That is, the required power will change as a cube function with a change in vessel speed. For example, at 18 knots, the estimated power required is 211 BHP. At this lower power demand, the vessel endurance increases to 17.8 hours and range increases to 321 NM.

Assume:

- Original Speed, S_1 = 26 Knots
- Original Power, P_1 = (318 BHP)(2) = 636 BHP
- New Speed, S_2 = 18 Knots

New Power, P_2 = $[P_1 \times (S_2 / S_1)^3]$ = $[(636 \text{ BHP}) \times (18 / 26)^3]$ **= 211 BHP**

Calculating the endurance and range at this new power, all assumptions apply from the original calculation, except the heat rate of the Rotary Power International engine (Section 2.1.4) increases to 9,300 BTU/HP-HR at the lower power output.

Supply = [(1036 gal $NaBH_4$)*(0.55 Lb H_2/gal)*(61,100 BTU/Lb H_2)] = **34,814,780 BTU**

Demand = [(105.5 BHP/Engine)*(2 Eng.)*(9,300 BTU/BHP-Hr)] **= 1,953,000 BTU/HR**

Endurance = Supply / Demand = (34,814,780 BTU) / (1,953,000 BTU/Hr) **= 17.8 Hours**

Range = Speed x Endurance = (18 NM / Hr)(17.8 Hr) **= 321 Nautical Miles**

4.3.5 Main Engines and Reduction Gears

The Cummins VT-903-M engines are located port and starboard between Frames 7 and 9. They are four-cycle, turbocharged, V-8 marine diesel compression ignition (CI) engines with a maximum power output of 318 BHP each. The lube oil filters, lube oil cooler and associated raw and jacket water pumps are all engine mounted. The cost of retrofitting these engines with spark ignition (SI), injection systems and associated equipment for hydrogen combustion is estimated to be at least $500,000.00, including development and bench testing. The lower compression ratio of a spark-ignition engine also reduces the power output by as much as 40 to 50 percent. Replacement of the original engines with a physically larger pair of de-rated SI engines would be required to retain the 318 HP, per engine, for operation on hydrogen.

A more attractive technical and economical alternative would be to install an engine readily capable of burning diverse gaseous fuels such as the 580 Series rotary gas engine, manufactured by Rotary Power International. The rotary engine has a 50-year history, mainly with the U.S. Department of Defense, but most notably with Mazda, the Japan-based car manufacturer. Rotary Power International purchased its technology in 1991 from the rotary engine division of John Deere. The engines are designed for military, power generation and marine applications. The engines were once notoriously dirty and unreliable. Advances in material science have been applied to the rotary seals, thus improving engine emissions profiles and reliability.

Additionally, Mazda has successfully operated a test engine on pure hydrogen. The Rotary Power International engine has been designed to burn a variety of gases, including hydrogen. The specific units proposed for the 41' UTB is a pair of Model 2116RG, 500 HP engines. The engines can be de-rated to operate at a maximum rating of 318 BHP to match the current per-engine rating.

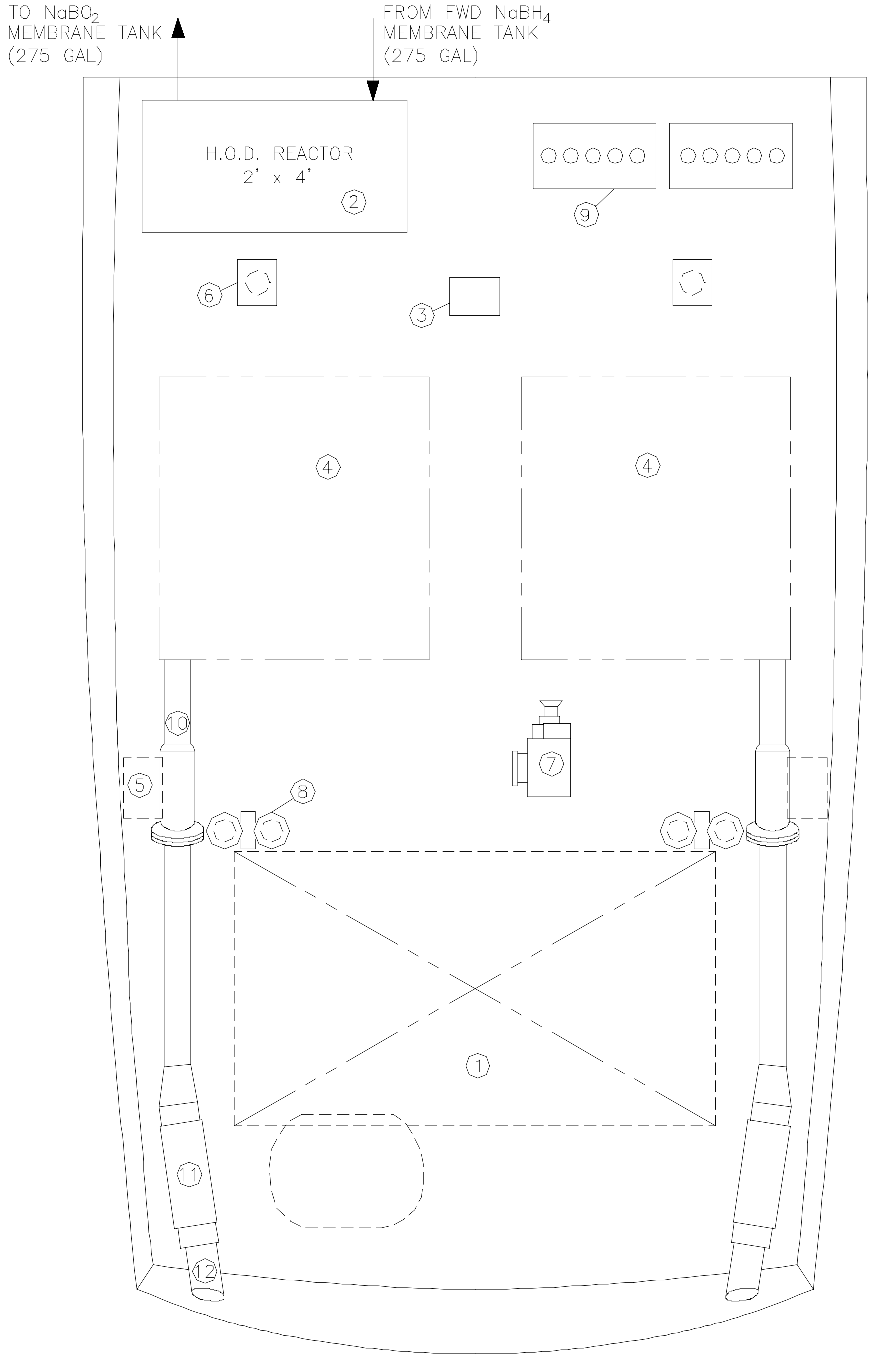
Another advantage of the rotary engine is its weight. With similar reduction gears included, the installed weight of the rotary engines is estimated to be 2,060 lbs. lighter than the existing Cummins diesel engines. This savings in weight allows for 240 additional gallons of $NaBH_4$ fuel solution (Section 4.2.1.3). The reduction gear will remain similar, also maintaining the same propeller shaft speed and power output, requiring no change in propulsors. A comparison of the original Cummins VT-903-M engine and the Rotary Power International engine is presented in Table 4.2.

Engine Make	**Cummins**	**Rotary Power International**
Engine Type	Diesel	Rotary
Engine Model	VT-903-M	2116RG-580 Series
Engine Fuel	No. 2 Diesel	Hydrogen
Max Power on Hydrogen	191	318
RPM at Max Power	2000	2500
Operating Range, RPM	1500-2000	1200-2500
H2 Heat Rate BTU/HP-HR	Unknown for Retrofit	8,550
Length, inches	65.46	50
Width, inches	40.88	49.3
Height, inches	39.81	52.2
Weight, lbs.	3200*	2170*
Reduction Gear	Twin Disc MG-509	Twin Disc MG 5114A
Reduction Gear Ratio	2:1, Forward/Reverse	2.5:1, Forward/Reverse

*Includes Reduction Gear.

Table 4.2: Comparison of Hydrogen-Fueled Propulsion Engines

Figure 4.5 depicts the HOD-modified machinery arrangement for the 41’ UTB.



Sodium Borohydride Fuel System

1. $NaBH_4$ and $NaBO_2$ Membrane Tanks (761 gal)
2. HoD Reactor Skid
3. MSA Ultima H_2 Gas Detector
4. Rotary Engine
5. Air Intake Fan
6. Air Exhaust Fan
7. Sea Chest
8. Duplex Raw Water Strainer
9. 12V Batteries
10. Exhaust Line
11. Neoprene Muffler
12. Tail Pipe

Figure 4.5: 41' UTB Machinery Arrangement Plan View After HOD Modification

4.3.6 HOD/ SI Engine System Phase II Estimated Cost and Schedule

Table 4.3 presents a summary of the estimated Phase II costs for the design, installation test and demonstration of the HOD/twin rotary engine propulsion system in the 41' UTB, as described in Section 4.2.0. The estimated period of performance for the phase II effort is 12 to 24 months, depending on the possible development of a 636 BHP-capacity HOD system and the delivery schedules for long-lead items such as the rotary engines and reduction gears.

Item	**Estimated Cost, $**
1. LABOR	
• Program Management	75,000
• Engineering and Design	150,000
• Instrumentation	35,000
• Testing	250,000
• Rip out / Removal	100,000
Sub-Total:	**$610,000**
2. MATERIALS	
• 318 BHP Rotary Engines (x 2)	710,000
• 636 BHP HOD Reactor	1,000,000
• $NaBH_4$ for 30 Days, 12Hrs/Day, at 18 Knots	1,178,900
• Installation Materials (fiberglass resins, paint, piping, fittings, wire, wire harnesses, terminal blocks, fasteners, etc.)	120,000
• H_2 Detection/Alarm System	7,000
• HOD/Engine System Controls	40,000
• HOD/Engine Room Vent Fan	5,000
• HOD/Engine Room Supply Fan	5,000
• $NaBH_4$ Supply Pump	6,200
• $NaBO_2$ Return Pump	6,200
• $NaBH_4$ Storage Tank	17,100
Sub-Total:	**$3,095,400**

3. MISCELLANEOUS

• Travel	20,000
• Courier, Postage, Reproduction, Etc.	3,500
• Shipping and Transportation	25,000
Sub-Total:	**$48,500**
Total Estimated Cost:	**$3,753,900.00**

Table 4.3: 41' UTB HOD / Rotary Engine Phase II Cost Summary

4.4 The Duffy Electric Drive Passenger Launch

Marshall Duffield founded the Duffy Electric Boat Company after he developed a personal watercraft powered by an electric golf cart motor and marine-type lead acid batteries. Over the years, Duffy has developed a variety of pleasure craft models ranging from 18 to 30 feet in length, with sophisticated, emissions-free, electric propulsion systems. These vessels are used for harbor cruising and similar applications. The boats are sold nationwide, as well as in Europe, Canada, Mexico and the Far East. One environmentally friendly model, a catamaran-type water taxi, currently serves in Venice, Italy, where wave action and water pollution from conventional motorboats has damaged the infrastructure of the city.

There are several distinct advantages to these electric-powered boats. The Duffy boats are virtually silent. They are re-charged at night simply by connecting the on-board charging system to a 240 VAC pier-side power source (110 VAC units are also available). The charging time is approximately 10 hours for 10 hours of cruising service. The boats are free of exhaust emissions and water pollution, as compared to typical high speed, low output two-cycle marine internal combustion engines, which exhaust partially burned fuel and lubricating oil, often directly into the sea. The batteries operate reliably for five to seven years before requiring replacement.

The mono-hull Duffy/Herreshoff 30 is a viable candidate for water-taxi service in California and worldwide. As the largest vessel in the Duffy catalog, it has a length overall of 30 feet, a 9-foot beam, and a top speed of 8 knots. The passenger capacity is variable, depending on the configuration of the boat's interior. Its cruising endurance is 10 hours, depending on operating profile. Duffy, as an option, can provide a small diesel generator to re-charge the battery system while underway to extend the vessel's endurance. The generator engine (when fitted) draws from an 18-gallon fuel tank located in the forward section of the hull. Alternatively, the on board battery charging circuit, at 20 amps, is a relatively low power demand and could be supported by a 3 kW proton-exchange-membrane (PEM) fuel cell. A PEM fuel cell chemically converts hydrogen to DC electric current and exhausts only heat and water vapor to the atmosphere. Its operation is almost noiseless. With an equally clean and quiet Hydrogen-on-Demand system supplying hydrogen directly to the fuel cell, the conventional underway diesel generator-based charging circuit can be replaced with a quiet, emission-free battery charging system to extend the boat's cruising endurance between pierside charges. The Duffy/Herreshoff 30, pictured below, in Figure 4.6, can be converted for use as a commuter water-taxi with relative ease.

Figure 4.6: The Duffy / Herreshoff 30

4.4.1 HOD System / Fuel Cell Modification

4.4.2 HOD / Fuel Cell Compartment Ventilation

The existing diesel generator compartment where the proposed HOD system reactor and fuel cell would be located is aft of the passenger space and forward of the transom. Its dimensions are approximately (due to hull curvature) 5' wide by 2'-6"deep by 2'-6" long fore and aft, for a total of 31.25ft^3. On boats equipped with an auxiliary diesel generator in this space, there is an air duct to provide natural ventilation. This air intake passage would remain intact with the HOD reactor/fuel cell installation. A supply fan is expected to be a part of the fuel cell assembly. A small centrifugal exhaust fan will be added, powered by a sealed, brushless motor for intrinsic fire safety in the unlikely case of operation in a hydrogen-enriched atmosphere. In the event that hydrogen was detected in the HOD reactor/fuel cell compartment by a gas detection sensor, the fan will energize and rapidly ventilate the space. The sensor and gas detection system, manufactured by Mine Safety Appliance, Inc., (MSA), will be added to the boat as part of the HOD/fuel cell system modification package.

4.4.3 Electrical Systems

The electrical system will be modified to include one (1) engine room exhaust fan, one (1) $NaBH_4$ (fuel) forwarding pump, one (1) $NaBO_2$ (fuel byproduct) return pump for the HOD reactor, and control relays from the MSA gas detector. The alarm system will also include a MSA Ultima Gas Monitor for hydrogen detection. The Ultima monitor is designed for a 12 VDC power supply and outputs alarm signals on two levels on a scale of 4-20 Ma. The monitor mounts to the overhead, where hydrogen, if leaking, would first be detected. At a pre-set level of hydrogen concentration in air, the sensor will generate a 4-20 mA signal to sound the alarm, energize the exhaust fan, and interrupt power to the $NaBH_4$ forwarding pump and the $NaBO_2$ return pump. The HOD reactor control system will simultaneously initiate a shutdown, stopping the production of hydrogen. The pre-set alarm level for the hydrogen in air concentration is 20 percent of the lower explosive limit (LEL) of hydrogen. The LEL of hydrogen is 4 percent by volume in air. At 20 percent LEL, the HOD/fuel cell system will shut down and the space will be ventilated when a concentration of hydrogen in air of 0.8 percent is detected by the MSA gas

detection system. In short, the system will secure and ventilate the space when hydrogen is detected at one-fifth of the concentration that would be required for it to ignite.
The propulsion system consists of a 15 kW (20 BHP) DC, variable-speed propulsion motor and 16 batteries, 12 volts each. The batteries are wired in two series banks of eight, each bank having a maximum voltage output of 96 volts. The batteries store approximately 500 amp-hours of electrical energy. If the propulsion motor drew 500 amps of battery current, the battery charge would theoretically last for one hour. Drawing one amp, the battery charge could last for 500 hours. In normal service, the propulsion motor will draw no more than 158 amps at full power. Operating at this maximum amperage draw (about 8 knots), the 500 Amp-hour charge will provide 3.2 hours of operation. At 5.5 knots, the motor will draw 45 amps, and the battery charge will sustain 11 hours of operation. At 4.4 knots, with the propulsion motor drawing 20 amps, the 500 amp-hour battery charge will provide 25 hours of service.

However, in actual service, current draw from a battery and battery charging is somewhat more complex. As the batteries charge, the battery voltage approaches the line voltage of the charging circuit, and the charge rate slows. The charging current decays from 20 Amps and approaches zero as the batteries become fully charged and accept a trickle charge, a charge rate that approaches zero. The optional diesel generator provided by Duffy for the Duffy/Herreshoff 30 is rated for 6.7 kW, which appears to be somewhat high for this application. With the batteries fully drained, the charging circuit permits a charge rate of 96 volts and 20 amps. Therefore, the maximum charge rate required is estimated to be 1.92 kW, (96 Volts x 20 Amps = 1920 Watts = 1.92 kW). With a maximum charge demand of 1.92 kW, good engineering and operating practice suggests the installation of a 3 kW fuel cell. The 1.1 kW margin will provide added capacity to address periods of high propulsion motor and amp-hour draw to ensure the availability of at least two hours of additional endurance, each day.

Figure 4.7 presents the current electrical system installed in the Duffy 30' launch. Besides the main propulsion motor and batteries, a step-down converter, drawing off the main 96 Volt battery bank feeds 13.8 volts to a 12 volt house battery. The house battery circuit supplies a deck machinery panel, a navigation panel, and an inverter that supplies 120 VAC service to a galley panel. The optional bow thruster, when energized, is such a high amperage draw, however, that it has been known to interrupt service to the navigation equipment on the navigation panel. The 12-volt house battery is sized to handle the amp-hour load of the equipment that it powers for an entire day. If the house battery's charge is depleted, it will draw from the main battery bank. In normal operation, all batteries are recharged alongside the pier, and the house battery loads do not limit vessel endurance by drawing off the propulsion batteries.

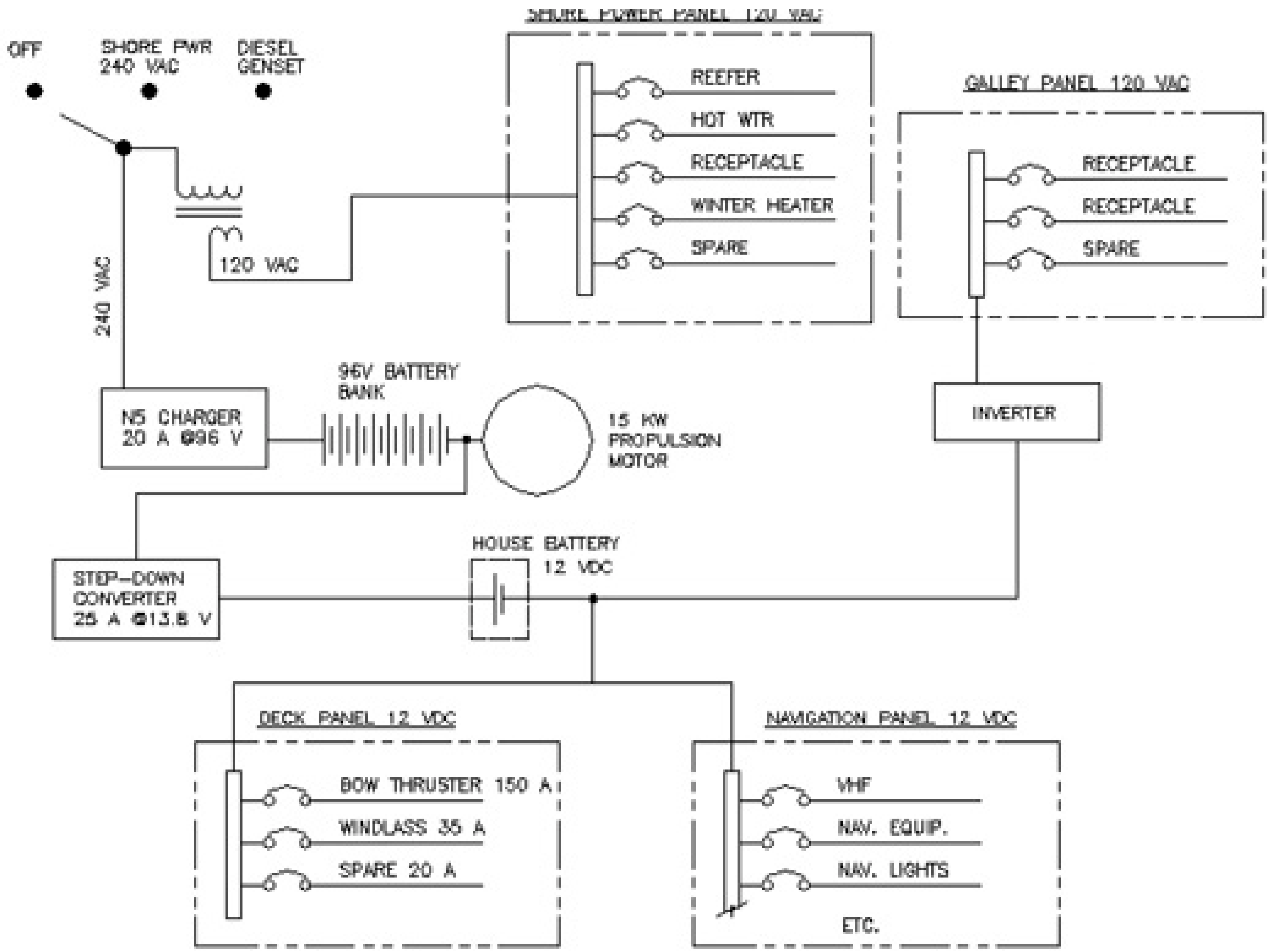


Figure 4.7: Duffy 30' Launch Existing Electrical System

The proposed electrical system for the HOD/fuel cell system is depicted in Figure 4.8. In this case, the 3kW fuel cell replaces the diesel generator and supplies 96 VDC directly to the propulsion batteries. As shown, the modified electrical system has the house battery supplying primarily the larger loads for the bow thruster and windlass. The heat rejected from the fuel cell will serve as a hot water heater, removing it from the galley service panel, and can be used for any other heating options aboard the launch. This will prevent interruption of service for the critical HOD/fuel cell system auxiliaries. The second 12 volt 240 amp-hour HOD system battery is placed in parallel with the house battery. The HOD system battery circuit will be sized to power the following equipment: $NaBH_4$ supply pump, $NaBO_2$ return pump, exhaust fan, MSA hydrogen gas detector, and the navigation sub-panel. Preliminary estimates of power demands for these components are calculated below, to support a maximum fuel cell output of 3 kW.

Load Calculations:

- $NaBH_4$ Flow rate, **Q =** [(3 kW-Hr)(3413 BTU/kW-Hr) / (0.3 efficiency)(61,100 BTU/ Lb, H2)(0.55 Lb H2/Gal of NaBH4)] = 1.02 Gal/Hr = **0.017 gpm.**
- $NaBH_4$ Supply Pump power, **P_s =** (0.017 Gal/min)(50 psig delivery pressure)(2.311 Ft head/psig)(1.03 specific gravity) / (3960)(0.55 pump efficiency) = (0.000929 BHP)(745.7 W/HP)(1.15 for motor losses) **= 0.797 W**, or 12 V and 66.3 mA.
- $NaBO_2$ Return Pump Power, **P_r=** (Ps)(0.75 $NaBH_4$ flow) **= 0.6 W**, or 12V and 50 mA.
- Heat Exchanger Fan Power, **P_{xf} =** (CFM)("H_2O Pressure)/(6356)(Efficiency) = (31.5)(4)/(6356)(0.6) = (0.033 BHP)(745.7 W/BHP)(1.15 for motor losses) = **28.3 W**, or 12V and 2.4 A.
- Exhaust Fan power, **P_f =** (CFM)("H_2O Pressure)/(6356)(Efficiency) = (31.5)(4)/(6356)(0.6) = (0.033 BHP)(745.7 W/BHP)(1.15 for motor losses) **= 28.3 W**, or 12V and 2.4 A.
- MSA Hydrogen Gas Detector and Relays, from the OEM specification sheet, **P = 4.92 W**, or 12V and 410 mA.

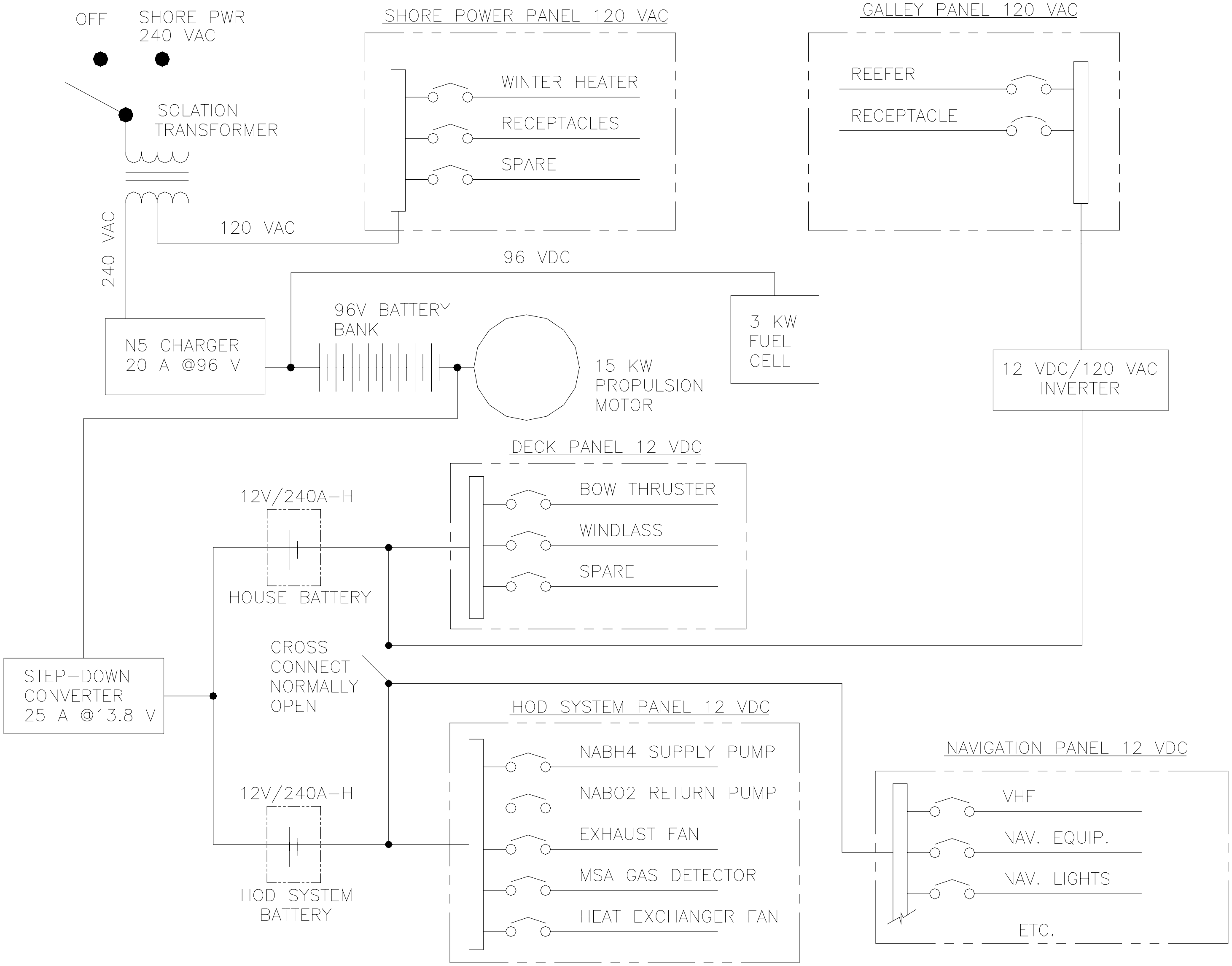


Figure 4.8: Duffy 30' Launch Modified Electrical System

- Navigation Instruments Panel **Pn =** Assume 12V feed to GPS (0.3 A), Depth Finder (0.1 A), Navigation Lights (0.75 A), Speed Log (0.1 A), and Marine VHF Radio (6.0 A transmit / 0.3 A standby) **= 87 W** maximum, with radio transmitting.

The house battery serves all non-critical loads. The batteries are each sized to independently support their loads for at least one full day underway, thus preserving main propulsion battery endurance. In the event of a HOD system battery failure underway, there are two sources of backup power available, a cross connection to the house battery circuit or a draw from the main propulsion batteries through the step-down converter.

4.4.4 HOD Mechanical Systems Arrangement

The HOD system can be packaged in a variety of arrangements. In all cases the assembly ships in one complete package, skid-mounted. As shown previously in Figure 2.4, the reactor is accompanied by a fuel supply pump, a fuel byproduct (post-reaction) return pump, a catalyst chamber, a heat exchanger to cool to the hot, humid hydrogen after the reaction, and supply piping to the fuel cell. The $NaBH_4$ (sodium borohydride) supply pump will be located in the aft HOD/fuel cell system compartment and will draw from the forward tank. The $NaBO_2$ (sodium metaborate) return pump will also be located in this compartment, and will send the byproduct forward to its designated tank. With regard to fuel tankage, the existing 18-gallon diesel fuel tank space will be used for the storage of 18 gallons of $NaBH_4$ fuel solution. There is also space in the forward compartment of the hull to install another tank, of equal size, to accept the estimated 75 percent return volume of the spent fuel byproduct, $NaBO_2$.

Arrangements will be made to pump the $NaBO_2$ ashore for transport to the factory to be recycled into $NaBH_4$ fuel stock. In this case, the $NaBO_2$ return pump will be used to pump the spent fuel byproduct ashore. The discharge piping to the $NaBO_2$ storage tank will be used instead as a suction line, by valving open a branch around the pump to the suction side. A simple configuration of valves will permit operation in this manner, using a second branch line off the pump discharge to send the $NaBO_2$ to a deck connection. On the other hand, consultation with Millennium Cell, Inc., suggests that a simpler option for containing and shipping the $NaBO_2$ byproduct is likely. A 1.8 ft^3 receptacle, placed next to the reactor, will likely be used to collect the entire byproduct. The receptacle will be designed to be lifted out of the compartment and replaced with an empty one, while the full one is shipped for processing. In this case, no $NaBO_2$ pump and associated valves would be necessary.

A voltage control system will regulate the operation and output of the fuel cell, by sensing the charging demand by the main propulsion battery bank. As the fuel cell output is regulated, the control system will work simultaneously to adjust the flow of hydrogen from the reactor. In this manner, the $NaBH_4$ supply pump will cycle via a speed control or a modulating recirculation valve to match the demand of the HOD reactor system. A heat exchanger and fan will operate whenever the reactor is in service, cooling the hydrogen stream on its way to the fuel cell. The MSA Ultima hydrogen detection system will interface directly with this control system to secure the HOD system, and the fuel cell, and energize the exhaust fan, in the case of a hydrogen leak being detected within the HOD/fuel cell system compartment.

Figures 4.9 and 4.10 show the Duffy 30' launch profile before and after HOD/fuel cell system modifications. As indicated by these drawings, at this time it appears that only minor structural redesign and alterations will be required to accommodate the HOD / 3kW fuel cell underway battery charging system.

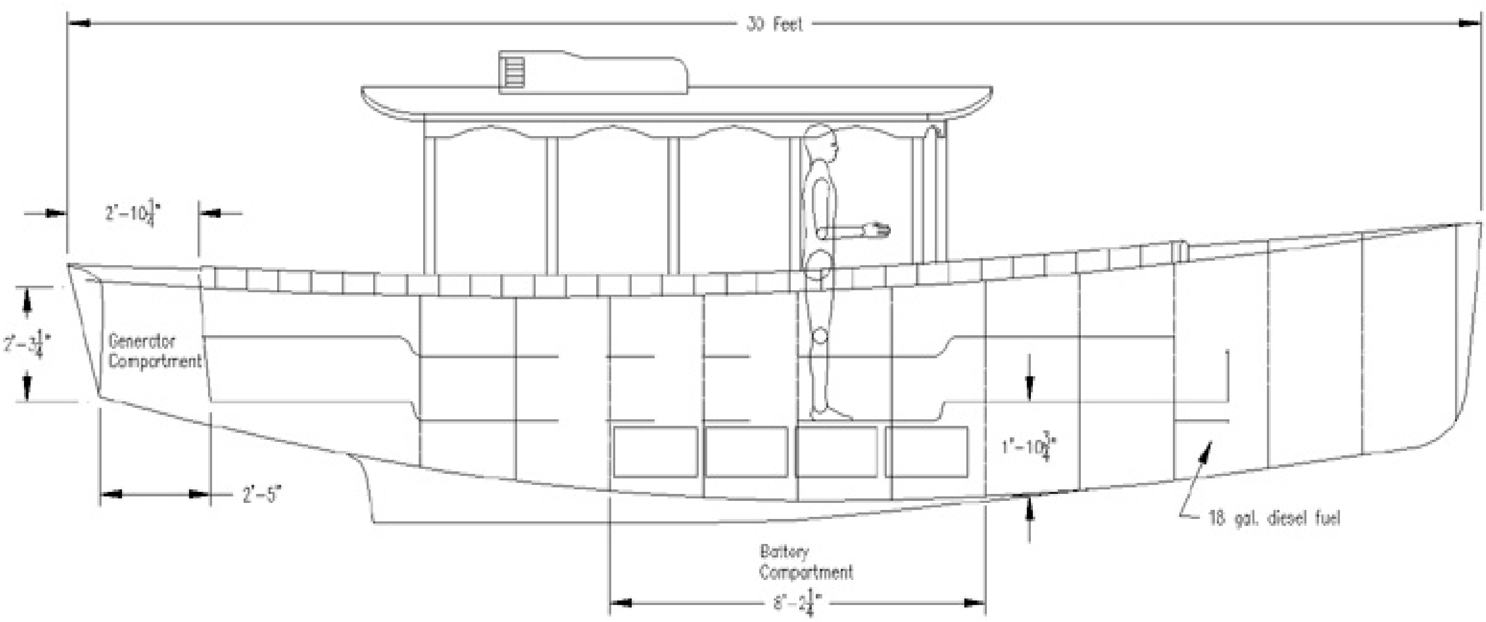


Figure 4.9: Duffy 30' Launch Before Modification

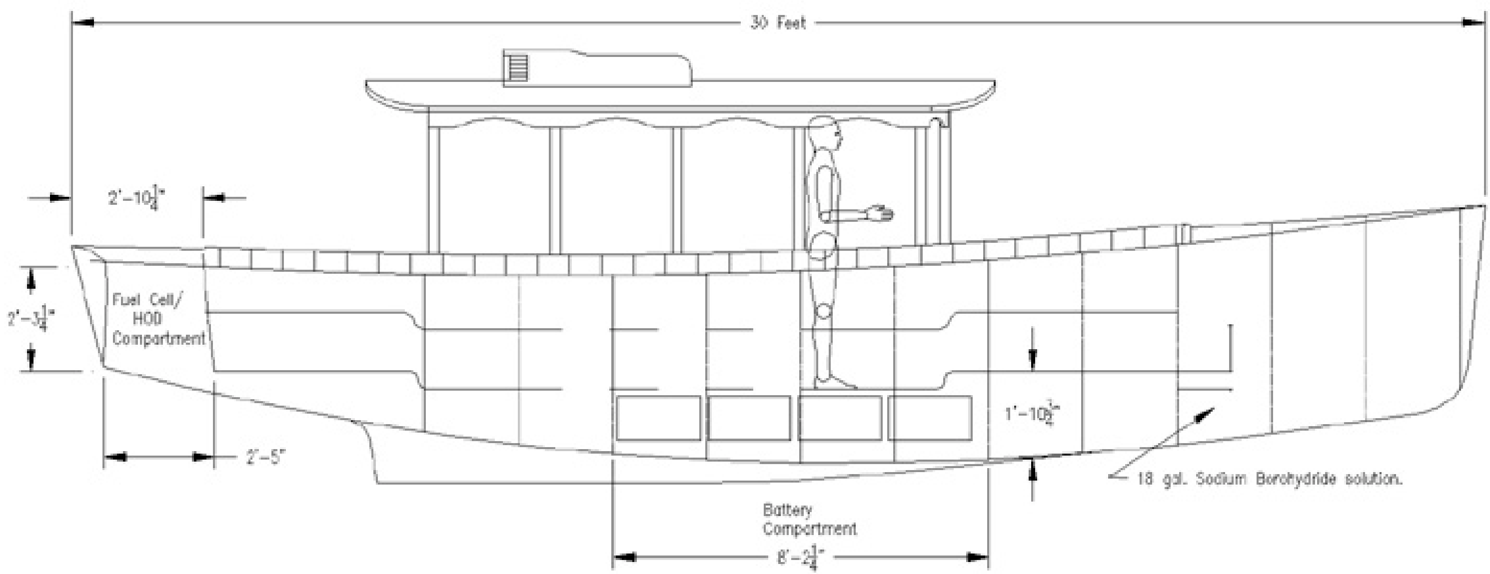


Figure 4.10: Duffy 30' Launch after HOD/Fuel Cell Modification

4.4.5 HOD System Endurance

Using the HOD system, and assuming a sodium borohydride solution of 30% by weight, the hydrogen yield from the existing 18 gallon tank capacity for diesel fuel is 9.9 lbs., or 604,890 BTU, based on a hydrogen higher heating value (HHV) of 61,100 BTU/Lb. For the 96V electric propulsion system, the launch's cruising endurance is directly proportional to the amperage draw by the propulsion motor. As shown below, at a 5 knot cruising speed with a propulsion motor draw of 45 amps, the boat's endurance could be extended by as much as 10 hours. There is sufficient energy in one tank of $NaBH_4$ to extend underway operation at 5 knots for two hours per day for five days.

Assume:

- 5 knot cruising speed
- 96 Volt, 45 Amp motor draw
- 18 gallons of $NaBH_4$ per tank
- 0.55 Lb hydrogen/gallon of fuel solution at 30-wt%.
- 61,100 BTU/Lb hydrogen (HHV)
- 30 percent fuel cell thermal efficiency
- 81 percent electrical system efficiency (98 % battery and transmission; 83% motor)

Calculate available supply energy, to include battery, transmission and motor losses:

Available Supply = (0.55 Lb H_2 / Gal $NaBH_4$)*(18 Gal $NaBH_4$)*(61,100 BTU / Lb H_2) *(0.000293 kW-Hr/BTU)*(0.3)*(0.81) = **43.25 kW-Hr.**

Calculate Demand at 5 knots:

Demand = (96 Volt)(45 Amp) = 4320 Watts = **4.32 kW**.

Calculate Endurance:

Endurance, Hours = Supply / Demand = 43.25 kW-Hr / 4.32 kW = **10.0 Hrs**.

Endurance, Days = 10 Hrs./ 2 Hrs. per Day **= 5 Days**.

The HOD/Fuel cell system controls will be configured so that the system can be operated automatically or manually at an output of up to 3 kW for a corresponding period of time to provide a daily cumulative underway propulsion battery charge of 8.64 kW-Hr (90 Amp-Hrs at 96 volts). For example, the HOD/fuel cell battery charging system would need to be operated for 2.88 hours at 3 kW (31.25 Amps at 96 Volts) to deliver 8.64 kW-hours of energy to the batteries, or operated for 10 hours at 0.864 kW (9 Amps at 96 volts) to provide the same cumulative charge.

4.4.6 HOD / Fuel Cell System Phase II Estimated Cost and Schedule

Table 4.4, below, presents a summary of the estimated Phase II costs for the design, installation test and demonstration of the 3 kW HOD/fuel cell system in a Duffy 30' electric drive launch, as described in Section 3.0. The estimated period of performance for the phase II effort is six to twelve months, depending on the delivery schedules for long-lead items such as the fuel cell and HOD system.

Item	Estimated Cost, $
4. LABOR	
• Program Management	17,200
• Engineering and Design	60,100
• Instrumentation	19,900
• Testing	11,400
• Rip out / Removal	6,700
Sub-Total:	**$115,300**
5. MATERIALS	
• 3 kW PEM Fuel Cell	71,100
• 3 kW HOD Reactor	68,250
• 150 Gallons of 30 wt% $NaBH_4$ Solution	9,950
• Installation Materials (Fiberglassing resins, paint, piping, fittings, wire, wire harnesses, terminal blocks, fasteners, etc.)	11,950
• H_2 Detection/Alarm System	3,340
• HOD/Fuel Cell System Controls	3,920
• 12V/240 Amp-Hour Marine Battery	240
• HOD/Fuel Cell Compartment Vent Fan	1,370

• $NaBH_4$ Supply Pump		620
• $NaBO_2$ Return Pump		620
• $NaBH_4$ Storage Tank		1,710
	Sub-Total:	**$172,100**
6. MISCELLANEOUS		
• Travel		8,000
• Courier, Postage, Reproduction, Etc.		800
• Shipping and Transportation		3,800
	Sub-Total:	**$12,600**
	Total Estimated Cost:	**$300,000.00**

Table 4.4: Duffy 30' Launch HOD / Fuel Cell Phase II Cost Summary

4.5 Conclusions

To make it suitable as a test vehicle for an initial marine HOD system demonstration, the re-powering and refitting of the 41' UTB is a very complicated and complex undertaking. In fact, this conversion would require both the development and conversion of an SI engine to burn pure hydrogen, as well as the production of the highest throughput HOD system yet delivered by Millennium Cell, Inc. These two requirements are the primary drivers that result in an estimated Phase II cost that is approximately 12.5 times the estimated Phase II cost for the Duffy Electric Boat-based HOD / 3 kW fuel cell option. Also adding significantly to this cost in the case of the 41' UTB modification is fuel the required to conduct a minimum of 30 days of underway endurance testing (21,435 Gallons / $1,178,900.00). Additionally, given the complexities of this conversion, retrofit, and associated component development efforts, it is reasonable to anticipate that the 41' UTB project could require a period of performance approaching 24 months. However, despite the present programmatic, financial and technical hurdles facing this option, the demonstration or the HOD system in a marine SI engine application remains worthy of consideration as a viable "next step" alternative.

In contrast, the Duffy electric boat is a more practical application for the HOD technology. Requiring less than 3 kW of power for intermittent battery charging, as opposed to constant propulsion demand, it is based in fuel cell and HOD reactor technology and experience that exist today. By using and adapting this technology to a marine application, it is reasonable to anticipate that this HOD Phase II demonstration effort can be completed within a six to twelve month time frame. Moreover, an 18-gallon tank of $NaBH_4$ solution, costing $990, can provide the required endurance extension for as much as five days. Physical modifications to the Duffy boat would be minimum, adding no extra fuel capacity while maintaining approximately equivalent weights on board. Therefore, for technological and economic reasons, the Duffy 30' launch is the better suited of the two options investigated herein to serve as a test vehicle for an initial demonstration and proof of concept of a marine HOD system.

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