TECHNICAL REPORT – STUDY/SERVICES

DESIGN, BUILD, INSTALL PROCESS

Submitted to:

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On Demand Hydrogen Generating System: Phase II – System Demonstration

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DEMONSTRATION OF AN ON-DEMAND HYDROGEN GENERATING SYSTEM, PHASE II: SYSTEM DEMONSTRATION

TASK 3.0: Technical Report – Design, Build, Install Process

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EXECUTIVE SUMMARY

The demonstration of an on-demand hydrogen generating system in a marine vessel comprised the integration of three distinct commercially available products. These are: Millennium Cell, Inc.'s sodium borohydride derived Hydrogen On-Demand (HOD™) hydrogen production system, Anuvu's Power-X™ 3kW fuel cell and Duffy Electric Boat, Inc.'s Model DH30, 22 passenger, 15kW electric drive launch. The objective of this unique integration process was to demonstrate the feasibility and viability of adapting an intrinsically safe, load following hydrogen fuel generating and metering system in an electrically propelled craft that eliminated the cost, weight, space and safety issues and concerns associated with compressed and liquefied hydrogen fuel storage and delivery methodologies when employed in transportation applications. Because the three primary components of the on-demand hydrogen generating system Phase II demonstration effort were, design and development-wise, mature market ready products, there was also no sub-component/system level concept to breadboard to prototype hardware and attendant documentation development, design and test cycle required for this project. Rather, these three products were integrated "on the shop floor" and installed, commissioned and successfully tested with minimal new design, installation, start-up, testing and associated documentation. This minimal additional design and development approach afforded by the careful selection of the three primary system components previously described also ensured that the Phase II system demonstration effort was completed within budget ($300,000.00) and on time (October 1, 2002, through September 30, 2003).

This report presents an overview of the manufacturing, integration and testing processes for the two primary components of the HOD/fuel cell system, Millennium Cell, Inc.'s Hydrogen On-Demand™ hydrogen fuel generating system and Anuvu's Power-X™ 3kW fuel cell system, as well as the integrated HOD/fuel cell system. Shop testing of the combined system began on June 13, 2003, and was successfully completed on June 20, 2003.

1.0 INTRODUCTION

The air quality in many United States ports meets or exceeds 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 siting 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 only 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 arises from New Jersey-based Millennium Cell, Inc., which has developed a chemical process to extract 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.

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 fueled by an on-demand hydrogen generating system that utilizes commonly occurring non-petroleum based constituents to generate hydrogen will eliminate most environmentally harmful effluent streams produced by these prime movers when compared to operation 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-output propulsion systems using seawater as a primary ingredient in the hydrogen generation process also offers longer term potential. 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 II portion of this program has been segmented into the following discrete tasks.

Task 1.0: System/subsystem Design Description – On Demand Hydrogen Design
Task 2.0: System Fabrication and Installation Report
Task 3.0: Technical Report – Design, Build, Install
Task 4.0: Field Testing Plan
Task 5.0: System/Endurance – Field Test
Task 6.0: Technical Report Field Operations

The objective of Task 3.0 is to complete the shop construction and bench performance tests of the HOD and fuel cell systems.

2.0 BENCH TEST

2.1 Fuel Cell System

Construction of the fuel cell system was completed by Anuvu Fuel Cell Products at its facility in Sacramento, California by mid-June 2003. The system was assembled to match the confines of a rectangular rack made of hollow aluminum square-stock. The rack is specially shaped to drop athwartships into the stern of the DH30 water taxi. The HOD™ system, similarly space constrained, is also in a rack of aluminum square-stock. The HOD™ rack bolts directly to the top of fuel cell rack. Design, procurement and construction of the 3 kW (net) fuel cell system began with the initiation of a purchase order on February 1, 2003. The system required approximately 14 weeks to complete. Much of this time was used to acquire long-lead items, such as fuel cell membrane material, a variable speed air compressor, and a special inlet air filter, made by Donaldson, for service in the marine (salt air) environment.

Anuvu engineers crated and air shipped their fuel cell system to the Millennium Cell facility at Eatontown, NJ for bench testing with the HOD™ system. The fuel cell skid arrived on Friday, June 13, 2003 and setup began directly. Millennium Cell and Anuvu engineers spent two days connecting the HOD™ system and reconstituting the partially disassembled PEM fuel cell. The test was configured to run the systems exactly as they will perform once installed in the DH30 water taxi. The two differences between the bench test and the conditions of final installation were the vast array of signal wires loose on both systems and the real-time conditions monitoring via laptop display of system parameters. The wires were left open for simplicity of monitoring, as well as to effect any operational changes and adjustments to the systems. Once installed permanently on the boat, all wires and connections will be neatly harnessed and stowed. Similarly, the installed system will not have a laptop display of control parameters. For operational simplicity, the operator interface will be reduced to on/off only.

Once on location in NJ, Lyn Cowgill, Anuvu's principal design engineer, installed the new DC Voltage Boost Converter system that Anuvu purchased from NJ-based Advanced Power Associates Corp. The boost converter is the integral electrical circuitry that monitors electrical load (battery charge and propulsion motor demand) and commensurately controls the fuel cell output, and therefore the HOD™ system output. For economic reasons, the typical fuel cell block will develop relatively low voltage and high current. In most installations, including the DH30 water taxi, the required voltage is significantly higher than the (40 to 60 VDC) output of the fuel cell stacks. The voltage must be boosted to levels suitable for application, in this case 111 VDC. This function is provided by the boost converter. The boost converter, like any power converter, is an energy loser, so it must above all be efficient.

Many competing converters operate in the range of 60 percent efficient, wasting large amounts of electrical energy to achieve a necessary voltage. The DH30 boost converter is the most efficient of its kind, and consistently maintained conversion levels of approximately 97 percent efficiency during bench testing. Moreover, the converter is designed to sense battery charge requirements and optimize fuel cell performance. It does this by varying the pulse width of power output from the converter, using technology known as Pulse Width Modulation (PWM), which allows the fuel cell to run "blindly" as the boost converter optimally meters power output to meet the electrical load. In this case that load is the battery banks and propulsion motor in tandem.

The boost converter is custom programmed for temperature compensated charging. Batteries perform longer and more efficiently if they are charged at a rate that follows an empirically tested temperature curve. In other words, the charging current (Amperes) is varied according to battery temperature. The boost converter has been programmed to follow the temperature/charge curve developed by the manufacturer of the batteries on the DH30 to maximize battery life even in variable temperature conditions. The boost converter performed without flaw for the entirety of the three-day bench test.

Once assembled, the fuel cell was first operated on pure hydrogen gas out of a pressurized cylinder. The hydrogen was humidified in a chamber before it was admitted to the fuel cell. The fuel cell ran reliably as Mr. Cowgill brought up the controls on a specially designed display on his laptop. This display was developed only for bench testing and field service. In normal operation, the controls will be housed in a black box with no operator interface. The temporary test display was used to operate the controls in manual, stroking valves, varying output, varying the speed of the inlet air compressor, initiating purge cycles, and cycling the entire system up and down in load.

Meanwhile, Vladimir Brunstein of Advanced Power Associates Corp. used the time to adjust the boost converter that he designed and built into a stainless steel cover that is the size of a breadbox. In place of a battery bank, Millennium Cell provided a resistance-type load bank to handle the electrical output of the system tests. The resistance bank comprised a dozen large resistors immersed in a barrel of water (for heat dissipation). The resistors were toggled on, in series, adding more and more load to the system until the electrical output held steady at 3 kW net power – the system design point.

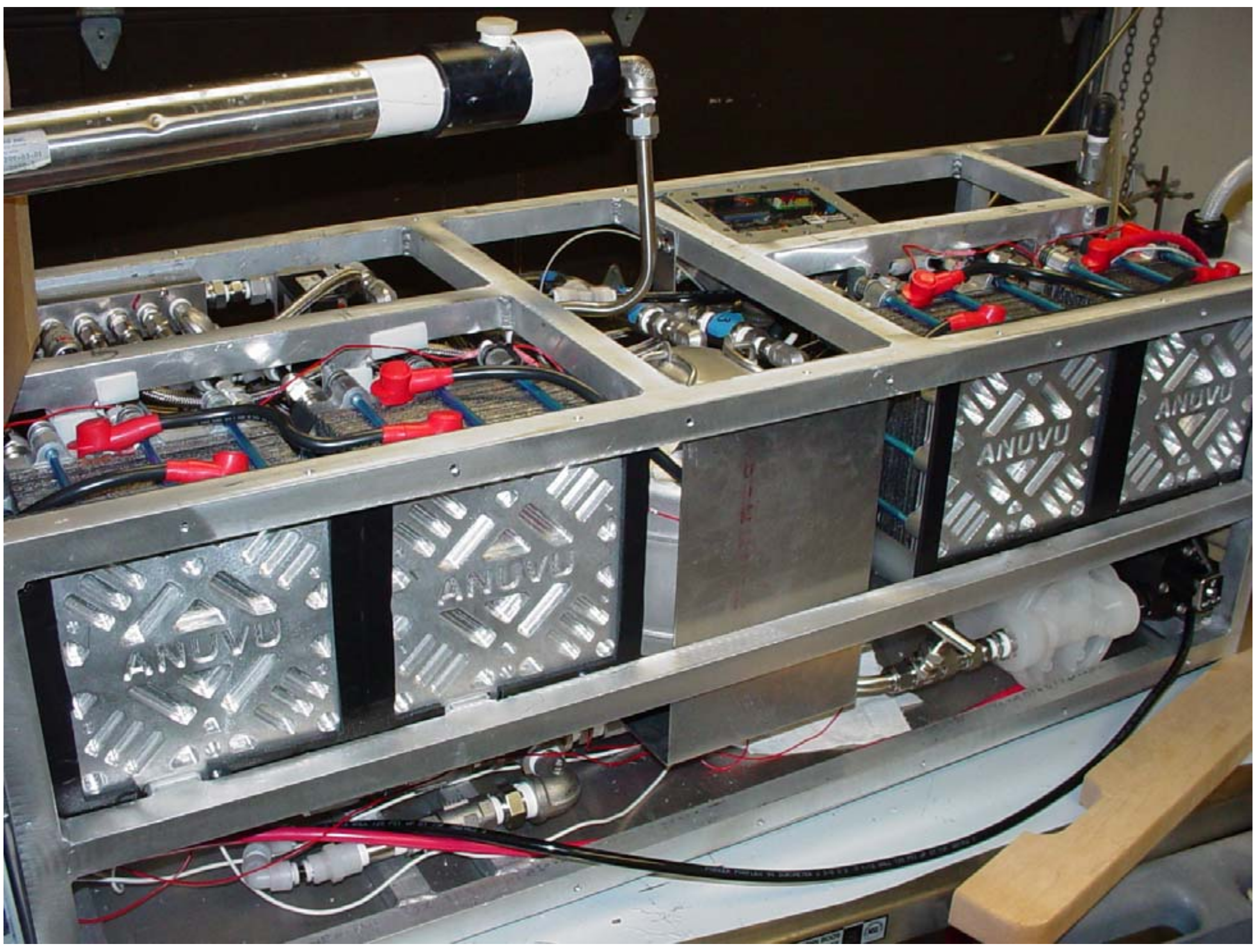

Figure 2.1: Front view of the Anuvu Fuel Cell Products Proton Exchange Membrane 3 kW (net) fuel cell system at the Millennium Cell facility in Eatontown, NJ.

Once the engineers were satisfied with the steady state operation of the fuel cell, they removed the test-gas cylinder and connected the HOD™ system to the fuel cell. The systems connect via a stainless-steel reinforced flexible hose from the hydrogen outlet of the HOD™ system to the hydrogen inlet of the fuel cell. Each system has its own normally closed 12 VDC solenoid valve to stop hydrogen flow, if necessary. The valves are closed during system shutdown.

Figure 2.2: Bench test computer display of the control and data acquisition interface for the fuel cell system.

2.2 Hydrogen on Demand^{TM} System

The HOD^{TM} system was designed, procured and constructed in the same time period as the fuel cell. In its history, Millennium Cell Inc. has developed systems in a variety of sizes, from automotive use to micro applications such as to power a small fan. In all cases, the system components are the same, and differ only in size to match a prescribed output. In the beginning, Anuvu fuel cell engineers calculated a required design flowrate of 45 liters/minute of gaseous hydrogen at standard temperature and pressure for the PEM fuel cell to develop 3 kW net power. Millennium Cell engineers used that number as the design point to build their system. All components, from cooling water, to the borate staging area, to diameters of valves and piping were sized to develop 45 liters/minute of hydrogen. The system is therefore scalable.

The HOD^{TM} system reliably developed 45 standard liters per minute at the bench test. And the fuel cell reliably used this amount of fuel to develop 3 kW of power. The original design calculations proved accurate. The bench test demonstrated also that there was margin available in each system. That is, the HOD^{TM} system was capable of exceeding the design fuel rate, and the fuel cell was capable of exceeding 3 kW net power. Both systems will be governed by the control software to not exceed these design points, however, in the final installation.

The HOD^{TM} system sat idle for the first two days of the test week while the fuel cell system was reassembled from its breakdown for cross-country shipping, and then while the fuel cell was pre-tested on bottled hydrogen fuel. Once the fuel cell demonstrated steady state operation, the HOD^{TM} was connected and ready for trial. Eileen McComiskey, engineer at Millennium Cell, operated the hydrogen system from her laptop, again, to monitor and adjust performance online. In the final install, control will be limited to on-off only. A Coreolis type flow meter, temporarily installed in the hydrogen stream, confirmed development of the 45 liter/minute hydrogen flow rate.

Figure 2.3: Bench test computer display of the control and data acquisition interface for the HOD™ system.

The HOD™ performed exactly as described in the System Description report. It primed the sodium borohydride pump first with water, then the three-way valve switched suction from the condensate reservoir to the sodium borohydride fuel solution tank, and fuel began to flow. Fuel entered the catalyst chamber and reacted to form hydrogen gas and sodium metaborate byproduct. Both streams flowed to the borate staging area (BSA), which is a residence tank to drain the borate solution out the bottom and to vent the hydrogen gas through the top. The borate drained to the borate (waste) tank, and the hydrogen, still under regulated pressure from the exothermic catalytic reaction, streamed through a heat exchanger to cool down. The hydrogen then continued through two coalescing filters, to remove entrained water droplets. From there the hydrogen exited the system across the now-open solenoid discharge valve and entered the fuel cell in the amount required by the fuel cell. As demand for hydrogen scaled up and down, the sodium borohydride fuel pump scaled up and down to match output.

The water from the coalescing filters drained into the condensate tank, where it was held until needed to flush the system during shutdown. At shutdown, the fuel supply pump flushes the system by switching suction (just as for priming, at startup) with a three-way valve over to the condensate tank. The fuel pump moves condensate through the catalyst chamber and into the BSA, removing any borate granules that might have built up in the lines during operation. The system flushes automatically at each shutdown.

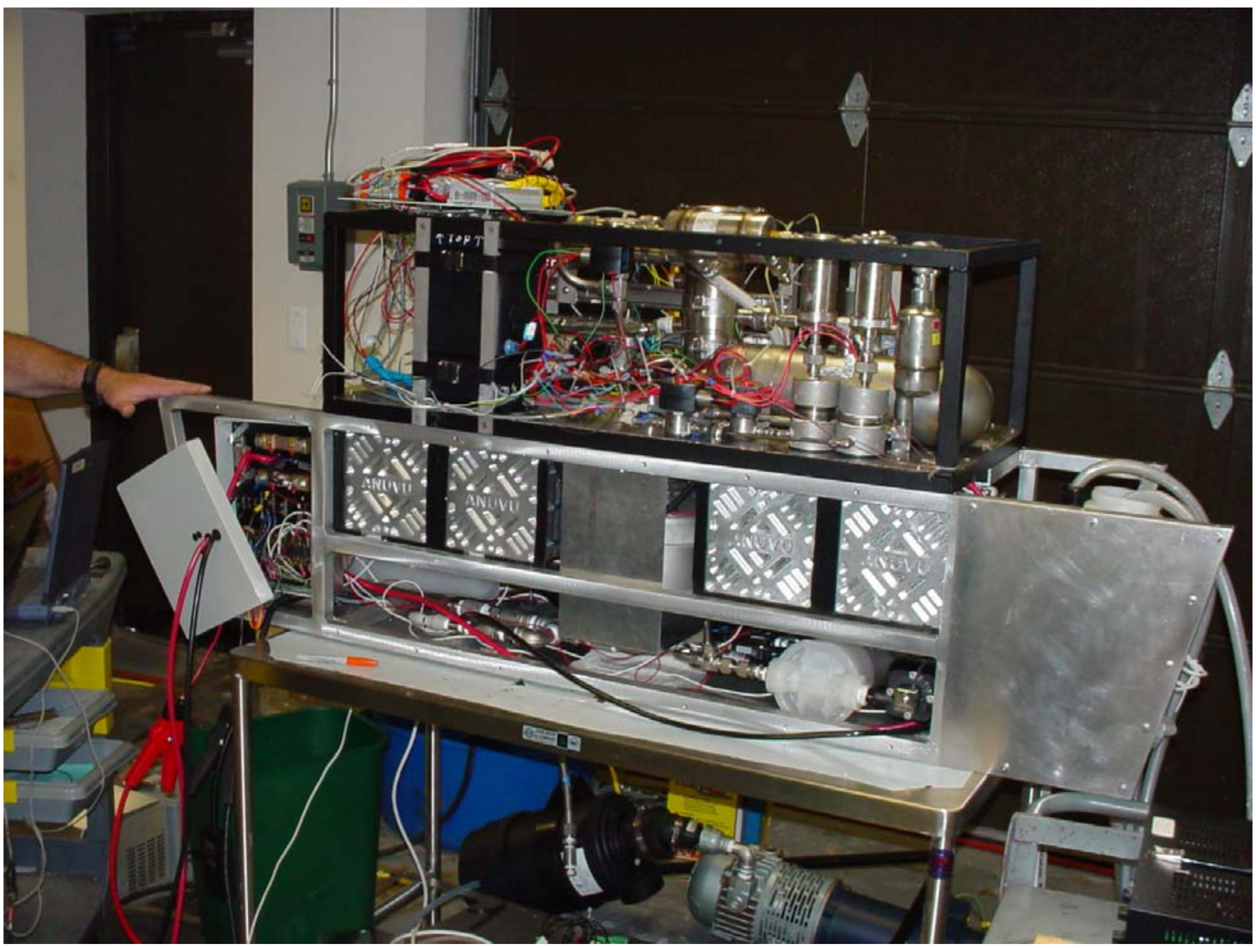

Figure 2.4: The HOD™ system, stacked above the fuel cell system, resting on a lab table. The array of wires was purposeful, to maintain access to all components for test and adjustment.

3.0 CONCLUSION

The bench test was successful. The test revealed two problems with the control software for the fuel cell, and these were promptly fixed. The test also revealed a problematic solenoid valve on the HOD^{TM} system, and the valve was promptly replaced. Small glitches were expected, and they were corrected. Once accomplished, all control software and automation functioned reliably throughout the three days of bench testing.

The systems capably maintained pressure, temperature and hydrogen conversion efficiency (>97 %) well within design parameters. The heat exchanger and central cooling water loop, which runs in parallel through both systems was found to be satisfactory. Overheating was not a problem, nor was overcooling. The control logic was effective. The system valves and pumps cycled in optimal sequence as designed. At the conclusion of testing on Friday, June 20, 2003, engineers from Anuvu and Millennium Cell were satisfied that the systems were ready for install. The fuel cell was returned to Anuvu's facility at Sacramento, California. Installation at the Duffy Electric Boats factory in Adelanto, California was scheduled for the week of July 21, 2003.

4.0 LIST OF ABBREVIATIONS

BSA	Borate Staging Area
CCDoTT	Center for the Commercial Deployment of Transportation Technologies
DH30	Duffy/Herreshoff 30-foot passenger boat
HC	Hydrocarbons
HOD	Hydrogen on Demand
kW	kiloWatt
NJ	New Jersey
NO_x	Oxides of Nitrogen
PEM	Proton Exchange Membrane
PWM	Pulse Width Modulation
SO_x	Oxides of Sulfur
™	Trademark
VDC	Volts Direct Current