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Improved Energy Source for NDI Equipment Tools

Final Summary Report

Reporting Period: May 25, 2016 to September 24, 2018

Contract No. FA8100-16-C-0002

Submitted by:

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Executive Summary

In this Phase II project, pH Matter and its partners have built a 25 W prototype ethanol fuel cell power system and demonstrated operation of Olympus-Nortec 600D NDI equipment with the system. In the report that follows, we review work completed during the Phase II project. pH Matter has incorporated novel membranes and ionomer delivered from its subcontractor Bettergy and demonstrated excellent cell performance and stability at target air flows using up to 10 molar ethanol fuel. This fuel concentration enables energy density on par with lithium ion batteries at the 25-Watt scale. Further, the company demonstrated up to 15-cell stacks with external air manifold that reduced pressure drop to an acceptable level for COTS blower options, and a novel anode current collector to enable fuel delivery with a COTS pump option. Lockheed Martin (subcontractor on the project) built and delivered a printed circuit board (PCB), which was integrated with the direct ethanol fuel cell stack, the pump, the blower, an on/off switch, and a start-up battery. The integrated system was able to power on Olympus-Nortec 600D NDI equipment without a battery connected, and the system will be delivered to the Air Force. A conceptual production design was presented to the Air Force based on the components used in the prototype. The conceptual design shows the expected size and weight for a system made using next-generation productions parts. Barriers to technology adoption that need to be addressed in future work will include: improving the ruggedness of the stack (mechanical/leaking, hydration cycles), removing KOH from the fuel, and miniaturizing the system through alternative stack compression approaches and production component designs.

Research and Development (R&D) Project Work Plan

A Gantt Chart with the proposed project schedule and key milestones in shown below in Exhibit 1. The Summary Report for the second year is a contract deliverable for invoicing in the final quarter.

Table 1. Project work plan task timing and milestone Gantt Chart.

Tasks and Milestones/Deliverables	Quarter after Project Initiation							
	1	2	3	4	5	6	7	8
Task 1. Stack Development (pHM)	▬	▬	▬	▬				
⇨ 3-cell stack demonstrated		★						
⇨ 15-cell stack demonstrated				★				
Task 2. Membrane Development (Bettergy)	▬	▬	▬	▬	▬	▬		
⇨ Delivery of initial membranes	★							
⇨ Membranes with 10X less crossover			★					
Task 3. Design & Integration (pHM / LM)	▬	▬	▬	▬	▬	▬	▬	▬
⇨ Breadboard electronics demonstrated		★						
⇨ Initial prototype design complete				★				
⇨ Prototype system complete						★		
Task 4. System Testing (pHM / LM)					▬	▬	▬	▬
⇨ Breadboard system tests reported					★			
⇨ Integrated prototype system tests reported							★	
⇨ Environmental testing complete								★
⇨ 25W Prototype delivered to Air Force								★
Task 5. Management and Reporting (pHM)	▬	▬	▬	▬	▬	▬	▬	▬
⇨ Formal Meetings	★			★				★
⇨ Quarterly Engineering Progress Reports and Final Reports	★	★	★	★	★	★	★	★

Milestone/Task Status

Overview

A Gantt Chart overviewing the project work plan tasks, timing, and key milestones was shown above in Table 1. Four technical tasks and a management task were worked on during the project. All tasks were completed, as elaborated below, with the following key results:

- **Task 1. Stack Development**. Within this task pH Matter improved cell performance and long-term stability. Key issues addressed included improving anode catalyst adhesion, and tuning pressure drop across both sides of the cell with current collector / flow field design. Further, an external-manifold cell stack was designed, built, and tested; target performance was demonstrated with the external air manifold approach. An unplanned sub-task was optimization of the cathode for operation with new developmental membranes. Target cell performance was achieved using the low-crossover membranes. Cell performance was replicated in a 15-cell stack. In order to achieve higher voltages a multi-pass stack design was employed. Even with the experimental membranes, flooding of the cathode (with electrolyte) was found to occur over time; however, performance could be recovered. Future work will examine removal of KOH electrolyte
- **Task 2. Membrane Development**. Bettergy developed and delivered novel membranes with 10X lower ethanol crossover, achieving the month 9 milestone. Additionally, Bettergy delivered ionomer to pH Matter. The new membranes were tested at pH Matter and demonstrated that at least 10 M ethanol concentration operation can be achieved without fuel loss to the cathodes. However, electrolyte crossover, likely due to Osmotic drag, occurred as a function of current density and electrolyte concentration, which could lead to long-term flooding under operation. Future work will examine dual layer membranes that block electrolyte crossover, and/or electrolyte removal from the fuel.
- **Task 3. Design and Integration**. A system design review was held between pH Matter, Lockheed, and the Air Force. Lockheed completed design and delivery of a PCB to control the voltage regulation, power source (start-up battery versus fuel cell), and distribute power to the system components. pH Matter integrated the components into a breadboard system, then into an enclosed prototype system. A next-generation production design was also generated and presented to the Air Force.
- **Task 4. System Testing**. The integrated system was tested and demonstrated under various scenarios using an electronic load box. Then, the system was integrated with an Olympus-Nortec 600D NDI equipment and demonstrated to power on the equipment. For explosive atmosphere operation, the individual components were tested separately, then the integrated system was demonstrated in a flammable environment. The system was delivered to the Air Force for presentation of its operation.
- **Task 5. Management and Reporting**. This report is being submitted as the milestone/deliverable for invoicing at the end of year 2.

Projected Performance

The key projected performance features of the production alcohol fuel cell system have not deviated from the performance projected in the proposal. The prototype deliverable for the project changed over the course of the project when it was decided to design the system for integration with the Olympus-Nortec 600 series of equipment instead of the Nortec 2000 (which was phased out). Table 2 compares the proposed, projected, and prototype systems.

Table 2. Comparison of non-proprietary proposed prototype feature values and current projected end-product performance values.

End Product Feature	Proposed Design Targets	Projected Production Design	Delivered Prototype
Power (Watts)	25 W (average)	25 W (max); 14 W (average)	25 W (max); 14 W (average)
Size (L)	Fits on back of NDI	Fits on back of NDI	See design; smaller footprint than NDI
Dry Weight (kg)	< 1 kg	<1 kg	See design
Fuel Source	Denatured Ethanol	Denatured Ethanol	200-proof Ethanol

Accomplishments

The details of the key results for individual tasks are included in the proprietary versions of the quarterly reports. Key major accomplishments of the work included:

- Bettergy's development of a membrane that prevents ethanol cross-over and enables long-term cell operation in at least 10 M ethanol.
- Demonstration of a direct ethanol fuel cell for over 100 hours (when the test was stopped) using 5 M ethanol. To the best of our knowledge, this has never been demonstrated in any published data.
- Design, development, fabrication, and demonstration of an external air manifold for the stack.
- Optimization of the anode and cathode current collectors / flow fields for cell performance and pressure drop.
- Design, fabrication, and demonstration of a 15-cell stack.
- Design, fabrication, and demonstration of a PCB by Lockheed.
- Design and integration of a 25-W prototype system with COTS pump, blower, switch, LED indicator, and start-up battery, in-house built fuel cell stack, Lockheed-manufactured PCB, custom fuel tank, custom air manifold, and custom housing.
- Successful explosive atmosphere testing of the prototype.
- Successful in-house operation of NDI equipment with the prototype.
- Design of a production prototype that can meet the application targets.

Designs

Two system designs were established during this project:

1. A 25-W prototype system design with COTS pump, blower, switch, LED indicator, and start-up battery, in-house built fuel cell stack, Lockheed-manufactured PCB, custom fuel tank, custom air manifold, and custom housing. This design was built and delivered to the Air Force.
2. A 25-W production concept with COTS pump, blower, switch, LED indicator, and start-up battery, pH Matter-built fuel cell stack (with next generation compression design), Lockheed-

manufactured PCB, custom fuel tank, custom air manifold, and custom housing. This design was 3D-printed and presented to the Air Force.

Outstanding Problems

Cathode Electrolyte Leaking. Previously, we reported cathode flooding (with ethanol) as the primary challenge. These issues were addressed with membrane modifications in single cell tests. Mechanical problems with membrane expansion and curling that lead to immediate fuel leaking were solved with further membrane development. Excellent stability results were obtained with Bettergy's developmental membranes under low current operating conditions or open circuit voltage and negative pressure on the anode side or in single cell tests. However, during stack testing under current loads we found the membranes will leak electrolyte through the cathode side at higher current density, leading to some cells becoming blocked. Performance can often be recovered by flushing the air side out with water.

Prototype Size. The prototype system design is currently larger and heavier than desired because of the need for external compression of the cell stack. Attempts were made to replace the compression system with only epoxy adhesion, but more development time and budget will be required. Other fuel cell manufacturers have demonstrated fuel cell stacks with bonded cells, so the approach is feasible. A "production prototype" concept design was 3D printed to show what the final size could be with elimination of the compression system. This design was presented to the Air Force.

Significant Results (presentation and publications)

Results from the project were/will be published at the following conferences:

- Abstract submitted to 2018 Department of Defense Maintenance Symposium, Tampa, FL (December, 2018).
- 2017 Fuel Cell Seminar in Long Beach, CA (November, 2017).
- 2015 ASNT Annual Conference in Salt Lake City, UT (October, 2015).

A patent application for the direct ethanol fuel cell concept was originally filed: U.S. 14/322,164

Other Information

pH Matter moved to a new facility during the project on June 1, 2017. The new address is:

6655 Singletree Dr.
Columbus, OH 43219

Future Plans

The Phase II project has been completed. Future work will focus on obtaining funding to further develop the fuel cell stack and build a production prototype system based on the production concept design. Technical fuel cell development will focus on removing KOH from the fuel, improving stack ruggedness, reducing electrolyte osmotic drag across the membrane, and miniaturizing stack compression.

Itemized Man-hours and Costs

A summary of itemized labor-hours, and contract expenditures are as follows:

Paul Matter, PI: 893 man hours, Chris Holt, Sr. Scientist: 322 man hours, Michael Beachy, Sr. Engineer: 1,896 man hours, Minette Ocampo, Chemist: 344 man hours, Technicians/Interns: 3,280 man hours. Total salary expended for the project was $207,998.13. Indirect and fringe expenses were $121,678.91 and $62,399.44, respectively. Supplies and equipment expenses were $26,280.24 and $16,063, respectively. The Bettergy and Lockheed Martin sub-awards and third-party machine shop costs for the project were $230,849.14, with $38,458.86 expected to be invoiced from Bettergy and Lockheed in the next 30 days. pH Matter charged a fee of 4.53% for a total of $33,783. The total expenditures for the project totaled $746,509.31 (including contractually obligated funds to be invoiced by subcontractors Lockheed and Bettergy). There are $0.00 funds remaining on the project (after satisfying obligated outstanding invoices) as of this reporting date. The total Project budget was $746,509.31.

Deliverable Status

The status of deliverables, including item and contract identification, shipping/transmittal ID, status, security classification, and schedule due date information are given below:

Item	CDRL	Shipping ID	Status	Security Classification	Due Date
Kick-off Presentation	004	0001AA	Accepted	Distribution B	6/25/16
Interim Report #1	001	0001AB	Accepted	Distribution A	9/25/16
Interim Report #2	001	0001AC	Accepted	Distribution A	11/25/16
Interim Report #3	001	0001AD	Accepted	Distribution A	2/25/17
Summary Report #1	002	0001AJ	Accepted	Distribution A	5/25/17
Interim Report #4	001	0001AF	Accepted	Distribution A	8/25/17
Interim Report #5	001	0001AG	Accepted	Distribution A	11/25/17
Interim Report #6	001	0001AH	Accepted	Distribution A	2/25/18
Summary Report #2	002	0001AJ	Current	Distribution A	12/25/18*
Final Report	003	0001AJ	Current	Distribution B	12/25/18*

*after 6-month no-cost extension

Report Preparer

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