VI.2 Advanced Manufacturing Technologies for Renewable Energy Applications - a DOE/NCMS Partnership*

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Project End Date: March 31, 2009

*Congressionally directed project

Objectives

This project will address selected key manufacturability issues needing solution in two hydrogen technology areas: storage and the production of components. It will evaluate, identify, and develop manufacturing technologies vital to affordable hydrogen-powered systems. In addition, the project is leveraging manufacturing technologies from other industrial sectors and work with the extensive NCMS industrial membership to do feasibility projects on those technologies identified as key to reducing production cost by rendering a system component or subcomponent of the targeted hydrogen-powered systems producible in volume.

Technical Barriers

This project addresses the following technical barriers from the Manufacturing section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

(A) Lack of High-Volume Membrane Electrode Assembly (MEA) Processes
(B) Lack of High-Speed Bipolar Plate Manufacturing Processes
(C) Lack of High-Speed Sealing Techniques
(D) Manual Stack Assembly
(E) Lack of Manufacturing Processes for Balance-of-Plant (BOP) Components for Proton Exchange Membrane (PEM) Fuel Cell Systems
(F) Low Levels of Quality Control and Inflexible Processes
(H) Lack of Carbon Fiber Fabrication Techniques for Conformable Tanks

Contribution to Achievement of DOE Manufacturing Milestones

This project will contribute to achievement of the following DOE milestones from the Manufacturing section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- **Milestone 14.** Develop fabrication and assembly processes for polymer electrolyte membrane automotive fuel cell that meets cost of $30/kW. (4Q, 2015)
- **Milestone 15.** Select processes to be developed and metrics for manufacturing BOP components. (2Q, 2009)
- **Milestone 20.** Complete development of standards for metrology of high-pressure storage systems. (4Q, 2008)
- **Milestone 22.** Demonstrate pilot scale, high volume manufacturing processes for high-pressure composite tanks. (4Q, 2011)
- **Milestone 23.** Develop prototype sensors for quality control of high-pressure composite tanks manufacturing. (4Q, 2012)

- **Milestone 24.** Develop fabrication and assembly processes for high-pressure hydrogen storage technologies that can achieve a cost of $2/kWh. (4Q, 2015)
- **Milestone 40.** Demonstrate pilot scale, high-volume manufacturing processes for electrolysis membrane assemblies. (4Q, 2012)

Accomplishments

- Developed design of tank with metallic liner and composite overwrap (Type 3) with separation of fiber placement and resin processing, achieving a 30-minute cycle time.
- Developed a novel methodology to control fiber wrap for composite storage tanks.
- Demonstrated process for achieving 20 minutes tank cycle time; currently implementing more robust and repeatable systems.
- Qualified four new plastics for use in PEM fuel cell BOP.
  - Developed method to identify potential contamination sources within molded material.
  - Fabricated components using new plastics resulting in >90% cost savings and >70% weight savings compared to currently used metallic systems.
- Successful demonstration of automation of catalyst-coated membrane (CCM) manufacturing, incorporating advanced catalyst inks and hydrocarbon (HC) membranes.
- One-step injection molding process was demonstrated for 250 W fuel cell stacks; results were repeatable at scaled-up manufacturing facility.
  - Multiple systems based on this technology are in development for both Department of Defense and commercial markets.
- Demonstrated throughput and yield of the manufacturing process for fuel cell stacks and adopted into production.
  - Modular BOP design significantly reduced labor costs (from 16 hours to less than 4 hours).
- Developed a hydrogen storage cartridge manufacturing technology, and executed pilot production of cartridges.
  - Reduced fabrication process times by more than a factor of 10.
  - Projected manufacturing processing costs reduced by a factor of 8-10.
- Determined that modal acoustic emission (MAE) can be used to detect the possible area of failure in high-pressure storage vessels, based on source/receiver relationship, source type, and source orientation.
  - Prediction of flaws in carbon fiber tanks using MAE phased arrays is possible.
- Completed first in its kind testing of 42-inch diameter by 40-foot long pressure composite vessels at TransCanada New Brunswick facility. These types of vessels are very difficult and expensive to inspect with ultrasound and X-ray due to the materials used in construction. MAE source locations were correlated to flaw growth failure locations. Crack growth in the composite over-wrap could be separated from crack growth in the steel liner, and it was able to detect and locate growing flaws in the steel liner during fatigue cycling and burst tests with eight sensors on a 40-foot vessel.
- Implemented stacked piezoelectric transducers into modal acoustic emission phased arrays and testing.

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Introduction

Great strides are being made in improving the performance of hydrogen-powered systems. To date, the research and development (R&D) focus has been on performance and efficiency of the systems. However, to make affordable hydrogen-powered systems, addressing manufacturability issues will be vital to ultimate commercialization. Highly performing systems cannot be used unless they can be efficiently and repeatably manufactured. This project addresses several manufacturing issues that need to be solved for successful commercialization. Solutions to manufacturing R&D issues are the key for widespread usage of fuel cell systems. Failure to address manufacturing R&D issues early in the process will delay the domestic commercialization of hydrogen-powered systems, which endangers ceding this industry to non-domestic manufacturers. Without a strong effort towards the manufacturing of fuel cell and storage systems, the U.S. is in danger of losing its leadership role in the production and use of fuel cell systems. This industry is vital to our national energy future.

Approach

Our approach includes:

1. Working with key stakeholders, development of a prioritized, consensus list of current barriers, concerns, and issues related to manufacturability:
   - Extracting information from currently available industry and government roadmaps, specifically regarding identification of process technology needs.
   - Consulting with and consensus building among stakeholders to prioritize manufacturability

needs and formulate potential project designs to address these needs.

2. Structuring and conducting collaborative projects addressing selected prioritized manufacturing technologies to demonstrate and/or substantially improve the economic production of hydrogen storage systems and the production of components.

Results

A series of workshops at the beginning of the project identified and helped to prioritize manufacturing issues in storage systems, and fuel cell components. Key manufacturing issues were identified in the following areas:

1. Hydrogen storage structures
   - Manufacturing processes
   - Assembly processes
   - Joining technologies
   - Manufacturing of fittings, valves, tubing, (plumbing)
   - Parts reduction/simplification
2. Efficient/lean manufacturing of fuel cells
   - Coating processes
   - Automated manufacturing
   - Assembly technologies
3. Sealing Technologies
   - Fuel cell stacks
   - Components
4. BOP
   - Discrete parts manufacturing and assembly
   - Parts reduction/simplification
   - Water/heat management
5. Inspection and Safety
   - Non-destructive testing and evaluation methods
   - Leak-testing
   - Sensor technologies

A call for project ideas based on the above criteria was issued, and 52 project ideas were submitted for consideration. Working with the DOE, 12 project teams were asked to submit full proposals to NCMS, of which nine projects were identified for funding under this NCMS/DOE project. One project team decided not to continue participation.

As a result, eight manufacturing efforts are being performed under this project. This section summarizes these endeavors.

1. Non-Destructive Testing and Evaluation Methods

Several non-destructive evaluation methods were evaluated for composite pressure vessels with MAE techniques being the primary focus. Subjects of these MAE evaluations were overwrap plastic-lined pressure vessels as for automotive applications, and composite fiberglass reinforced plastic (FRP) overwrap metal vessels with domes welded to either end similar to transport vessels for compressed natural gas. In the first application, vessels were submitted to pre-damage proof testing to 18 ksi and MAE-monitored to verify manufacturing consistency. Defects evaluated were drilled holes, cut fibers, and impact damage. MAE detected newly introduced damage on first pressurization after damage occurred. Emission did not stabilize, indicating that the damage continued to grow during the pressure holds. A pressure proof test was repeated to 12,500 psi and emission detection confirmed. Frictional acoustic emission (FRAE) occurs upon pressurizing and depressurizing the vessel and MAE detected this emission at a higher sensitivity setting (24 dB of gain was added to the internal preamplifier – a factor of almost 16 times the waves displayed at the trigger threshold). Using FRAE, much lower energy events will be detected, such as very small acoustic emissions excited by previously created fracture surfaces rubbing against each other. MAE was also able to detect and locate growing flaws in the steel liner of the second vessel application during fatigue cycling (leaking occurring at 11,494 pressurization/depressurization cycles) and burst tests with eight sensors on a 40-foot vessel (see Figure 1). Phased array sensor technology was also evaluated and found to detect flaw location with stacked sensor

FIGURE 1. Burst Test of Composite Over-Wrapped Steel-Lined Pressure Vessel

attachments composed of polyvinylidene fluoride film, an inexpensive transducer that is easily configured for detection sensitivity requirements.

2. Affordable High-Rate Manufacturing of Vehicle-Scale Carbon Composite High-Pressure Hydrogen Storage Cylinders

Developed novel methodology to control fiber wrap, allowing for more than an order of magnitude acceleration of fiber placement and improved processability of materials relative to current filament winding processes and resin systems (see Figure 2). Developed unique short cycle time molding process. Demonstrated process for achieving 20-minute cycle time and currently implementing a more robust and repeatable process, including process control automation. Tooling up for a full-scale cylinder, and redesigned tooling approach as required for control of overall process in an automotive production environment.

3. Manufacturable Chemical Hydride Fuel System Storage for Fuel Cell Systems

Twenty-nine bladder assemblies were delivered to NextEnergy, and tested operating at ~1,000 sccm hydrogen flow and ~20 psig pressure. The system was turned off for periodic cooling cycles (off for 200 minutes every 3,500 minutes of use) to simulate usage. Reactor temperature drops of 30°C (from 80°C to 50°C) were typical during the stoppage. The bladder assembly showed no sign of liquid leaks. After fixing a faulty test fixture check valve, there was a 100% pass rate on the final 13 bladder assemblies. As a result of these improvements:

FIGURE 2. Composite Storage Tank

- Sub-assembly fabrication scrap rate fell from 75% to less than 5%
- Bladder assembly process steps reduced by 25%
- Total fabrication process time was reduced by more than a factor of 10
- Projected manufacturing processing costs were reduced by a factor of 8 to 10

4. Novel Manufacturing Process for PEM Fuel Cell Stacks

Demonstrated one-step injection molding process for fuel cell stacks in Phase I (see Figure 3). Over 250 optimized fuel cell stacks have been manufactured to date. Performance exceeded stack power density targets (target 368 W/kg – actual 500 W/kg). Phase II of the project focused on a low cost integrated BOP for a portable 250 W fuel cell system. The deliverable for the project is a 250 W stack and integrated fuel cell BOP that offer high performance and robust, scalable manufacturing.

5. Innovative Inkjet Printing for Low-Cost, High-Volume Fuel Cell CCM Manufacturing

Cabot successfully developed advanced electrocatalyst inks with good stability (acceptable pot life) and compatibility for catalyst layer deposition. Their new manufacturing platform based on a spray-process technology, produced high-performance, low-

FIGURE 3. One-Step Injection Molded Fuel Cell Stack

cost and durable CCM/MEAs with high production yield. Fabricated CCM/MEA products were validated by two portable DMFC manufacturers, after which Cabot established a pilot manufacturing line. The low-cost, durable DMFC CCM/MEAs with less Pt content is aiding in the commercialization of DMFC systems.

6. Manufacture of Durable Seals for PEM Fuel Cells

This project developed a process and equipment for highly automatable application and curing of seals. The number of seal components was reduced from 4 to 2, with the design potential to further reduce to a single seal component. Sub-scale 20-cell stack using these interfacial seals passed 1,000 hours of durability testing, and currently, these seals are being implemented into two full-scale (200 cell) fielded stack assemblies. A Phase 2 project on the development of manifold seal materials and seal application processes (project was strongly endorsed by FreedomCAR Hydrogen Tech Team) has resulted in two candidate materials which are currently under test; the leading material system under evaluation has great promise in achieving order-of-magnitude reduction in seal application/assembly cycle time for full-scale stacks.

7. Qualifying Low-Cost High-Volume Manufacturing Technologies for PEM Fuel Cell Power Systems

The project qualified four new plastics (polyolefins and nylons) for use in PEM fuel cells, and developed a leachate method from the polymer pellets to identify potential contamination sources within molded material (see Figure 4). Using the new plastic materials, fabricated components demonstrated greater than 90% cost savings, and 70% weight savings over conventionally used materials.

8. Develop Low-Cost MEA3 Process

A study of the effects of manufacturing parameters on the performance of the low-cost MEA3 (DuPont trade name for their MEA) was completed. All MEA3s were first evaluated on a 25 sq cm DMFC. To establish their performance correlation and to understand the effect of active area increase, improved MEA3s were evaluated in both 25 and 50 sq cm SFC Smart Fuel Cell hardware. The correlation parameters were used for process improvement and then to fabricate improved MEA3s for stack evaluation. A 21-cell DFMC stack was assembled using MEAs from the improved process. The performance of the stack was 500 mV under the SFC's operational condition. After 2,500 hrs of operation, the performance of the stack was 380 mV, with an overall decay rate of 48 μV/hr.

FIGURE 4. Injection Molded BOP

Conclusions and Future Directions

Manufacturing issues are increasingly important to the widespread development and usage of fuel cell systems, ranging from storage to component processing. DOE needs to balance their portfolio of work to promote manufacturing development in alternative energy systems in order to maintain U. S. leadership into the future. Future directions in the individual project efforts include:

- Phased array MAE sensor development, particularly with wireless sensors, will allow not only faster setup, but the ability to monitor large structures such as pipelines.
- Initiate development and commercialization of production-capable systems for health monitoring of cylinders over a commercially important range of cylinder sizes, types and pressure ratings.
- Begin development of 70 MPa cylinders using a high-rate production technology.
- Achieve high-rate production process readiness for 35 MPa cylinders.
- Conduct large-scale evaluation of cartridge and component manufacturing, assess failure rates, process yield and scrap. Refine cartridge and component design, and minimize assembly steps, scrap, and costs.
- For hydrogen storage cartridges, move to fully recyclable materials, and scale-up to higher power levels.

- For the injection molded fuel cell stack, future work will scale-up to higher power levels, reduction of BOP parasitic losses, demonstrate in portable systems and improve operational envelope.
- Inkjet printing of CCMs will continue to improve manufacturing efficiency, optimize the depositing process to maximize MEA performance with reduced platinum loading, and demonstrate >1,000 hours durability.
- Full-size (200 cell) stack application trials will be conducted using optimum interfacial and manifold seal materials and automated application processes.