IV.G.2 150-kW PEM Fuel Cell Power Plant Verification

Thomas Clark
UTC Fuel Cells
195 Governor's Highway
South Windsor, CT 06074
Phone: (860) 727-2287; Fax: (860) 998-9811; E-mail: Tom.Clark@UTCFuelcells.com

DOE Technology Development Manager: Kathi Epping
Phone: (202) 586-7425; Fax: (202) 586-9811; E-mail: Kathi.Epping@ee.doe.gov

Subcontractors:
United Technologies Research Center
Connecticut Light & Power
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Objectives

1. Verify reliability of low-cost proton exchange membrane (PEM) cell stack components.
2. Improve the durability of PEM cell stack assembly.
3. Verify the specification, durability, and reliability of natural gas fueled PEM power plant.
4. Verify that a power plant can be connected to a distribution feeder with no adverse interconnection effects.
5. Analytically confirm useful application of PEM power plant heat.

Technical Barriers

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

<u>Components</u>

- O. Stack Material and Manufacturing Cost
- P. Durability
- Q. Electrode Performance
- R. Thermal and Water Management

<u>Distributed Generation Systems</u>

- E. Durability
- F. Heat Utilization
- G. Power Electronics

Approach

- Evaluate PEM 150-kW Beta fuel cell baseline performance. Document critical cell component, cell stack, and power plant reliability and durability issues.
- Understand critical failures identified to be the most frequent from a fundamental standpoint and implement design- and material-related corrective actions to achieve long-term durability and reliability.

Accomplishments

- Operated PEM 150-kW Beta fuel cell through multiple runs ranging from 1 hour to 100 hours continuous operation. Achieved maximum power of 139 kW DC/117 kW AC (net). Accumulated a total of 570 load time hours and 166 start/stop cycles.
- Demonstrated hands-off automatic startup, achieved less then 10 ppm CO from fuel processing system (FPS), and reduced power plant startup time to 25 minutes.
- Applied a mathematical model to analyze inlet flow channel design for maximum humidification. Predicted required humidification levels that provide uniformly liquid-equilibrated membrane over the entire active area.
- Developed accelerated test strategy for seal material screening. Identified 15 seal material candidates currently being screened for chemical and mechanical stability.
- Defined operating conditions for 20-cell fuel cell demonstration. The stack is expected to be built and tested during the 4^{th} quarter. Under the defined operating conditions, the short stack is expected to demonstrate a lifetime of 15,000 hours.

Future Directions

- Initiate and complete market analysis comparing natural gas fueled power plant to hydrogen fueled power plant for stationary applications.
- Conduct systems study for best options to utilize power plant heat.
- Validate next-generation power plant design concept, confer with utility customers for best design going forward, and evaluate power plants in field trials.
- Design experiments to validate the inlet humidification conditions. Employ the optimum inlet design in a test at the 20-cell stack level.
- A fuel cell stack with 15,000-hour potential lifetime using the inlet flow channel design will be built during the 4^{th} quarter of 2004.
- Continue with characterization of seal materials for chemical and mechanical stability. Initiate analysis of accelerated test data to estimate seal lifetimes.

Introduction

Verification of technical targets for individual components and assessment of overall power plant performance will require validation testing of power plants in real-life conditions. As an initial phase of this validation, a UTC Fuel Cells PEM 150-kW Beta fuel cell power plant is being tested to provide baseline conditions. Metrics will be prepared from this testing to facilitate future comparison of component durability, subsystem integration, and overall power plant reliability. Lessons learned from operation will be used for the next-generation power plant design.

Improvements in component durability and reliability are prerequisites for mass acceptance of fuel cells. These improvements hinge on understanding the fundamentals of the critical failure modes and adopting corrective actions. These corrective actions could be material or design related. Interfacial seals and membranes are the two critical repeat components that require attention for achieving tens of thousands of hours of lifetime.

An improvement in the mechanical and chemical stability of interfacial seals is required to achieve acceptable durability. Mechanically, the seals need to maintain their sealing capability for the duration in the acidic PEM environment. Chemically, the seal is expected not to contaminate the internals, especially the catalyst layers provided for reaction. Dry operating conditions accelerate membrane decay. One way to maximize membrane life is to maintain contact with saturated vapor across the entire cell area. To accomplish this with dry inlet gases, special consideration needs to be afforded to the design of the reactant inlet flow channel.

Approach

- The PEM 150-kW Beta power plant was evaluated to baseline performance of critical components and to document any cell component, cell stack, and power plant reliability issues. Test plans along with pretest model predictions were prepared, operations and testing standards defined, and tests conducted to evaluate system and subsystem performance under steady-state and transient conditions. Through testing, software was optimized for automatic startup and unattended operation, controls were tuned for transient response, and gas composition was analyzed for optimum fuel processing system (FPS) performance.
- Screen for durable seal material via accelerated mechanical and chemical integrity tests. The accelerated data will be analyzed to estimate seal lifetimes.
- Utilize mathematical modeling to verify inlet flow channel design for maximum humidification and water liquid equilibration across the entire active area.
- Demonstrate 15,000 hours durability on a 20-cell stack with an optimized inlet design.

Results

The PEM 150-kW Beta power plant performance summary is shown in Figure 1. The power plant operated for 570 load time hours with 166 stop/start cycles and achieved a maximum performance of 117 kW AC (net). Startup time from an energized off state (Figure 2) is less than 25 minutes. Carbon monoxide from the fuel processor averaged less than 10 ppm at steady-state and less then 100 ppm through small power load transients. The power plant operated nonstop in automatic unattended mode for durations up to 100 hours.

	Requirement	**Current**
Maximum Power	150 KWAC	117 KWAC
Number of Start Stop Cycles	250 Cycles	166Cycles
Run time	15,000 hrs	570 hrs
FPS Exit CO	<10 ppm (steady state) <100 ppm (large step change)	< 10 ppm <100 ppm (small step change)
Maximum Continuous Run	10 hrs @ max. power	100 hrs up to 103 KWAC

Figure 1. Power Plant Testing, Technical Accomplishments

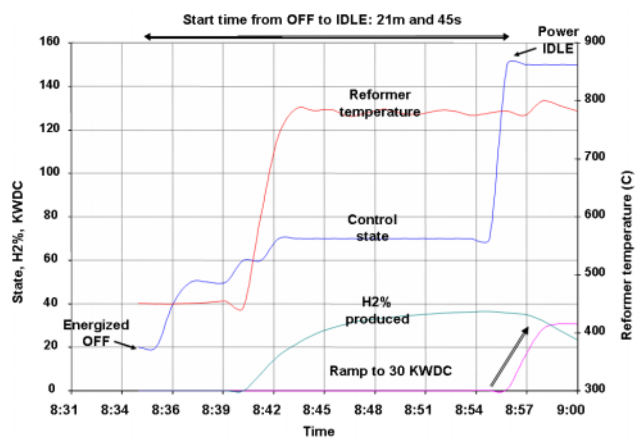

Figure 2. Power Plant Startup Time

Initial tests identified an unanticipated problem related to subsystem integration of the water treatment system with the power section stacks. Water treatment ion exchange resin beads were identified residing on the inlet water port of the four PEM stacks. One of the four stacks showed a high heat load with a resulting detrimental performance impact. This stack was removed from the power plant to prevent masking any damage to the stack

	Target 150 KWACNET (with 4 CSAs)	Target 70 KWACNET (with 4 CSAs)	Actual 68 KWACNET (with 3 CSAs)
Efficiency			
• System (%)	34.1	35.1	27.6
• CSA (%)	51.5	54.7	54.1
• Mechanical (%)	93.8	93.1	90.7
• FPS (%)	73.1	74.2	60.0
• PCS (%)	96.6	92.9	93.9
Fuel Flow (g/s)	9.2	4.1	4.6
CO, steady state (ppmv)	<10	<10	5 to 20 (avg.<10)
CO, transient (ppmv)	<100	<100	5 to 300 (avg.<100)
Parasitic Power (kWDC)	10.5	5.4	4.3
Gross Power (KWDC)	183.7	79.1	76.7 (Avg.)
Net Power (KWAC)	150.0	70.0	68.0

Figure 3. Power Plant Overall System Performance

from the port blockage. A root cause analysis is in process to identify the cause of the resin bead transfer and to identify any potential long-term performance, reliability, and durability concerns.

After removing the fourth stack, the remaining three stacks were back-flushed to remove the resin beads, and the power plant returned to operation in a 3-stack configuration. This 3-stack configuration operates in a non-standard design, limiting the total power output level and reducing the total overall efficiency. The test plan was adjusted to shift focus from transient response analysis to a component and subsystem reliability/durability analysis. Of the 570 load hours, 481 load hours are with the 3-stack configuration.

All components and subsystems of the PEM 150-kW Beta power plant generally met their technical targets and goals (see Figure 3). The overall efficiency averaged 27.6% at 68 kW AC (net) with the 3-stack configuration. Target efficiency for a 4-stack configuration is 35%. The low 3-stack efficiency is due to the election to operate the FPS and balance of plant (BOP) components at the maximum flow conditions possible. The high flow conditions provided better test results for component and subsystem reliability and durability analysis. The high flow conditions also resulted in low fuel and air utilization with corresponding low FPS (hydrogen utilization) and BOP (air utilization) efficiency.

Results of our emissions testing conducted on the anode exhaust/FPS process stream are presented in

(a) Concentration Basis (ppmv-dry)

50kW	THC	NOx	CO	SOx
Stack A anode exhaust	146.13	0.0034	-0.029	0.0013
Stack B anode exhaust	148.05	0.0032	0.027	0.0016
Stack C anode exhaust	142.23	0.004	0.011	0.0019
Average	145.47	0.0035	0.0026	0.0016
30kW	**THC**	**NOx**	**CO**	**SOx**
Stack A anode exhaust	237.89	0.0032	-0.023	0.0018
Stack B anode exhaust	226.22	0.0032	-0.039	0.0011
Stack C anode exhaust	199.55	0.0024	-0.095	0.0025
Average	221.22	0.0029	-0.052	0.0018

(b) FLUX BASIS (lb/MWhr)

Component	30kW	50kW	Model – 150kW
CO2	not measured	not measured	
H2	not measured	not measured	
NO_x (NO_2)	0.00	0.00	0.02
CO	0.00	0.00	0.07
NMHC	not detected	not detected	
THC	0.55	0.40	8.91
SO_x (SO_2)	0.00	0.00	0.02
Particulates	not measured	not measured	

Figure 4. Emissions Test Analysis

Figure 4. Tests at low- and mid-power levels show the power plant to have met or exceeded the target requirements previously set. There were virtually no emissions of carbon monoxide (CO) or oxides of nitrogen (NO_x). The only measured hydrocarbon emissions was methane that slipped through the fuel processor; the emission was in the vicinity of 150 to 225 parts per million (ppm). Total sulfur was negligible at less than 2 parts per billion (ppb). Figure 4A is in terms of measured volumetric concentration and Figure 4B is in terms of calculated pounds per megawatt-hour (lb/MWh), normalized to 15% O_2 equivalent. Figure 4B compares measured values to model prediction.

During this reporting period, accelerated testing strategies were developed to characterize the mechanical and chemical stability of seal materials. A schematic of the tests and the flow of testing is shown in Figure 5. As seen in the schematic, selected seal materials are tested for chemical and mechanical stability. The chemical stability tests include plate deposit test, hydrothermal leach test and thermo-gravimetric analysis (TGA). The plate deposit test requires contact of the seal with a bipolar plate material with saturated gases flowing across the interface. Periodically, the plate is tested for seal material deposits. If the seal material is not stable

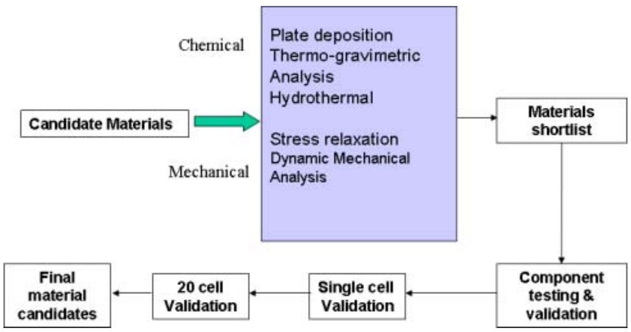

Figure 5. Accelerated Seal Testing Protocol and Test Flow Matrix

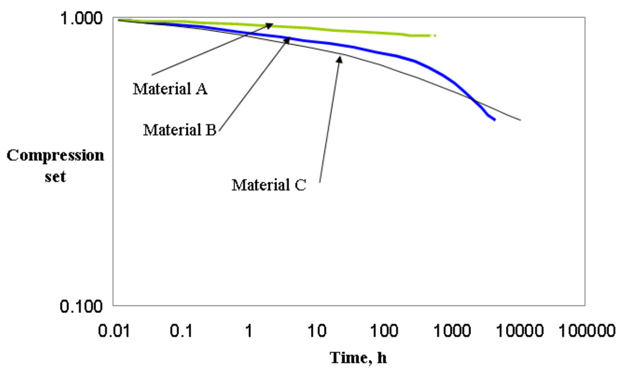

Figure 6. Compressive Stress Relaxation of Three Candidate Seal Materials

under the fuel cell operating conditions, it will decompose and organic vapors will deposit onto the bipolar plate. In the hydrothermal leach test, seal materials are soaked in de-ionized water at an elevated temperature, and the water is periodically tested for materials that leach out. Finally, the TGA is used for a quick screen of the materials to determine weight loss vs. temperature. The mechanical tests include stress relaxation and dynamic mechanical analysis (DMA). The compressive stress relaxation of the individual seal materials is measured to characterize compression set. The DMA affords a quick screen for the time-consuming stress relaxation test. Figure 6 contains the stress relaxation data for three candidate materials. As seen from the figure, the relative compression sets for materials A, B and C at the 1000 hour interval are 0.9, 0.7 and 0.6, respectively. Since a low compression set is desirable from a sealability standpoint, candidate A would be the material of choice for a fuel cell seal. The chemical

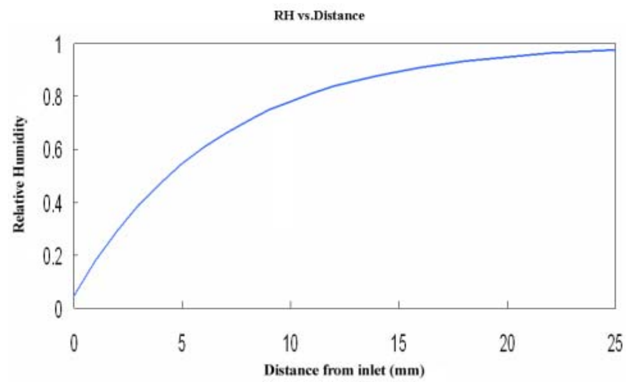

Figure 7. Increase of Humidity of Reactant Air as a Function of Inlet Distance

stability characteristics of candidate A are currently being measured.

Our in-house fuel cell proprietary model was modified to investigate humidification capability as a function of inlet flow channel designs. The in-house model is capable of calculating the saturation levels (percentage of available pores occupied by liquid water). The saturation level of the catalyst depends on the vapor- and liquid-phase water transport characteristics at the catalyst layer and gas diffusion layer (GDL) interface. The main variables controlling dry reactant gases are the inlet flow channel width, depth, and length and the mass transfer coefficient of the bipolar plate material. A number of simulations were run to characterize the designs. An example simulation is shown in Figure 7. In Figure 7, the humidity increase of the reactant air as a function of the length of the inlet flow channel is depicted. As seen from Figure 7, the humidity of the gas rises sharply in a very short distance and then approaches saturation for the length beyond 15 mm. This is due to the reduction in the driving force for the transport of water vapor. The corresponding catalyst layer saturation level as a function of inlet distance into the active area is shown in Figure 8. It is assumed that a saturation level of 0.1 corresponds to presence of liquid water in equilibrium with the membrane. Combining Figures 7 and 8, it can be inferred that when inlet air enters at 42%, the membrane is in contact with liquid water across the complete active area. Also, to achieve 42%, only 5 mm of the inlet channel is required in the baseline design.

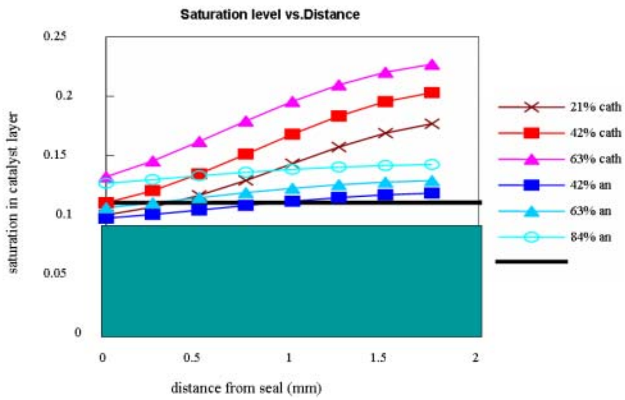

Figure 8. Catalyst Layer Saturation Level as a Function of Active Area Inlet Length