

# **Solid Oxide Fuel Cell Hybrid System for Distributed Power Generation**

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Kurt Montgomery, Nguyen Minh  
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**Honeywell**  
**Engines, Systems & Services, Airframe Systems**  
2525 West 190<sup>th</sup> Street  
Torrance, CA 90504

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## **ABSTRACT**

This report summarizes the work performed by Honeywell during the October 2001 to December 2001 reporting period under Cooperative Agreement DE-FC26-01NT40779 for the U. S. Department of Energy, National Energy Technology Laboratory (DOE/NETL) entitled "Solid Oxide Fuel Cell Hybrid System for Distributed Power Generation". The main objective of this project is to develop and demonstrate the feasibility of a highly efficient hybrid system integrating a planar Solid Oxide Fuel Cell (SOFC) and a turbogenerator.

The conceptual and demonstration system designs were proposed and analyzed, and these systems have been modeled in Aspen Plus. Work has also started on the assembly of dynamic component models and the development of the top-level controls requirements for the system. SOFC stacks have been fabricated and performance mapping initiated.

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## **EXECUTIVE SUMMARY**

This report summarizes the work performed by Honeywell during the October 2001 to December 2001 reporting period under Cooperative Agreement DE-FC26-01NT40779 for the U. S. Department of Energy, National Energy Technology Laboratory (DOE/NETL) entitled "Solid Oxide Fuel Cell Hybrid System for Distributed Power Generation". The main objective of this project is to develop and demonstrate the feasibility of a highly efficient hybrid system integrating a planar Solid Oxide Fuel Cell (SOFC) and a turbogenerator.

The work consists of three phases and will focus on defining and optimizing a suitable system concept, conducting experiments to resolve identified technical barriers, performing cost analysis, and testing a small hybrid system to demonstrate concept feasibility.

For this reporting period the following activities have been carried out:

- Conceptual and demonstration system design
- Development of the top level controls requirements for the system
- Dynamic component models
- SOFC stack performance mapping

## **EXPERIMENTAL**

All experimental work performed on the program is contained in sub-task 1A.2.1, Barrier Resolution – High Temperature Heat Exchangers and in sub-task 1A.2.2, Barrier Resolution -- Pressurized SOFC. The test procedures and the test methods used to perform the experimental work for these tasks have been described in previous Quarterly Technical Progress Reports.

## **RESULTS AND DISCUSSION**

### **Task 1A.1 – System Design**

#### **Subtask 1A.1.1 – Design Concept Development.**

The purpose of this task is to develop a system design concept for a hybrid system incorporating a planar SOFC with a commercial turbogenerator (e.g. Honeywell Parallon™ 75). Several system configurations based on pressurized fuel cell operation will be evaluated, and a configuration shall be selected as a baseline for reference design. This task involves the development of a set of criteria for the selection of the baseline design. Studies shall be performed to permit definition of all components/subsystems in terms of type, performance, and input and output

requirements. Focus shall be placed on the development of the fuel cell configuration including power level and control strategy including control structure.

Conceptual and demonstration system design were proposed and analyzed during the reporting period. Aspen Plus flowsheets for modeling of the conceptual and demonstration systems were completed. The goal of the modeling efforts is to generate system component problem statements from the system heat and material balance. The demonstration system was analyzed first to initiate material selection and component design activities for system hardware

### Demonstration System Design

In the proposed demonstration system design air and fuel are supplied to the fuel cell at pre-determined flow rates as well as at appropriate pressure and temperature. A compressor provides air to the fuel cell as a source of oxygen as well as coolant. The air pressure is further boosted in the turbocharger's compressor. Fuel (natural gas) is first fed to a fuel processor (a.k.a. the reformer) that uses the steam reforming process to convert the fuel into a gas containing  $H_2$  and CO. No fuel processor will be built during this program, and bottled simulated reformat gas will be used instead. However, the present analysis included calculations of the predicted processor yield to determine the composition of the reformed natural gas as well as effects of the fuel processor heat load on the system performance.

The fuel utilization in the fuel cell is fixed at 75%. The unconsumed fuel is mixed with the cathode exhaust and burned in the tail-gas combustor, which immediately follows the fuel cell. The heat recovered from the unconsumed fuel helps drive the turbocharger and provide additional air pressurization. The residual exhaust heat is transferred to air and fuel via heat exchangers throughout the system.

The proposed system design includes four heat exchangers for fuel cell reactant heat-up. Heat exchanger specifications are driven by requirement that the reactant temperature at the fuel cell inlet must be close enough to the fuel cell operating temperature (about 800°C) to minimize temperature gradients (more on this later). In general, the reactant inlet temperatures will be controlled to be between 750°C and 800°C. The following heat exchangers help accomplish this task:

- The recuperator transfers heat from the turbine exhaust gas to the fresh air supplied to the fuel cell. The temperature of the recuperator cold side outlet will still be below the required temperature and thus, the fresh air will be required to go through a second heat exchanger.
- The fuel cell air preheater completes the fresh air conditioning task by using the heat from the high-temperature fuel cell exhaust gas. The fresh air temperature will have to be controlled by a bypass with a control valve, preferably on the cold side (not shown on the schematic).

- The natural gas and water heater uses residual heat from the turbine exhaust after it goes through the recuperator to heat natural gas and vaporize water required for the steam reformer.
- The temperature of the reformer output, a gas containing hydrogen and carbon monoxide, will be below the fuel cell operating temperature. Therefore, the reformat heater will bring the fuel inlet temperature up to the fuel cell operating temperature (or close to it) by using the heat from the fuel cell exhaust gas.

Additionally, the steam reforming reaction in the reformer is endothermic and hence, requires a heat input. The system design proposes employing the fuel cell exhaust gas for this purpose. The reformer design would likely include an integrated heat exchanger for heat supply to the endothermic reaction. The reformer heat exchanger will not be built in this program therefore, no further analysis and design will be provided on this subject.

The system was modeled in Aspen Plus. The solid oxide fuel cell was modeled as a stoichiometric reactor, whose power output was set by the specified reactant utilization and single cell voltage. No attempt has yet been made to rigorously analyze the fuel cell performance. Since the purpose of the system design is to determine problem statements for heat exchangers, each heat exchanger was modeled as two coupled heaters, without specifying the type of heat exchanger and performance maps.

Availability of a turbocharger drives the system design. There are a number of options available from Honeywell's Garrett Turbocharger line, which differ in size as well as design. Given the fact that the system is a prototype, the most natural choice seems to be the smallest turbocharger available.

Both air and natural gas compressors will be selected based on the system flow requirements. The air compressor specifications will be primarily determined by the performance of both the fuel cell and the turbocharger, while the natural gas compressor specifications will stem from power demand and turbocharger matching requirements.

A few assumptions about the component performance had to be made:

- (1) An air compressor is available to drive the air through the system. At this time, a constant pressure head of  $\Delta p = 3$  psi for all flows was assumed. The compressor efficiency is 70%. These assumptions will be refined in the next iteration, when possible compressor candidates are identified.
- (2) A natural gas compressor must have flow-pressure characteristics to match the system operating profile (to be determined from the analyses). A flat efficiency of 70% was again assumed, which will also be revisited as possible compressor options are identified.
- (3) The fuel processor steam-to-carbon ratio is 1.5. This will require internal reforming in the fuel cell (approximately 80% of the fuel is reformed in stack). This



assumption is only for the initial problem statements. This assumption will be investigated in more detailed before finalizing the preliminary concept.

- (4) Fuel cell average temperature is 800°C (1472°F).
- (5) The maximum temperature rise in the fuel cell sets the requirements for the reactant inlet temperature.
- (6) Fuel cell single cell voltage is 0.75V. This assumption will be revisited after fuel cell performance data becomes available.
- (7) Effective fuel utilization in the fuel cell is 75%. It might be too aggressive and will have to be redefined as well.
- (8) Turbine inlet temperature is limited to 649°C (1200°F).

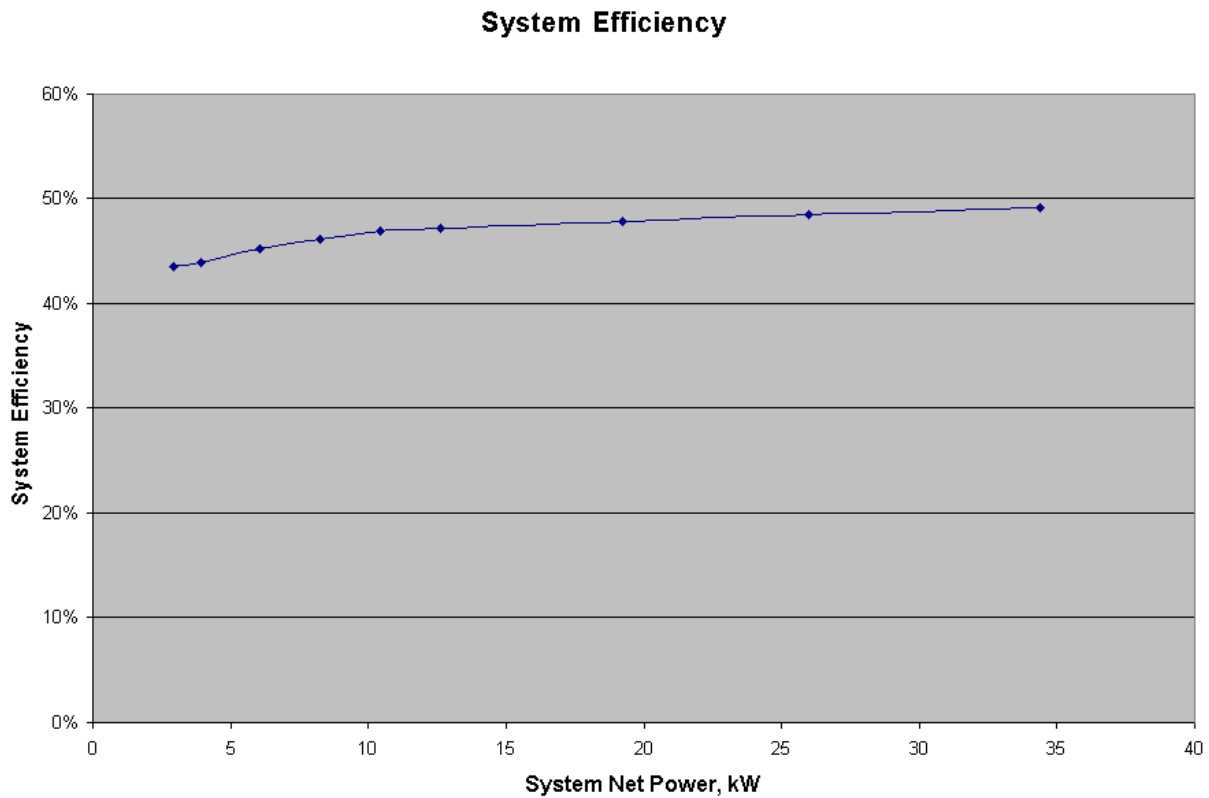
### Demonstration System Design Results:

#### *Maximum Power*

The system peak net power was determined to be around 34.4 kW. This value corresponds to the maximum turbocharger speed of 210 krpm. The minimum airflow that satisfies restrictions set by assumptions (5) and (8) should be chosen as the operating airflow at maximum power. As it turned out, the value of this airflow rate is roughly 130 g/sec (or about 215 scfm, or 6080 SLM). At this flow rate, the turbine inlet temperature was just below 650°C, and the fuel cell temperature rise was around within expected levels. The corrected compressor airflow rate was determined to be 13.85 lbs/min, and the compressor ratio was equal to 3.262.

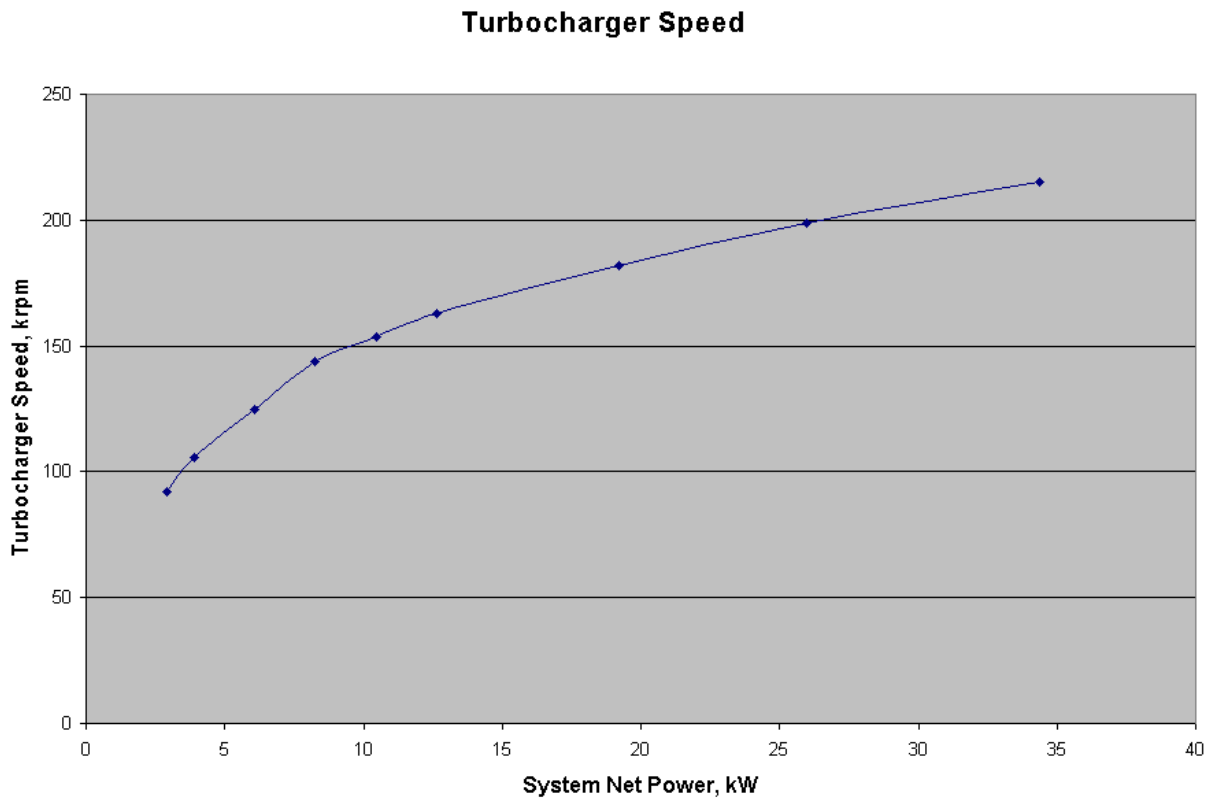
#### *Part-Load Performance*

The system performance at part load between the minimum and maximum turbocharger speeds was analyzed. A total of seven operating points between the minimum and maximum speeds were considered. The straight line connecting the “minimum” and peak power points was selected as the turbocharger operating line for this exercise. The main objective was to tabulate individual component requirements at each part load and outline preliminary performance characteristics of the system.



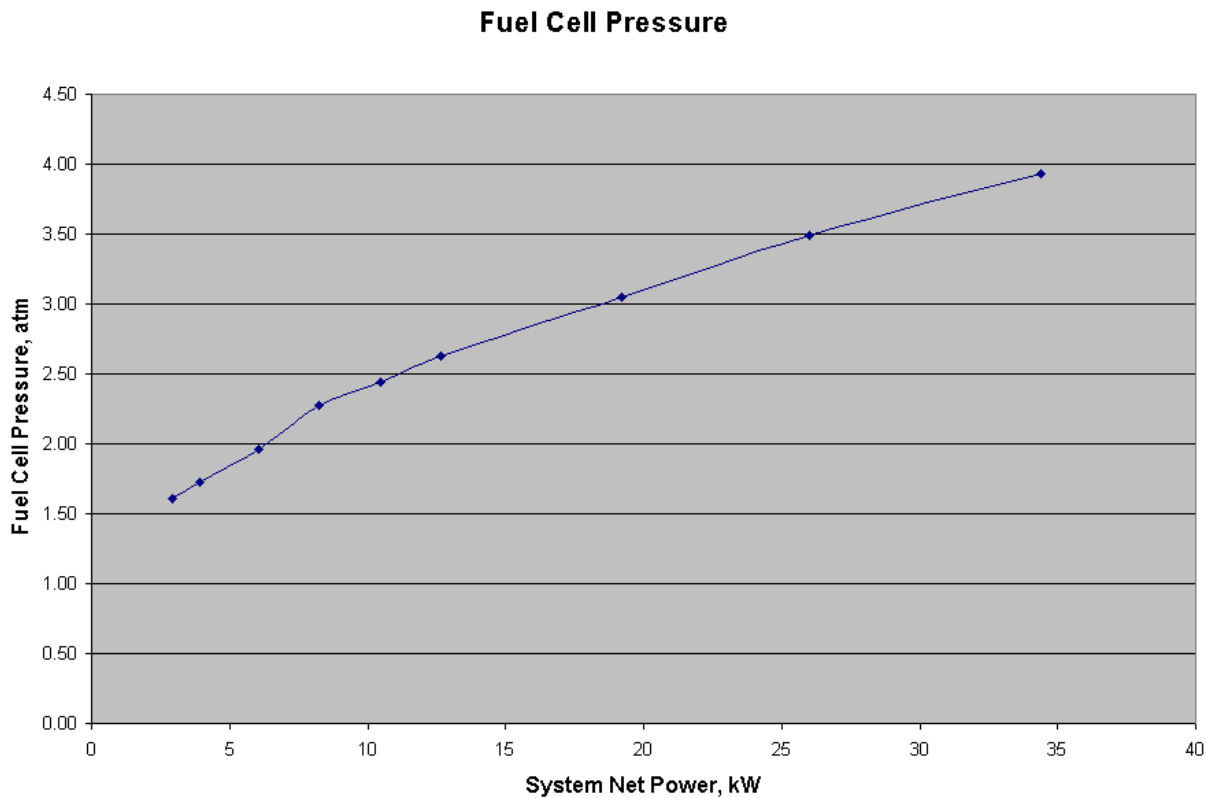
**Figure 1. Preliminary Projected Efficiency of the Demonstration System**

The results of efficiency calculations are presented on Figure 1. Please note that these numbers are heavily dependent on fuel cell performance data and the amount of fuel reformed within the stack and therefore, are very preliminary. Nonetheless, the system efficiency was estimated to be in the 43-49% range. The general trend of the curve is to grow as power load increases. The calculations did not take into account the effect of operating pressure on the fuel cell voltage, which can be very important. This feature will be added to the model as fuel cell performance data become available.



**Figure 2. Preliminary Turbocharger Speed as a Function of Demonstration System Power**

Figure 2 shows the change of the turbocharger speed with the power load. It should be emphasized that the turbocharger speed at a particular power load is highly dependent on the fuel utilization as well as air compressor performance. Therefore, a disclaimer that the results are very preliminary should be added to this figure.



**Figure 3. Preliminary Fuel cell Operating Pressure, Demonstration System.**

A parameter that has a particular significance to the fuel cell is the operating pressure profile. Figure 3 displays the pressure dependence on the system net power. The profile is relatively linear with power. It too is highly dependent on the fuel utilization and the air compressor performance.

Based on the *Demonstration System Design* results, the following primary component problem statements were developed:

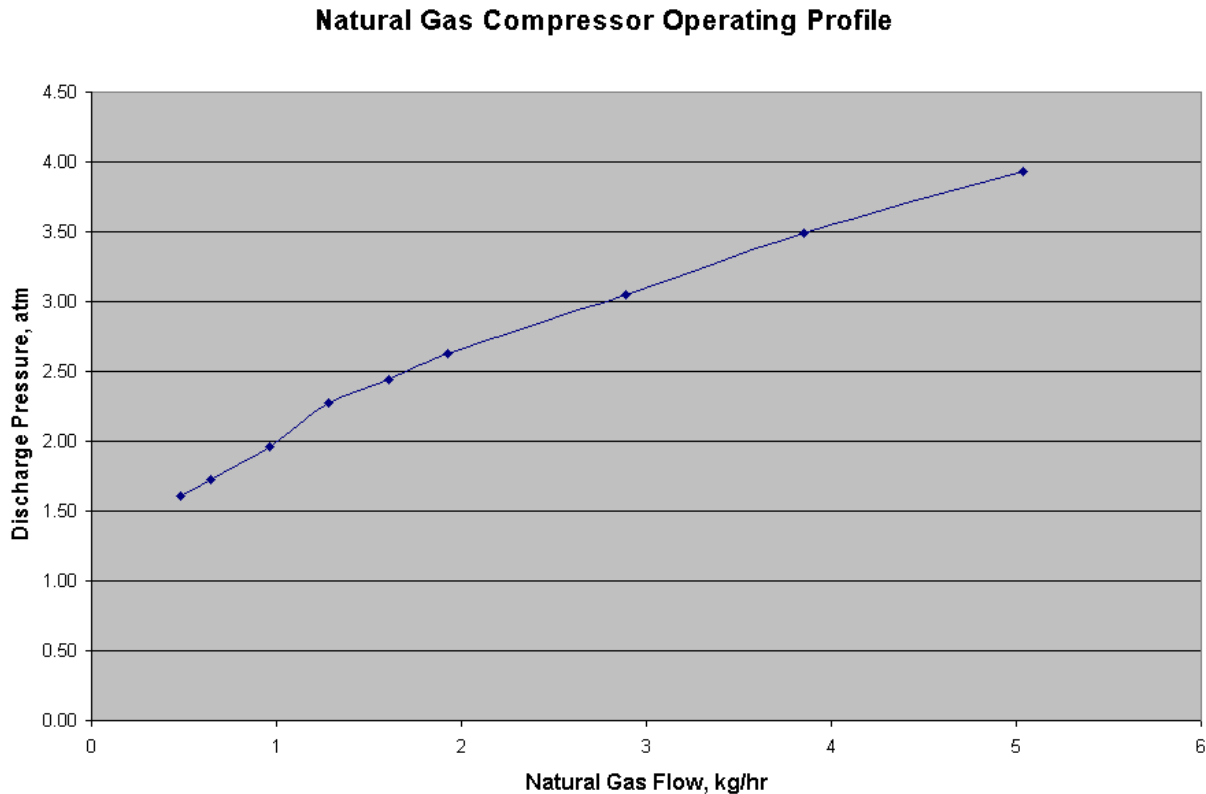
1. Air Compressor

The maximum air compressor flow rate is 215 scfm. The compressor pressure head requirement has not been specified yet as additional system pressure drop analysis is required.

2. Natural Gas Compressor

The natural gas compressor flow operating line is shown on Figure 4. The line has a positive slope, while typical compressor performance characteristics display negative slopes. Hence, either a variable speed compressor or some

kind of flow control device (bypass valve) will be required to operate the system at part load.



**Figure 4. Natural Gas Compressor Problem Statement, Demonstration System**

### 3. Heat Exchangers

The problem statements for the systems heat exchangers were developed for the nine operating points. There are three air-to-air heat exchangers in the system as well as one phase change heat exchanger, the natural gas and water heater. A 10°C pinch point was assumed for the natural gas and water heater. Overall, the specified requirements are rather aggressive. However, they are essential for successful system operation. Particularly, both the cold and hot side effectiveness values for the recuperator range from 0.8 to 0.9 at all nine operating points. Relaxing this requirement would cause a shift of heat duty from the recuperator to the fuel cell air preheater thus lowering the turbine inlet temperature and limiting the effectiveness of turbocharger assist. In addition, the air preheater effectiveness requirements would rise to between 0.8 and 0.9. Two possible ways to lower the recuperator and air preheater effectiveness requirements are to either relax the fuel utilization assumption or burn additional

fuel in the SOFC combustor. Both methods make more heat available for the fuel cell air preheat and come at a substantial system efficiency penalty.

In addition to the four heat exchangers, simulated reformer heat exchanger requirements are displayed. As noted above, the fuel cell exhaust gas will be used to supply heat to the reformer. The reformer design will include provisions for a device that will accomplish that. Nonetheless, the reformer heat balance computations were included in the design for completeness.

### Conceptual System Design

Two system design concepts were proposed for the conceptual full-scale system design. The first concept is a material-coupled design as it uses the microturbine's compressor air as the reactant feed to the fuel cell and the fuel cell exhaust as the inlet to the turbine. The second concept is a heat-coupled system, in which the heat from the fuel cell subsystem is transferred to the microturbine subsystem. The second concept has a drawback of a lower efficiency but an advantage of the atmospheric pressure operation, which results in less stringent requirements on the fuel cell materials. The analyses on both systems are underway and will be presented in the next quarterly reports.

### Control Architecture Development

Work has started on assembly of dynamic component models to support dynamic performance evaluation of system design and control system design. The development of the top level controls requirements for the system was also initiated. These requirements include:

- Stack operating requirements and constraints
- Balance of plant (BOP) components operating requirements and constraints
- Preliminary failure modes and mitigation

Initial efforts have also started on developing the top level control architecture for the systems.

### **Task 1A.2 – Technical Barrier Resolution**

#### **Subtask 1A.2.2 – Pressurized SOFC**

The purpose of this task is to fabricate and test planar SOFC's under pressurized conditions. The work will involve fabrication and testing of laboratory scale cells and stacks of increasing size to investigate their properties in pressurized environments.

Electrochemical performance and structural integrity at pressures shall be evaluated. Analysis and modeling will be carried out to identify performance degradation mechanisms under pressures, if any. Performance maps will be determined for various operating parameters. Thermal cyclability and lifetime under pressurized operation will also be investigated. The purpose of this task is to modify cell and stack designs if required to improve cell performance and structure.

### Performance Mapping

Following the feasibility of pressurized SOFC operation, performance mapping is to characterize the pressurized SOFC performance under various operating parameters.

A 3" module (RJ003) has been assembled and tested under various pressures. The module was constructed with a standard cell consisting of standard anode and SPC-4 cathode. 64% hydrogen balance 36% nitrogen was used as fuel, and air as oxidant. Cell polarization was taken at different operating pressures and temperatures, but all with fixed fuel and air flows (181 cc/min hydrogen and 101 cc/min nitrogen in fuel stream, 860cc/min air). As expected, the module performance improved with increased operating pressures. This trend was observed at all temperatures tested between 650 to 800°C. The performance improvement with pressure was more evident at high current densities, or at high fuel utilization given that fuel flow rate was fixed.

Another two 3" modules (RJ008 and RJ010) were constructed and tested for performance mapping purpose. However, neither of these tests gave a complete set of performance data due to relatively low OCVs (about 800mV). The possible causes were narrowed down to gas leakage and possible electrical shorting.

### Performance Modeling

As observed in the performance mapping test, the performance improvement with pressure was more evident at high current densities, or at high fuel utilization given that fuel flow rate was fixed. The increase in cell OCVs was in line with the Nernst potential calculation. However, performance improvement under load was much larger than the increases in OCVs. To better interpret these data and guide the future test and system design, a performance modeling effort was initiated. Preliminary modeling started with adapting fuel cell electrochemistry principles and fitting data in RJ003 and then projected the performance under higher pressures. The preliminary model has taken into account of dynamic Nernst potentials, exchange current density, and limiting current densities in an effort to capture the effects from both thermodynamic and kinetic aspects.

The preliminary analysis showed an acceptable fit between the experimental data in RJ003 and the model (Figure 5). The modeling also gave a performance projection at higher pressures, as shown in Figure 6. Although the modeling was only in the initial development stage, it did help draw some preliminary conclusions:

- Significant performance enhancement observed from 1 to 3 atm
- Moderate performance improvement expected from 4 to 10 atm
- Gap to be filled between proposed system design point (0.75V @ 75% fuel utilization) and current cell performance.

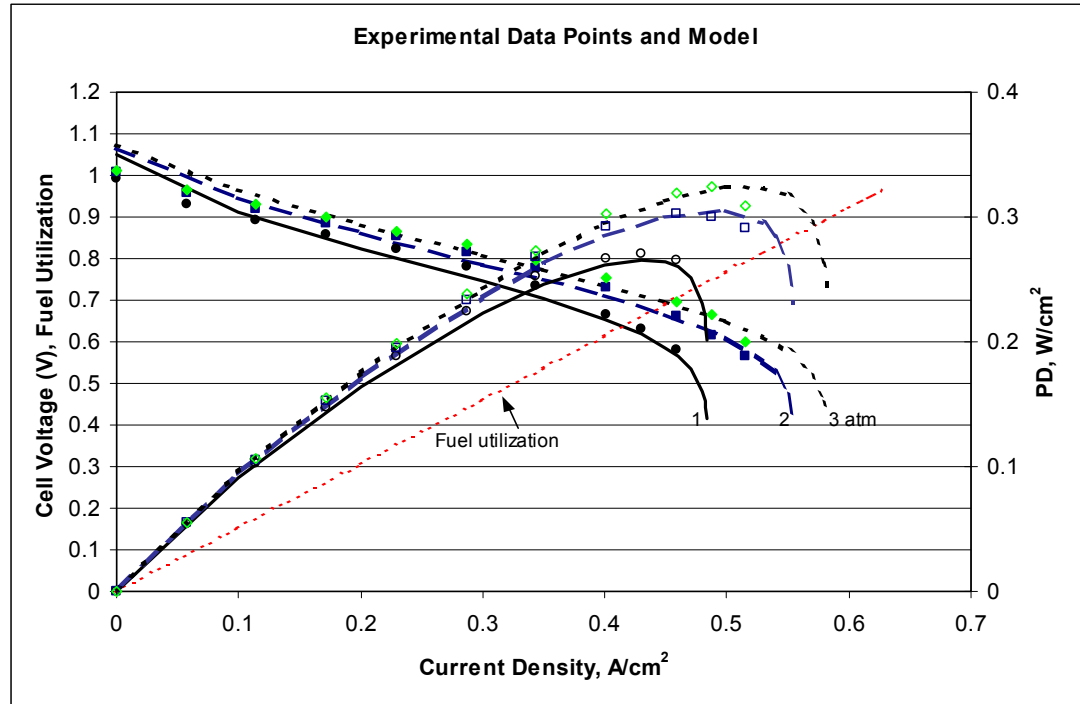


Figure 5 Model Fits Experimental Data from RJ003



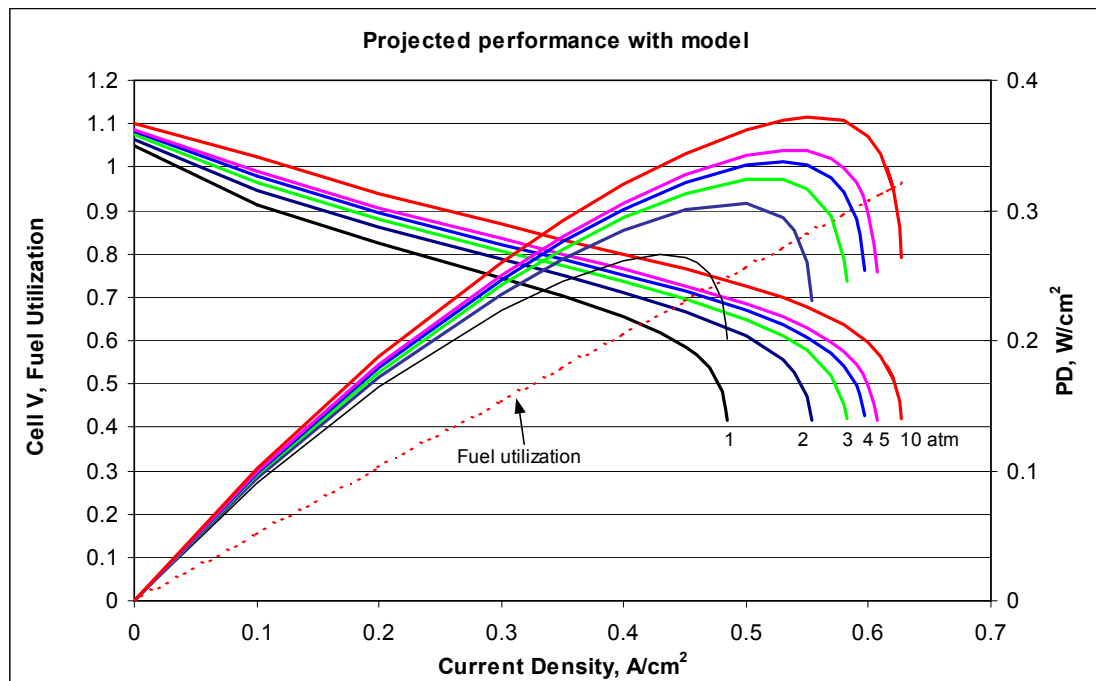


Figure 6 Projected Performance Using Fitting Parameter from RJ003

## CONCLUSION

For this reporting period the following activities have been carried out:

- Conceptual and demonstration system design were proposed and analyzed
- The system was modeled in Aspen Plus
- Dynamic component models are being assembled
- Development of the top level controls requirements for the system was initiated
- SOFC stack performance mapping started

## REFERENCES

None