Solid Oxide Fuel Cell Hybrid System for Distributed Power Generation

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DISCLAIMER

Abstract

This report summarizes the work performed by Honeywell during the January 2002 to March 2002 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.

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

- Conceptual system design trade studies were performed
- System-level performance model was created
- Dynamic control models are being developed
- Mechanical properties of candidate heat exchanger materials were investigated
- SOFC performance mapping as a function of flow rate and pressure was completed

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Executive Summary

This report summarizes the work performed by Honeywell during the January 2002 to March 2002 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 hybrid system is based on Honeywell planar SOFC and turbogenerator power technologies. The planar SOFC is based on thin-electrolyte cells and metallic foil interconnects. This technology leads to SOFC stacks that operate at reduced temperature (<800°C) and have reduced materials cost. This work will culminate in testing of a small SOFC-based hybrid system that will incorporate all of the components/subsystems required for a full-fledged system.

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.

The various phases and tasks to be performed under this program are attached. For this reporting period the following activities have been carried out:

- Conceptual system design trade studies were performed
- System-level performance model was created
- Dynamic control models are being developed
- Mechanical properties of candidate heat exchanger materials were investigated
- SOFC performance mapping as a function of flow rate and pressure was completed

Approach and Results

1. <u>TASK 1A.1 – SYSTEM DESIGN</u>

1.1 SUBTASK 1A.1.1 – DESIGN CONCEPT DEVELOPMENT.

Trade studies on conceptual system design candidates were performed and a system-level SOFC performance model was created during the reporting period. The goal of the SOFC modeling effort was to provide a tool to predict the influence of SOFC parameters on system performance. The model was then utilized in the trade studies of the conceptual system candidates. The influence of system parameters on the system efficiency was analyzed in detail for two concept candidates.

1.1.1 Conceptual System Design Trade Studies

Concepts

The proposed conceptual system design candidates are shown in Figures v2-1 through v2-3 (presented in EPACT protected volume). Concepts 1 and 2 were proposed in the last quarter. Concept 1, shown on Figure v2-1 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.

Concept 3 was added in the reporting period. Concept 3 is similar in its idea to Concept 2. A major difference between the two systems is that the turbine exhaust is the cathode feed to the fuel cell in Concept 3, while a separate compressor supplies cathode air in Concept 2. This difference results in Concept 3 being more efficient than Concept 2, since the additional compressor represents an extra power parasite. On the other hand, Concept 2 has an advantage of being modular, i.e. the fuel cell can operate independently of the turbine at a reduced power load. Since high efficiency is the primary goal of the program, Concept 3 is a better solution of the two concepts. Concept 2 will likely be eliminated in the system down-selection process in the next quarter.

Concept 1 system schematic was modified during the quarter. The air pre-heater, a heat exchanger that transferred heat from the turbine inlet to the cathode air inlet, was eliminated because of material concerns. The required operating temperature of this heat exchanger was above 925°C, which would likely require the use of exotic alloys or ceramics for the heat exchanger construction. In the updated Concept 1, the cathode air is preheated in an in-stack heat exchanger, a feature that will be incorporated into the stack design.

Aspen Plus system models were created during the reporting period to analyze the effects of system parameters on the system performance. The models included the turbomachinery models created earlier in the program and the fuel cell performance model created during the reporting period and described later in the report.

1.1.2 Efficiency Screening Calculations

Concepts 1 and 3 were analyzed to determine parameters that affect the system efficiency. A two-level Design of Experiment (DOE) was performed for each concept to screen for the extent of the effects of each parameter as well as those of any parameter interactions on system efficiency. The average fuel cell temperature was fixed at 800°C. The system efficiency at the peak power point, corresponding to the peak turbogenerator speed of around 65 krpm, was only considered. There is no guarantee that the results presented below would be valid at part-load operating points. However, the system design approach calls for the optimal efficiency at the peak power, therefore the detailed optimization studies will be done only at this design point. The system efficiency sensitivity at part-load operating points will be revisited during the part-load analysis activities. The details of the DOE's for the two concepts are as follows.

Concept 1

Five parameters were identified as having large effects on the system efficiency: the fuel cell current density; the reformer temperature; the fuel utilization in the fuel cell; the recuperator inlet temperature or, alternatively, the turbine inlet temperature; and the reformer steam-to-carbon ratio. The recuperator inlet temperature was chosen instead of the turbine inlet temperature to reflect the turbogenerator subsystem control strategy, where the recuperator over-temperature rather than turbine over-temperature serves as the limiting factor. The following table (Table 1) shows the ranges for each of the variables analyzed in the DOE.

Table 1. Parameters affecting the system efficiency of Concept 1

Variable	Low Limit	High Limit
Current Density, A/cm^2	0.2	0.3
Reformer Temperature, °C	650	725
Fuel Utilization	0.65	0.85
Recuperator Inlet Temperature, °C	600	700
Steam-to-Carbon Ratio	1.5	3.5

The full-factorial DOE was conducted by analyzing the system performance at the 32 different combinations of the system parameters and computing a regression the resulting system efficiency distribution. The outcome is the so-called transfer function, which displays the system efficiency dependence on the main parameters and their interaction, i.e. two-, three-, four-, and five-parameter products. Only statistically significant parameters are kept in the final form of the function, with a 5% confidence level. The analysis was performed using the Parallon 75 performance maps for the compressor, the turbine, and the recuperator as well as the SOFC system-level model utilizing the most recent fuel cell performance data as is discussed below. Some system constraints were ignored at this point to allow more breadth in the analysis. The constraints will be imposed on the system during the optimization studies. The system size was also allowed to float, as the ratio of the fuel cell power to the turbine power was found to be a critical parameter to efficiency.

The ratio of the fuel cell power to the turbine power was found to be a critical parameter to efficiency. The system efficiency is directly proportional to this ratio. Since the fuel cell is more efficient than the turbine, increasing the ratio improves the overall efficiency. However, there are limits to how far one can increase the ratio. These constraints can be attributed the amount of the airflow relative to the fuel cell size and are described by the following parameters: the stack temperature gradients, the turbine inlet temperature, the recuperator inlet temperature, and others. The turbomachinery speed and the turbine and compressor maps determine the airflow. At a fixed speed, the airflow varies only slightly when other parameters change. This also limits variations of turbine power. On the other hand, the fuel cell power was allowed to float with respect to the airflow and therefore, the turbine power, and this proved to be a critical parameter. However, the fuel cell power is an output of the analysis rather than a requirement. It is determined by the parameters listed in Table 1 above.

The regression analysis of Concept 1 yielded the following function:

(eq. v2-1) {presented in EPACT protected volume}

where

η = system efficiency

j = current density

T_{ref} = reformer temperature

U_f = fuel utilization

$T_{rec,in}$ = recuperator hot side inlet temperature

SCR = reformer steam-to-carbon ratio

All of the three- and higher variable interactions as well as some two-variable interactions dropped out during the statistical analysis. In addition, the steam-to-carbon ratio did not affect the system efficiency by itself. However, it was important through two-variable interactions with the reformer and the recuperator temperatures.

Equation v2-1 shows that the efficiency decreases with the increasing current density. This is hardly a surprise, since the efficiency is directly proportional to the fuel cell voltage, which decreases as more current is drawn from the fuel cell.

The efficiency improves with the fuel utilization, i.e. more fuel consumed in the system's most efficient part greatly improves the overall importance. The coefficient of proportionality between the system efficiency and the fuel utilization is less than 1 to reflect the fact that the fuel cell voltage somewhat decreases with the fuel utilization. This is effect becomes more important for very high utilization, as the fuel cell voltage is theoretically zero at 100% fuel utilization. There is in all probability an optimal value for the fuel utilization, somewhere between 0.85 and 1, where the efficiency of the fuel cell actually starts to drop with increasing utilization because of a rapidly decreasing fuel cell voltage. However, we do not have fuel cell voltage data for fuel utilization above 0.85 to aid the optimization.

The reformer temperature and the steam-to-carbon ratio in the reformer combine together to affect the steam reformer yield. It was found that the extent of internal fuel reforming in the fuel cell is a critical parameter to the system efficiency. The required extent can be controlled primarily by the reformer temperature and by the steam-to-carbon ratio. The actual achievable extent depends on many parameters, for example the cell and stack design, the operating point, thermodynamic parameters such as pressure and temperature, etc. In this analysis, we assumed that the required extent is achievable. As parameters affecting internal reforming become better understood, internal reforming will present additional system constraints. At this point however, we determined that a higher extent of internal reforming is very beneficial to the system efficiency. Since the steam reforming reaction is endothermic, it helps reduce the fuel cell temperature by offsetting the waste heat of the current generating reactions. This reduces cooling air requirements and allows one to increase the SOFC power relative to the turbine power. As was mentioned above, the system efficiency increases with the ratio of SOFC power to the turbine power. We found that higher reformer temperature decreases the required extent of internal reforming and therefore, decreases the system efficiency. This effect is more pronounced at higher steam-to-carbon ratios, as more natural gas is converted externally when more water is present.

The recuperator inlet temperature on the hot side was found to affect the system efficiency as well. It is closely related to the turbine inlet temperature. As the turbine inlet temperature increases, the turbine power increases as well. However, the fuel cell power increases relative to the airflow even more, since the requirement for the airflow rate for cooling purposes reduces. The combined effect is a higher ratio of the fuel cell power to the turbine power and higher system efficiency as a consequence.

Concept 3

Six parameters were identified as having large effects on the system efficiency: the fuel cell current density; the reformer temperature; the fuel utilization in the fuel cell; the recuperator inlet temperature or, alternatively, the turbine inlet temperature; the reformer steam-to-carbon ratio; and the fuel flow rate. The inclusion of the fuel flow rate as an independent parameter underscores the fact that this system a higher flexibility of varying the fuel cell power relative to the airflow rate from the compressor than in Concept 1. In Concept 1, the fuel flow is fixed for a specified combination of the turbine speed and the five parameters listed in Table 1. In Concept 3, the fuel cell is downstream from the turbine, and the fuel cell performance does not directly affect the turbine inlet temperature. This in effect unties the turbine inlet temperature and the fuel flow rate and allows the former to vary. The following table (Table 2) shows the ranges for each of the variables analyzed in the DOE.

Table 2. Parameters affecting the system efficiency of Concept 3

Variable	Low Limit	High Limit
Current Density, A/cm²	0.2	0.3
Reformer Temperature, °C	600	700
Fuel Utilization	0.65	0.85
Recuperator Inlet Temperature, °C	600	700
Steam-to-Carbon Ratio	1.5	3.5
Fuel Flow Rate, lb/hr	80	120

The full-factorial DOE is to be conducted by analyzing the system performance at the 64 different combinations of the system parameters and computing a regression the resulting system efficiency distribution. The transfer function for Concept 3 has not been completed at the time of the report and will be included in the next progress report.

1.1.3 SOFC System Level Performance Model

A SOFC system-level model is needed and used in system design and analysis activities to represent the fuel cell performance in the system. The model's purpose is to predict the most important fuel cell performance parameters to the system design such as fuel cell voltage and power, cathode and anode pressure drops, etc. It is meant to be of a relatively low sophistication level, since we are interested mostly in prediction of effects of fuel cell parameters on system performance rather than a rigorous and accurate description of the processes inside the fuel cell. At the same time, the model should represent enough resolution to enable system trade studies and performance predictions. The model has been written as a Fortran block in the ASPEN Plus simulation environment, and is based on the use of a few assumptions:

- all the cells in the stack are identical;
- the heat loss is assumed;
- the pressure drops across the fuel cell are assumed.

The model predicts the fuel cell voltage, the current density, the fuel cell DC power, and the outlet streams characteristics as functions of the inlet streams characteristics, the fuel and oxygen utilization, and the fuel cell characteristics. The central part of the model is the prediction of the cell voltage based on the current density and all the other system-level and cell-level parameters mentioned above, i.e. the prediction of the fuel cell polarization curve.

An initial version of such a model has been created based on limited single-cell performance data. The model predicts the single-cell voltage as a function of the current density, the reactant pressure, the cell temperature, the fuel and air stream compositions, the fuel and oxygen utilization, and the cell geometry and porosity. A semi-empirical approach has been used, in which cell mass transfer and kinetics phenomena were described analytically, however a few critical parameters were obtained through a regression of experimental data. The model showed a fairly good agreement with experimental data. However, the data used in the regression had limited ranges for the majority of the parameters. Therefore, the model's fidelity is limited at this point, and more test data for model improvement and validation activities is required.

Figures 1-2 below show some of the model's single-cell voltage predictions together with effects of the pressure, the temperature, and the fuel utilization.

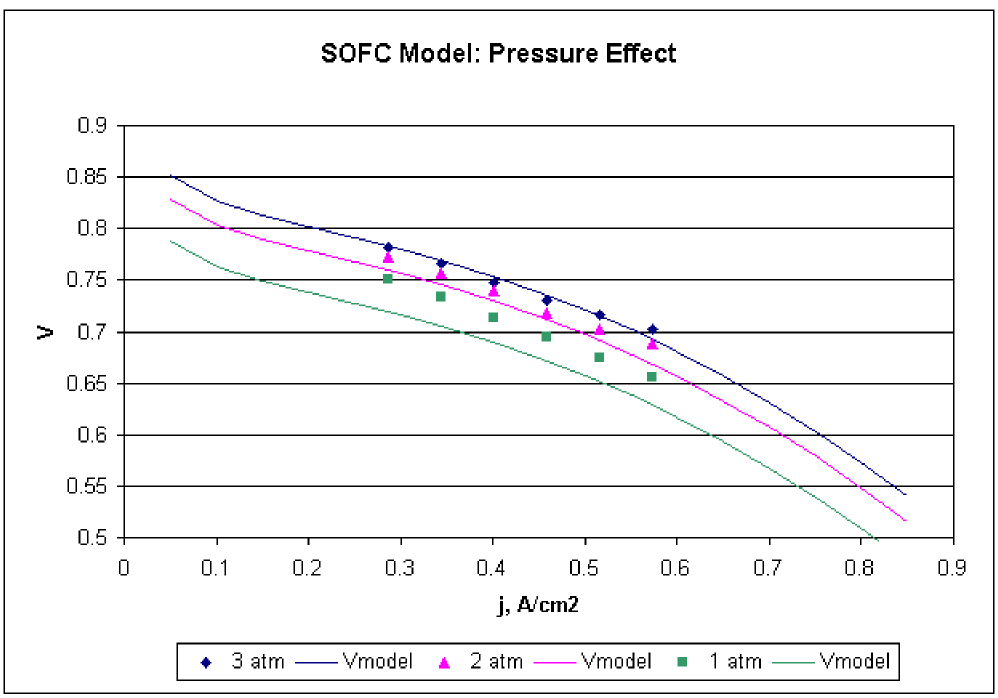

Figure v1-3. Preliminary results of the SOFC near-term model, pressure effect

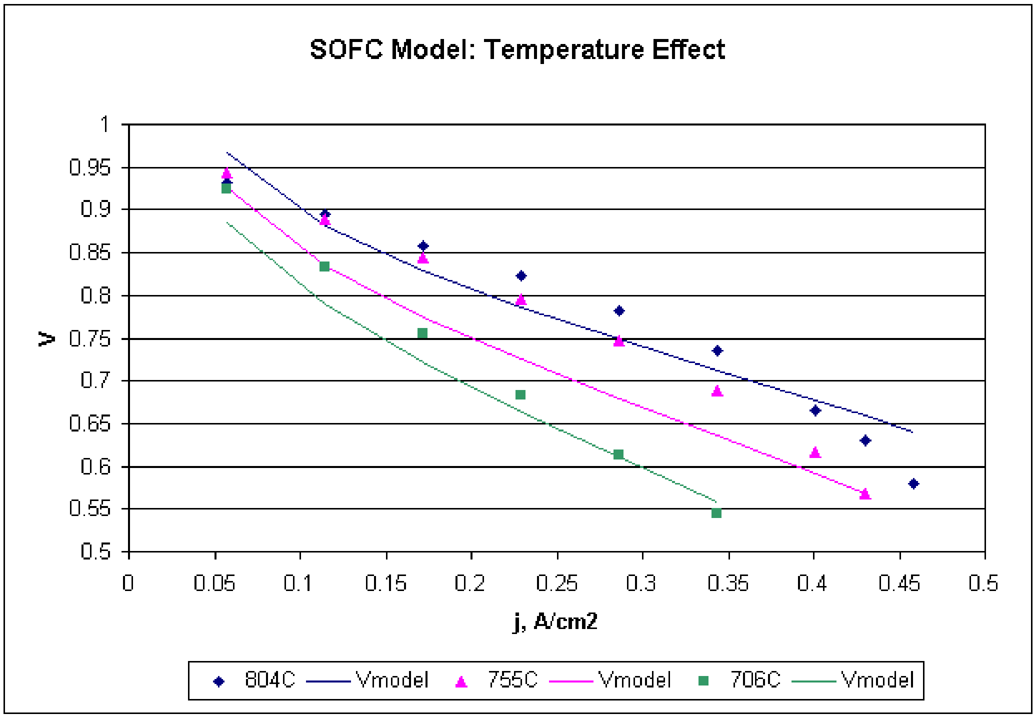

Figure v1-4. Preliminary results of the SOFC near-term model, temperature effect

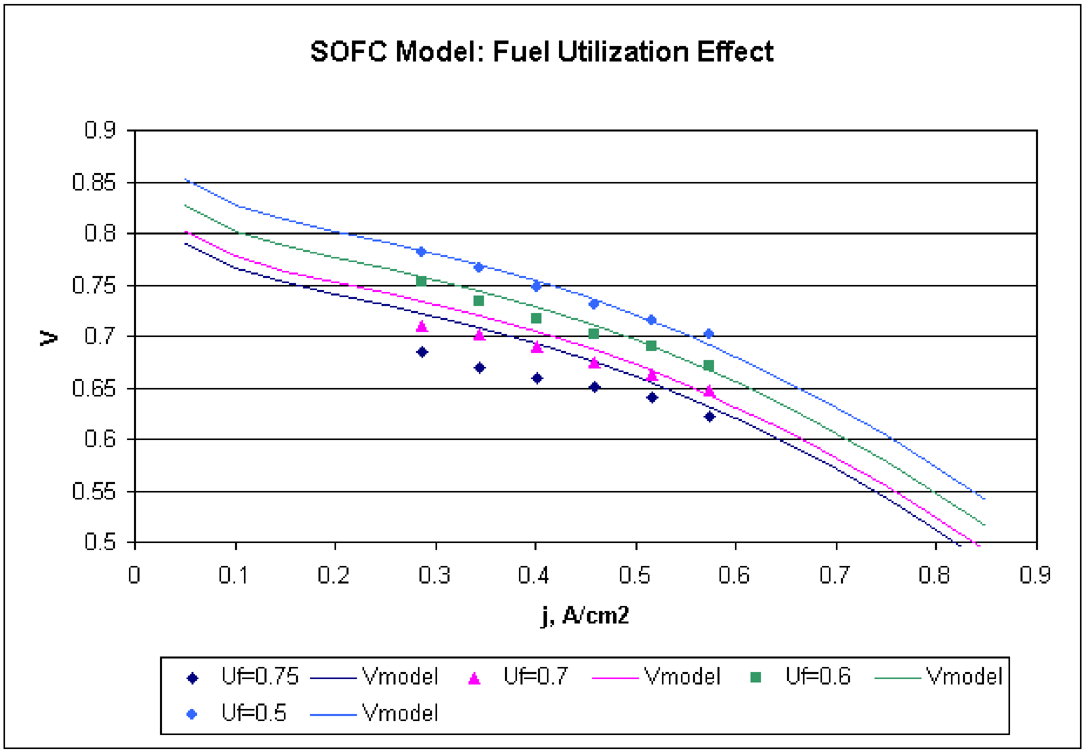

Figure v1-5. Preliminary results of the SOFC near-term model, fuel utilization effect

As Figure v1-3 and Figure v1-4 indicate, the reactant pressure and the cell temperature have positive effects on the fuel cell voltage. Figure v1-5 shows that the cell voltage drops with the fuel utilization. The model does a fairly good job in predicting the trends in the voltage, although its accuracy is still far from being satisfactory. Further improvements and refinements to the model are anticipated as more data becomes available.

1.2 CONTROL SYSTEM DEVELOPMENT

1.2.1 System Control Approach

The control system will provide the operator with the ability to automatically step through the startup sequence, regulate to commanded load demand points, step down through the normal shutdown sequence, perform basic health monitoring of the system, and handle emergency shutdown of the system. A dynamic model of the system is being developed using GE Hybrid Power Generation System's proprietary library of fuel cell system component models, and will be used to design and evaluate various control strategies prior to hardware implementation. The design of efficient controls for the fuel cell system requires consideration of many factors, significantly:

- With potentially wide load fluctuations, the controller should be able to maximize efficiency in different operational regions, and under different operating conditions. These include conditions that occur during startup, steady state operation and shutdown.

- The controller should be able to regulate power and voltage during steady state operation and maximize efficiency at setpoint.

- The controller should be able to minimize thermal stress and fatigue and limit component duty cycles that adversely affect the lifetime of the equipment.

Our baseline approach for the development of a control strategy will be using a combination of feedforward and feedback controls such as those implemented with the transportation PEM Fuel Cell system developed by Honeywell/GE for DoE (Figure v1-6). This control approach employs single loop proportional-integral-derivative (PID) type compensation for improved tracking and disturbance rejection, with a feedforward component that speeds up the system response and takes advantage of the a priori knowledge of system operation. Feedback state estimation is improved through the use of multiple measurement and sensor types where practical. Using this as a starting point, advanced control techniques will be investigated to determine an approach that best suits the performance requirements for the system.

In addition to the basic control functions, the controller will provide built-in test (BIT) and health monitoring around the system. The BIT will monitor sensors throughout the system and trigger alarms to shutdown the system if a sensor exceeds the specified operating range. Corrective and protective action will be programmed into the BIT to handle various failure modes or unscheduled events.

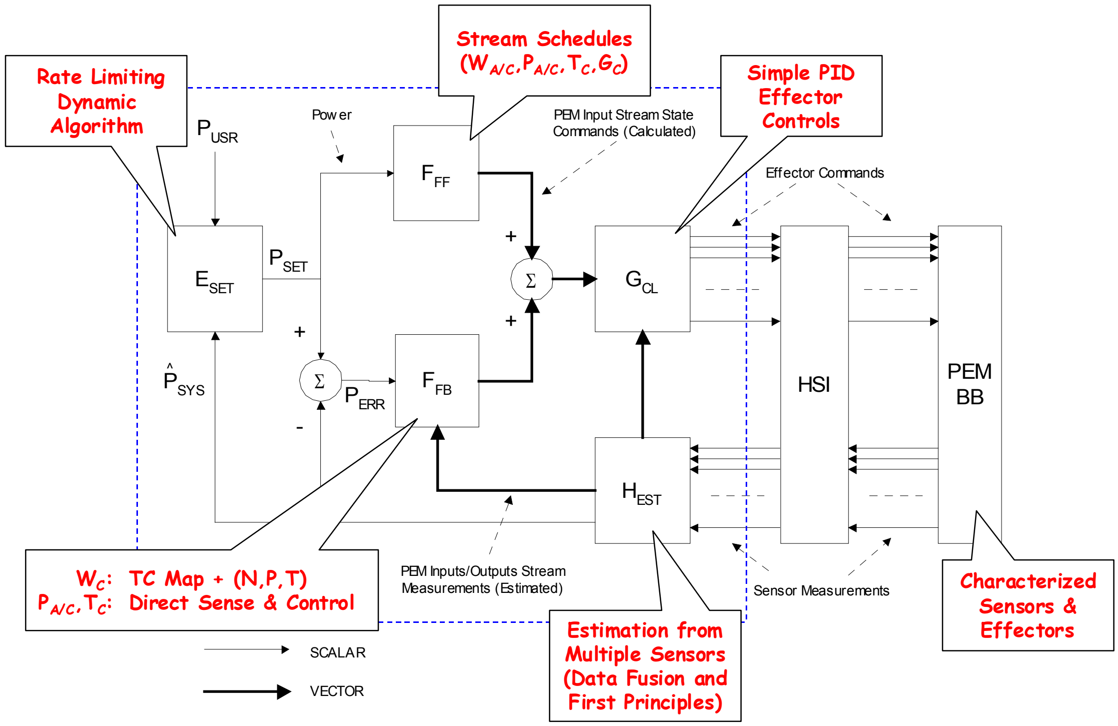

Figure v1-6. Control Strategy from Transportation 50 kW PEM Fuel Cell System Brassboard

1.2.2 Control System Development

A dynamic system model of the conceptual system is currently being assembled using GE Hybrid Power Generation Systems' proprietary Fuel Cell Dynamic Component Library. This model will be used to determine significant dynamic interactions within the system, perform various component and system level trade studies, and to develop the control system design. The model will be updated to allow dynamic issues to be addressed as the system design changes and matures. This approach minimizes costs by reducing hardware tests and the risk of damaging components.

A rapid prototyping system (RPS) will be used as the platform (Figure v1-7) for hardware implementation of the controls developed through simulation. Using a RPS, the same controller used in simulation studies can be automatically coded and downloaded to the RPS for control of the hardware system. Control development cycle times are greatly reduced by using this approach and allow for alternative control designs to easily be implemented in hardware.

A fuel cell system, such as the one being designed, requires integrated control among several subsystems, including the fuel cell, power management subsystem, the fuel processor, and the fuel cell system balance of plant. Use of the RPS will provide for the flexibility of incorporating new control laws and using existing controllers for individual subsystems. Controllers in the fuel processor and power management subsystems can be easily interfaced to the RPS or their functionality can be assumed by the RPS. The RPS will serve as both the supervisory controller for the overall fuel cell system, which interacts with the individual subsystem controllers, and a lower level controller for the balance of plant.

Figure v1-8 shows the design for control process that is being used for controls system development. The controls task is currently in the Controls Requirements Definition process block. During this stage of the process system models are being developed, subsystem models are being developed and analyzed, the control loop analysis is being conducted to determine the dominant dynamic interactions in the system, and preliminary controls requirements are being formalized. Q1 of 2002 has been primarily focused on building the dynamic system model and negotiating with other task teams on requirements for the system and various subsystems.

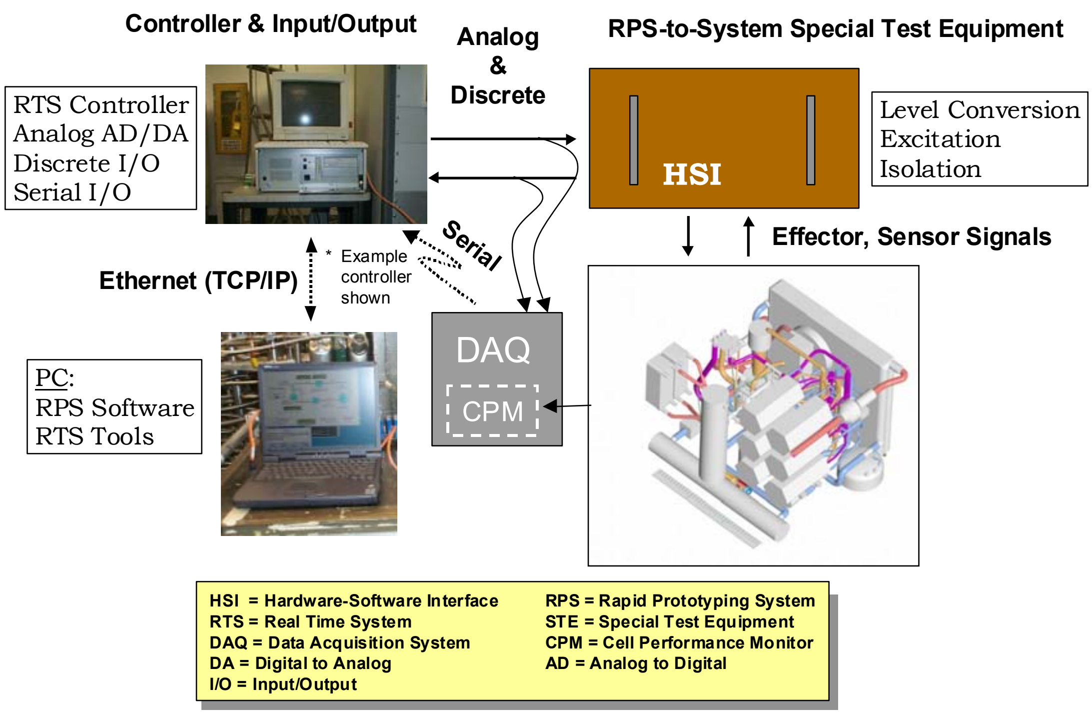

Figure v1-7. Real-Time Control System

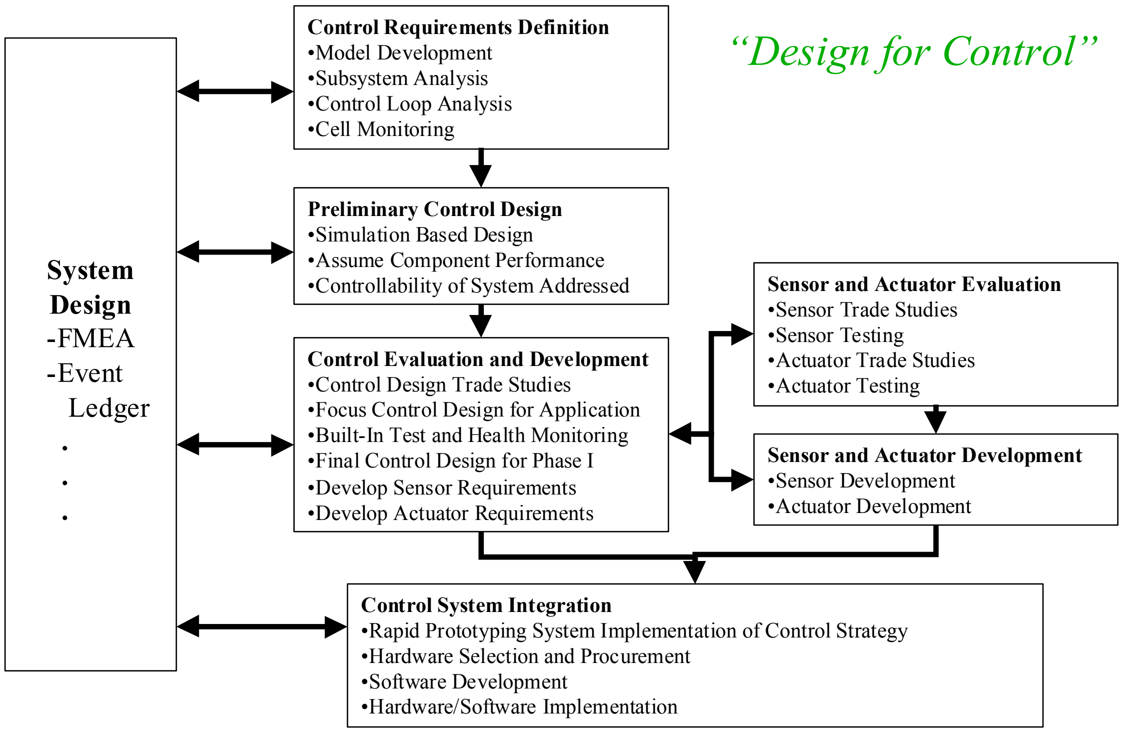

Figure v1-8. Controls Design Process

1.2.3 Sensor and Actuator Evaluation and Development

The proposed fuel cell system will have temperatures as high as 1100°C in crucial portions of the system. To control the system it may therefore be necessary to use high temperature sensors and actuators in portions of the system. The control system design will seek to minimize the use of high temperature sensors and actuators to reduce cost and maximize the reliability of the system.

Sensor and actuator requirements will be generated using the dynamic system model once the preliminary control design is created. Sensors will be evaluated in terms of their dynamic response, accuracy, operating environment requirements, and cost. Where the cost of a sensor is prohibitive for a production fuel cell system, the use of alternative sensors will be investigated as part of an indirect estimation technique to serve a similar function. A sensing strategy will be employed to create a cost effective, accurate, and fast responding set of sensors to indicate the state of the system to the controller.

Actuators will be evaluated in terms of their dynamic response and cost. This evaluation will seek to find low cost production grade valves that meet the temperature requirements for the different points in the fuel cell system. By considering controllability of the system from the initial stages of the system design, the requirements for the actuators in the system can be relaxed and the robustness of the system improved.

The preliminary sensor survey has shown that many off-the-shelf sensors exist that can be used directly or modified for use in the hybrid system. The conclusion of this survey is that sensors should not be a high risk item for the control design, but further work will be needed in this area as the control design matures and cost targets for the control system are addressed. The preliminary actuator survey has shown that while there are many off-the-shelf valves that might fit the conceptual design, further definition of the system is needed before the risk of finding high-temperature actuators can be quantified.

2. TASK 1A.2 – TECHNICAL BARRIER RESOLUTION

2.1 SUBTASK 1A.2.1 – HIGH-TEMPERATURE HEAT EXCHANGERS.

The purpose of this task is to develop, design, fabricate and test a high-temperature heat exchanger capable of operating with high-temperature exhaust gases to heat up the air before it is introduced into the fuel cell stack. A high-temperature heat exchanger was designed for a demonstration hybrid system with 15 kW power. With heat duty of 25.3 kW the air pre-heater heat exchanger operates at temperatures in the range of 450°C to 880°C. It is made of Inconel 625 with volume about 7.5 liters and weight about 15 kg.

In selecting the heat exchanger material, the maximum allowable temperature of metals is a limiting parameter. The yield strength, and oxidation dictate the maximum allowable temperature for a required lifetime. Figure v1-9 shows the yield strength of several candidate metals as function of temperature. Most conventional metals such as stainless steel and nickel alloys have maximum allowable temperatures less than 760°C (1400°F). Haynes 230 can be used at temperatures about 900°C; however, Haynes is an expensive metal. A better candidate is Inconel 625, which is lower cost than Haynes and has a good oxidation resistance at temperatures up to 800°C (about 0.0008 " erosion in 40,000 hours lifetime). A stress analysis will be conducted to determine if the required life is met with Inconel.

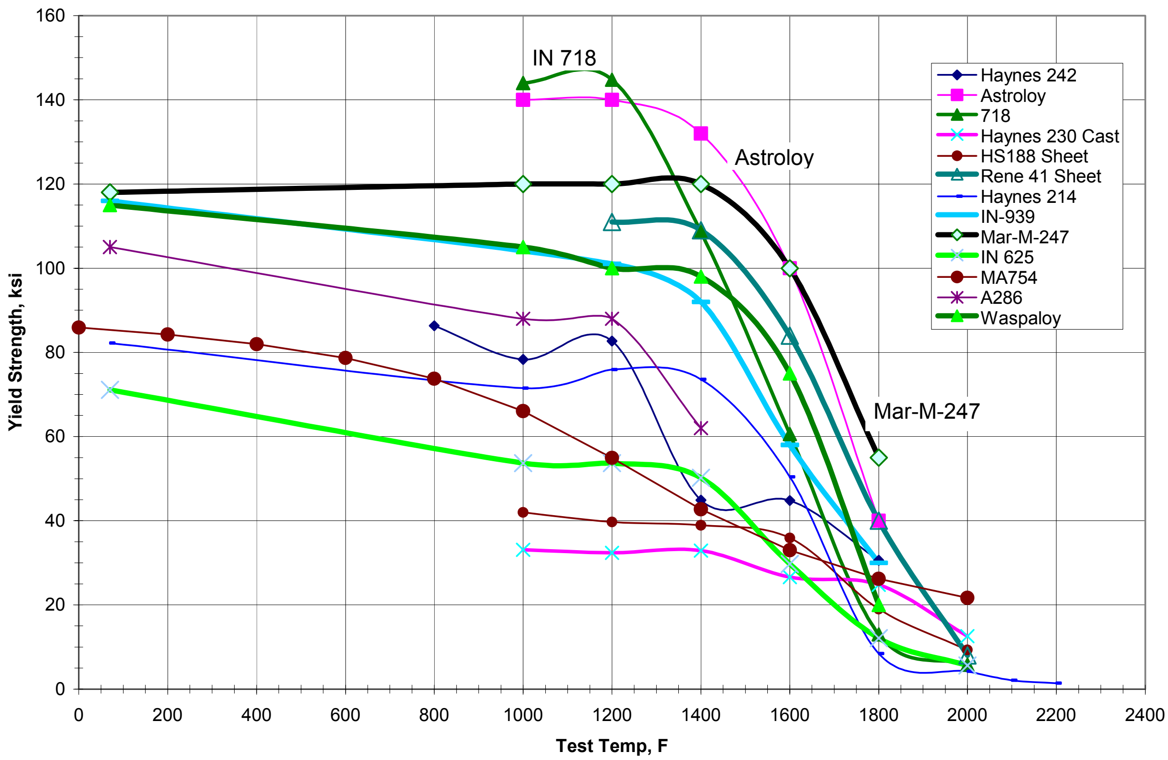

Figure v1-9. Yield strength of several candidate metals for the high-temperature heat exchanger

2.2 SUBTASK 1A.2.2 – PRESSURIZED SOFC

2.2.1 Performance Mapping

Following the feasibility of pressurized SOFC operation, performance mapping is performed to characterize the pressurized SOFC performance under various operating parameters. During this quarter, the effort has been focused on the effect of pressure and flow rate.

A 3" module (RJ012) has been setup and tested. Sixty-four percent hydrogen, balance 36% nitrogen was used as fuel, and air as oxidant. Cell polarization was taken at 800°C under different operating pressures. The flow rates were either fixed or varied with applied current to characterize the pressurized SOFC performance. Figure v1-10 shows the performance with fixed air and fuel flow at pressures from 1 to 3 atms. The max fuel utilization tested at 3 atm was 79% with power density of 0.327W/cm^2 at cell voltage of 0.6V.

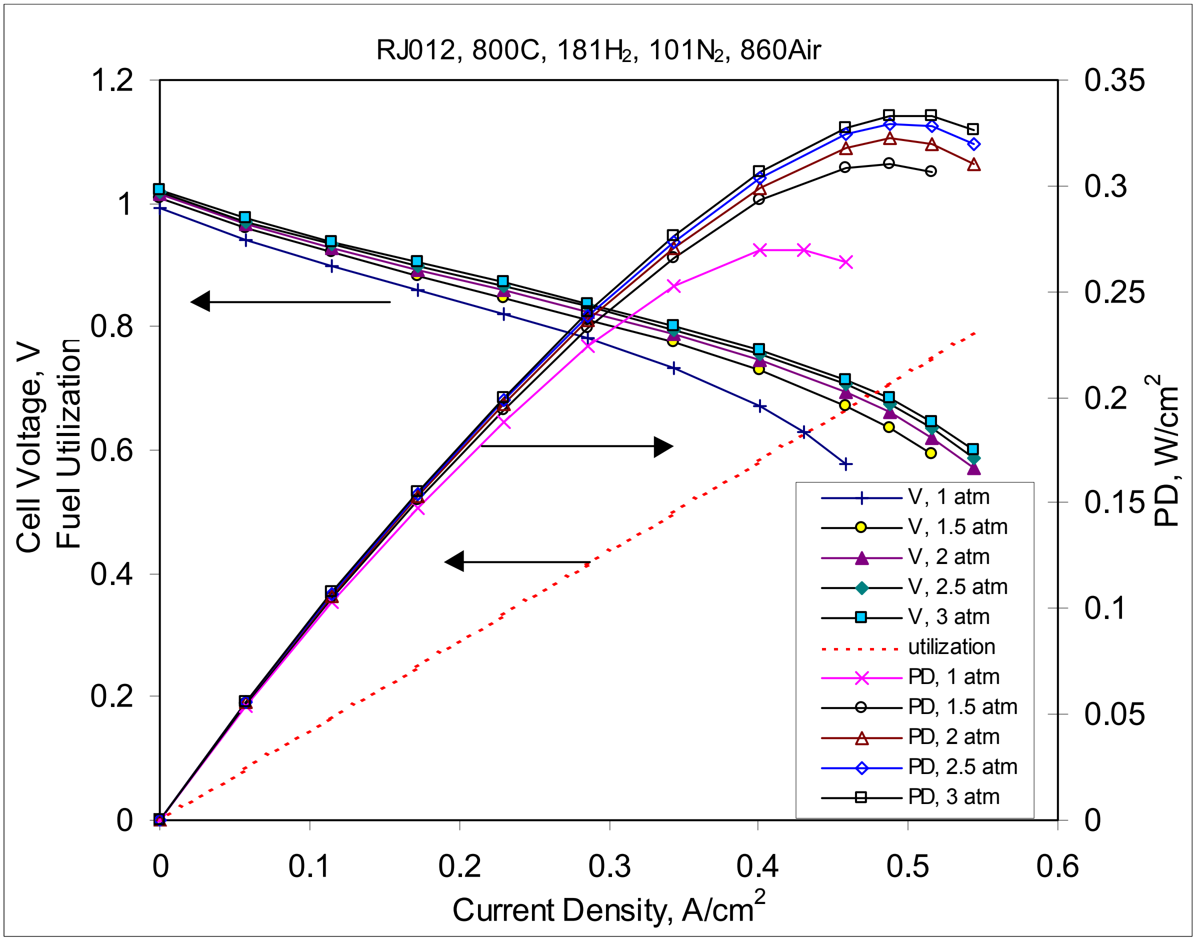

Figure v1-10. Performance of a 3" module (RJ012) under different pressures at 800°C

Cell performance under different fuel and air utilizations was also mapped out as showed in Figure v2-4. Clearly, The higher the fuel utilization, the more pronounced the pressure effect on performance.

2.2.2 Performance Modeling

Performance modeling effort continued during this reporting period. Preliminary modeling initiated during last reporting period was adapted here to fit the performance data at different fuel and air utilizations. The preliminary analysis showed an acceptable fit between the experimental data in RJ012 and the model (Figures v2-5 and v2-6). The model will be continuously optimized to fit and project the performance in the future tests.

2.2.3 Endurance Test

Endurance test effort has been initiated. A 3” model was assembled and under testing. Data will be compiled and analyzed when the test is completed.

Summary

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

- Conceptual system design trade studies were performed
- System-level performance model was created
- Dynamic control models are being developed
- Mechanical properties of candidate heat exchanger materials were investigated
- SOFC performance mapping as a function of flow rate and pressure was completed