Solid Oxide Fuel Cell Hybrid System for Distributed Power Generation

Quarterly Technical Progress Report

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ABSTRACT

This report summarizes the work performed by Hybrid Power Generation Systems, LLC during the October 2002 to December 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 following activities have been carried out during this reporting period:

- Conceptual system design trade studies were performed
- Part-load performance analysis was conducted
- Primary system concept was down-selected
- Dynamic control model has been developed
- Preliminary heat exchanger designs were prepared
- Pressurized SOFC endurance testing was performed

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EXPERIMENTAL

All experimental work currently performed on the program is contained in subtask 1A.2.2, Barrier Resolution -- Pressurized SOFC. The test stand constructed and the test methods used to perform the experimental work for this task has been described in the Quarterly Technical Progress Report for the July 2001 to September 2001 reporting period.

RESULTS AND DISCUSSION

1. TASK 1A.1 – SYSTEM DESIGN

1.1 SUBTASK 1A.1.1 – DESIGN CONCEPT DEVELOPMENT.

1.1.1 Conceptual System Design Trade Studies

The trade studies have focused on identifying the most promising system design based on performance, capital cost and system reliability considerations. Four system candidates were considered as possible system solutions. The approach undertaken in the trade studies consists of the following steps:

(1) The efficiency of all systems is analyzed as functions of system parameters;

(2) A local maximum of the resulting efficiency function is determined;

(3) System components are identified for the candidate concepts (some components may be shared between the candidates);

(4) System cost and reliability models are created;

(5) The reliability and capital cost of the systems is documented;

(6) The system design point is adjusted if necessary to improve system reliability and/or cost at the acceptable expense of system efficiency;

(7) Steps (1) through (6) are repeated until an optimized system design is found for each candidate;

The system with the “best” optimized solution is down selected.

1.1.2 Efficiency Screening Calculations

The system efficiencies of each of the four configurations were analyzed in detail to determine their dependence on the system parameters. The dependence of system efficiency on system parameters for each concept was determined through a Design of Experiments approach in conjunction with regression analysis of the resulting data. An Aspen Plus steady-state performance model was created for each system concept to compute the system efficiency for each point in the design of experiment.

The regression analysis yielded an empirical relationship between the system parameters and the overall system efficiency for each of the four concepts considered. In addition, regressions of other system parameters were also developed for formulating system constraints. The optimal value of the system parameters were determined from the efficiency functions for all four systems by optimizing the efficiency function subject to system constraints.

1.1.3 Concept Down-Selection

Preliminary component requirements were determined for each system configuration based on the system efficiency analyses. Components were then selected, and the system parameters re-calculated based on the component information. Reliability and cost models for the four systems are currently under development. The models are based on the component lists developed during the efficiency optimization analyses. Individual component reliability and mean time between failures will be estimated based on GE's experience with each type of component. The system reliability will then be determined by the system operational sequence. The cost model uses vendor and GE cost data to roll-up the first cost data for each system. Further trade-offs between the four systems will be conducted to determine the optimal system configuration based on the results of the performance, reliability and costs analyses.

1.1.4 System Part-Load Analysis

1.2 CONTROL SYSTEM

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 has been 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. 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.

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 1 shows the design for control process that is being used for control system development. The controls task is currently in the Controls Requirements Definition process block. During this stage of the process subsystem and system 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. The fourth quarter 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.

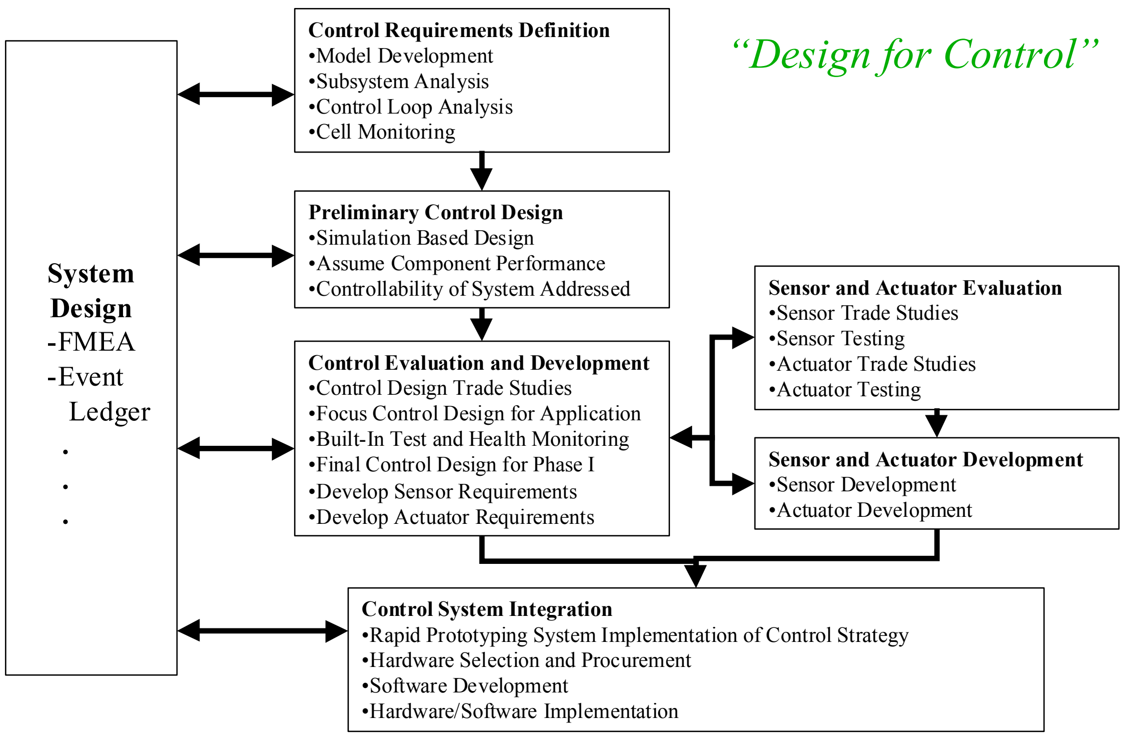

Figure 1: Controls Design Process

1.2.2 Control System Development

A dynamic system model of the conceptual system has been assembled using GE Hybrid Power Generation Systems' (HPGS) proprietary Fuel Cell Dynamic Component Library. The dynamic system model was improved to increase execution speed during Q4. 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.

Work has continued during Q4 in the area of feedback controls development. This work was primarily focused on the SOFC and fuel processor subsystem during Q4 since much of the control system complexity is driven from this subsystem. Work has continued on the supervisory controls in the following areas:

- Key independent variables
- Key System Constraints
- System Startup
- System Operating Modes and Transitions

2. TASK 1A.2 – TECHNICAL BARRIER RESOLUTION

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

The conceptual system design requires four heat exchangers that operate at high temperatures. Preliminary designs of these heat exchangers were presented in the previous quarterly report. In this task, the focus is on the development of a high temperature heat exchanger to understand the feasibility of using such a heat exchanger in the hybrid design.

The thermal design of a high temperature heat exchanger was completed based on the performance requirements of the demonstration system. The specifics of this design are presented in Table 1A.2.1.

Several options for hardware, testing, and analysis were formulated (see Table 1A.2.2). Two different heat exchangers from two partner suppliers were identified as suitable candidates for this unit. The first is a plate fin heat exchanger design made of Inconel 625 with stainless steel fins. The second heat exchanger is a welded plate fin design with all parts made of Inconel 625. As reported earlier, Inconel 625 provides adequate structural properties at temperatures as high as 750 °C. For temperatures higher than 750 °C, Hanes 230 may be used, however, Haynes is seen as prohibitively expensive.

Both heat exchangers will be tested for their performance. Performance maps will be generated for a range of system power level. Performance maps will be used to evaluate the system analysis models.

The heat exchanger's life and reliability will be assessed through coupon testing. Several pieces of Inconel 625 will be tested in a controlled environment of a furnace for their oxidation properties at high temperatures. Continuous testing will be conducted for durations up to 3000 hours. Coupons will be taken out of the furnace at intermediate stages of 1000, 2000, and 3000 hours and will be investigated for the oxidation level as function of time.

In addition to coupon testing, analyses will be conducted to evaluate the life of the heat exchanger at the system level thermal requirements. The analyses will include structural analysis for pressure containment and creep life assessment.

2.2 SUBTASK 1A.2.2 – PRESSURIZED SOFC

In the last quarter, progress has been made in the following two areas:

- Degradation and endurance test
- Performance mapping with methane

The results from these tests are summarized below.

2.2.1 Degradation mechanism analysis

Two approaches are being taken to understand the performance degradation mechanisms for SOFC cells operated at elevated pressures. The frist is to examine cell microstructure, interconnect oxidation thickness, and possible chromium vapor contamination in the cathode after 800 hours of testing. The second is to analyze interconnect oxidation kinetics and possible chromium vapor poisoning mechanisms under pressure. In conjunction, pressure effects on degradation rates are being characterized with more endurance tests.

To support this approach, an RJ026 cell test was planned for 300 hours operation at 2 atmospheres, followed by another 300 hours of operation at 1 atmosphere. The goal was to compare the impact of operating pressure on the degradation rate. The results of this test are shown in Figure 2. It is noted that the degradation rate of RJ026 cell at 2 atmosphere for the first 200 hours is very similar to the degradation of AJ082, tested before. Before the RJ026 cell test reached 300 hours, a power outage occurred in the test cell, resulting in a loss of air and fuel flow to the cell for approximately 40 minutes. After this incident, the degradation rate of the cell accelerated appreciably. The test was subsequently aborted.

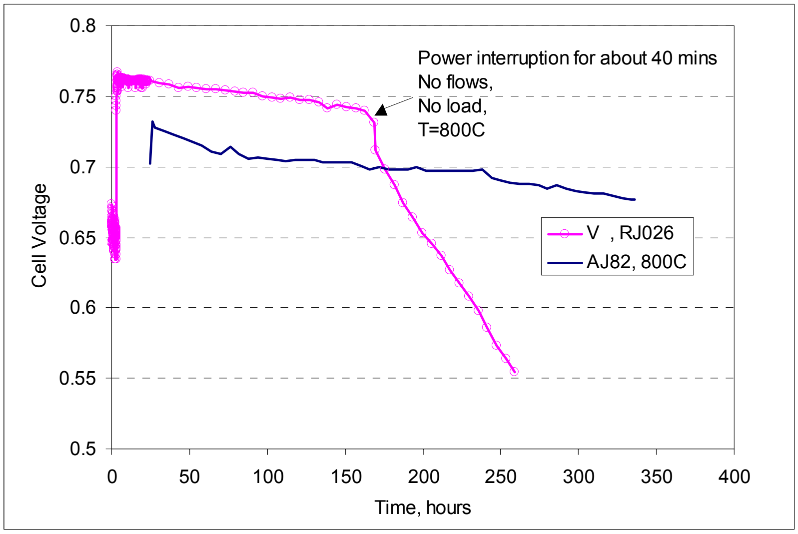

Figure 2 Degradation of RJ026 comparing to AJ082 at 2 atm and 800°C.

2.2.2 Performance Mapping

Performance mapping for this quarter has been focused on methane addition to fuel stream. A cell was first operated with 64%H_2 balance with 36%N_2 as a performance reference point. Then water and methane were added to the fuel stream while hydrogen was kept constant as shown in Figure 3. As 20% water replacing part of nitrogen, cell voltage was lower than that with dry hydrogen. When 9.6% CH_4 was added in to replace more nitrogen, the cell voltage increased a little, especially at higher current density (or higher fuel utilization). Very similar results were observed when the operating pressure was increased to 2 atm as shown in Figure 4.

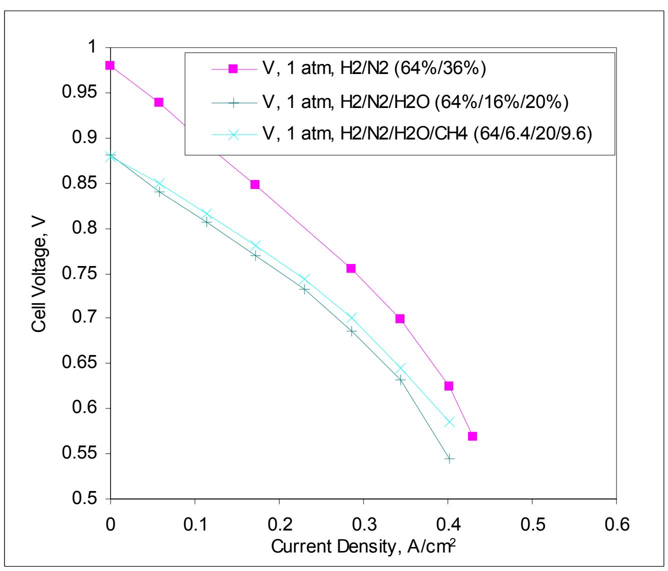

Figure 3: Effect of water (20%) and addition of 9.6% methane on performance at 1 atm.

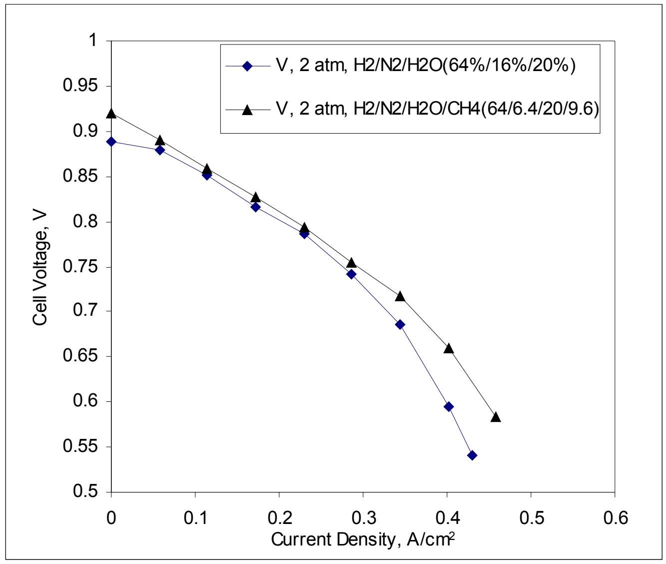

Figure 4: Effect of water (20%) and addition of 9.6% methane on performance at 2 atm.

The cell was also held for a few hours at 2 atm with about 17% CH_4. The cell was also tested under 10A with a hydrogen flow of 71 cc/min. If only hydrogen were assumed as fuel, then the fuel utilization was greater than 100%. This indicates methane participated in the electrochemical reaction either through reforming or direct-oxidation. The cell voltage was noisy during this period, probably due to issues related to water delivery. The degradation rate with methane addition seems faster than that with dry hydrogen as fuel (Figure 5).

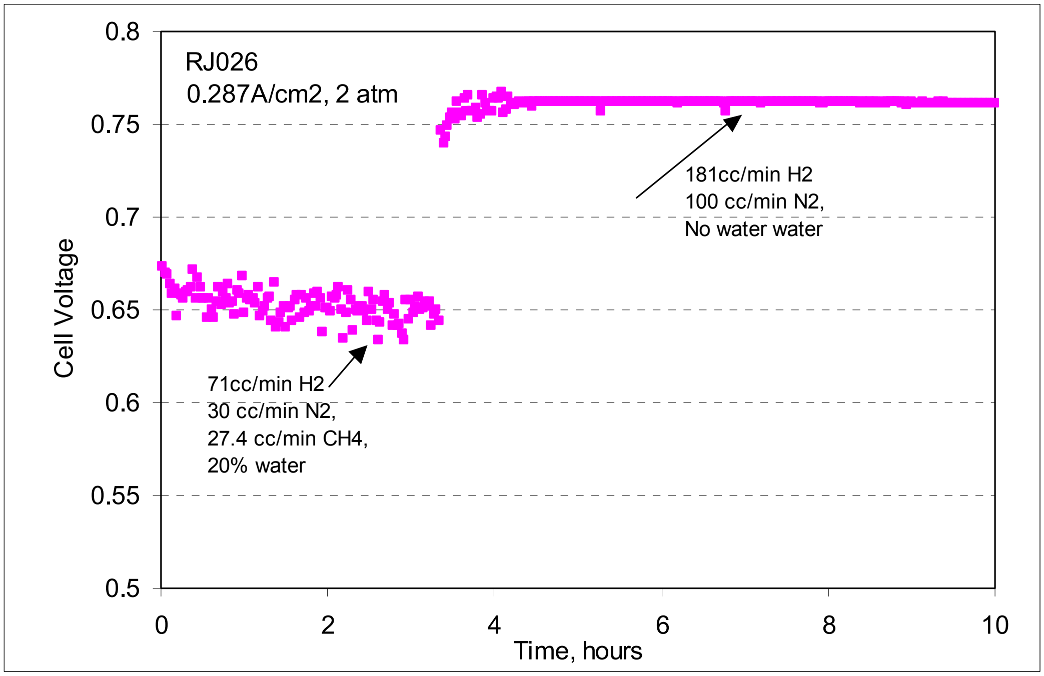

Figure 5. Performance degradation with methane and water at 2 atm, 800°C

CONCLUSIONS

A Design of Experiments approach was used in conjunction with multiple regression analysis to determine the empirical relationship of key system parameters on the overall system efficiency for the four system configurations considered in the system trade study subtask. This relationship was used to determine the system parameters that lead to an optimal system efficiency. The computed optimum system efficiency is then used as one criteria for down-selecting to the most desired system configurations. Other system down-selection criteria include reliability and cost. A dynamic model of the system has been developed to enable the design and evaluation of various control strategies prior to hardware implementation. This dynamic model will be used extensively to incorporate design for control as part of the system trade studies.

Preliminary thermal designs have been completed for all the high temperature heat exchangers in the baseline system. Suitable candidate heat exchanger units were identified for performance testing and subsequent feasibility analysis.

A test lasting over 250 hours at 2 atmospheres was completed to aid with the determination of the SOFC stack performance degradation mechanism. Power interruption part way through the test is likely to have impact the results from the test, as witnessed by an increase degradation rate after the event. The test was subsequently aborted and chemical analysis of the sample is underway. Performance mapping on the fuel cell at pressure is underway. Tests with the addition of water and methane have been completed.

REFERENCES

None