SOLID STATE ENERGY CONVERSION ALLIANCE (SECA) SOLID OXIDE FUEL CELL PROGRAM

Semi-Annual Report
April 2003 – September 2003

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Performed under DOE/NETL Cooperative Agreement
DE-FC26-01NT41245

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DISCLAIMER

ABSTRACT

This report summarizes the work performed for April 2003 – September 2003 reporting period under Cooperative Agreement DE-FC26-01NT41245 for the U.S. Department of Energy, National Energy Technology Laboratory (DOE/NETL) entitled “Solid State Energy Conversion Alliance (SECA) Solid oxide Fuel Cell Program”. During this reporting period, the conceptual system design activity was completed. The system design, including strategies for startup, normal operation and shutdown, was defined. Sealant and stack materials for the solid oxide fuel cell (SOFC) stack were identified which are capable of meeting the thermal cycling and degradation requirements. A cell module was tested which achieved a stable performance of 0.238 W/cm^2 at 95% fuel utilization. The external fuel processor design was completed and fabrication begun. Several other advances were made on various aspects of the SOFC system, which are detailed in this report.

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TABLE OF ABBREVIATIONS

ASR:	Area Specific Resistance
ATR:	Autothermal Reforming
BOM:	Bill of Materials
BOP:	Balance of Plant
CFD:	Computational Fluid Dynamics
CPOX:	Catalytic Partial Oxidation
CSD:	Conceptual System Design
CTE:	Coefficient of Thermal Expansion
CTQ:	Critical to Quality
DC:	Direct Current
DFP:	Design for Performance
DFR:	Design for Reliability
DFSS:	Design for Six Sigma
DOE:	United States Department of Energy
DOE:	Design of Experiments
DTC:	Design to Cost
FMEA:	Failure Mode and Effects Analysis
GE:	The General Electric Company
GE-EER:	GE Energy and Environmental Research
GE HPGS:	GE Hybrid Power Generation Systems
GEPS:	GE Power Systems
GR&R:	Gage Repeatibility and Reproducibility
IPD:	Ion Plasma Deposition
LSL:	Lower Specification Limit
LSM:	Lanthanum Strontium Manganite
NETL:	DOE National Energy Technology Laboratory
OCV:	Open Circuit Voltage
PID:	Proportional-Integral-Derivative Control
POX:	Partial Oxidation
PSD:	Prototype System Design
QFD:	Quality Function Deployment
RBD:	Reliability Block Diagram
S/C:	Steam-to-Carbon Ratio
SEM:	Scanning Electron Microscope
SOFC:	Solid Oxide Fuel Cell
SR:	Steam Reforming
USL:	Upper Specification Limit
YSZ:	Yttria-stabilized Zirconia

EXECUTIVE SUMMARY

This report summarizes the work performed for April 2003 – September 2003 reporting period under Cooperative Agreement DE-FC26-01NT41245 for the U. S. Department of Energy, National Energy Technology Laboratory (DOE/NETL) entitled "Solid State Energy Conversion Alliance (SECA) Solid Oxide Fuel Cell Program". The program focuses on the development of a low-cost, high-performance 3-to-10-kW solid oxide fuel cell (SOFC) system suitable for a broad spectrum of power-generation applications. The overall objective of the program is to demonstrate a modular SOFC system that can be configured to create highly efficient, cost-competitive, and environmentally benign power plants tailored to specific markets. When fully developed, the system will meet the efficiency, performance, life, and cost goals for future commercial power plants.

Technical highlights during this reporting period are summarized below

(i) System Design and Analysis

- A six-sigma performance analysis for a Phase III target of 40% was performed including required variabilities from 13 major subsystem parameters
- A performance variability analysis of the Phase I conceptual system was performed including estimated variabilities from 11 major subsystem parameters
- Four concepts were compared to the baseline system
- The baseline system concept was selected for the conceptual system design (CSD). The conceptual system design task was completed.
- Subsystem cost allocations were revised to meet the Phase I target of $800/kW
- A failure modes and criticality effects analysis (FMECA) for most of the subsystems has been performed
- Part load models for the fuel processor, stack, and inverter have been developed to be incorporated into a system part-load performance model; this will be used to predict the most efficient operational point and the maximum power rated operational point
- Preliminary analysis of a prototype system efficiency was estimated at the 5-kW design point if some "off-the-shelf" subsystems were utilized and the effects on efficiency evaluated

(ii) Cost Estimate

- Subsystem cost allocations were revised to meet the Phase I target of $800/kW
- The stack model was modified to include a capability of specifying the total cell area required of the stack

- A detailed fuel processor model is under development based on a detailed parts-list of the fuel processor to be used in the prototype system

(iii) Stack Technology Development

- Completed the flow field design for the selected go-forward stack concept
- Completed the design of stack test modules for validation of flow field design, manifold design and large stack design.
- About 5% performance loss was found in test modules after switching 64% diluted hydrogen to ATR fuel;
- A 10% performance loss @ 0.4 A/cm^2 and 35% FU was observed in a test module with simulated ATR fuel as temperature was reduced from 800°C to 750°C.
- Stable fuel utilization of 95% was achieved in a test module running in dilute hydrogen (64% H2/36% N2). Two tested modules achieved 80% fuel utilization at 0.7V with a power density >0.290 W/cm^2.
- Cathode processing factors such as cathode thickness, sintering temperature, surfactant incorporation, and particle size, were examined to reduce the polarization resistance of the cathode.
- A sealant material was down-selected and observed in validation tests to meet or exceed the stack sealing requirements through a minimum of 10 thermal cycles.
- Alternative interconnect materials have been identified which show the potential to satisfy the stack resistance and degradation requirements.

(iv) Fuel Processing

- A commercially available catalyst for autothermal reforming (ATR) was evaluated for potential use in the SECA prototype hardware.
- The external fuel processor hardware was designed and fabrication was initiated.
- The ability to internally reform a synthetic ATR reformate stream containing 14% methane was demonstrated using an operating, single cell SOFC at open circuit.
- Models were constructed and used to evaluate potential intracell thermal stress generated by on-anode internal reformation.

(v) Control and Sensor Development

- The dynamic system model for the conceptual system design was completed.
- Control strategies for startup, normal operation and shutdown were completed and verified through simulation.
- The sensor and actuator assessment was completed and incorporated into the CSD design.

(vi) Thermal Management

- Burner concepts have been evaluated and vendors identified for heat exchanger design.

(vii) Power Electronics Development

- The electrical system design for CSD was completed
- The power electronics requirements were completed
- The vendor identification and evaluation was completed
- Orders were placed for two different prototype inverters

1 INTRODUCTION

This report summarizes the work performed for April 2003 – September 2003 reporting period under Cooperative Agreement DE-FC26-01NT41245 for the U. S. Department of Energy, National Energy Technology Laboratory (DOE/NETL) entitled “Solid State Energy Conversion Alliance (SECA) Solid Oxide Fuel Cell Program”. The program focuses on the development of a low-cost, high-performance 3-to-10-kW solid oxide fuel cell (SOFC) system suitable for a broad spectrum of power-generation applications. The overall objective of the program is to demonstrate a modular SOFC system that can be configured to create highly efficient, cost-competitive, and environmentally benign power plants tailored to specific markets. When fully developed, the system will meet the efficiency, performance, life, and cost goals for future commercial power plants.

2 OVERVIEW

The SOFC system under development is a 5 kW stationary power module targeted for residential applications. The system consists of all the required components for a self-contained unit, including fuel cell stack, fuel processing subsystems, fuel and oxidant delivery subsystem, thermal management subsystem, and various control and regulating devices. The system is also designed to be modular and can be integrated to form a larger system. Figure 2.1 shows an example of the concept system.

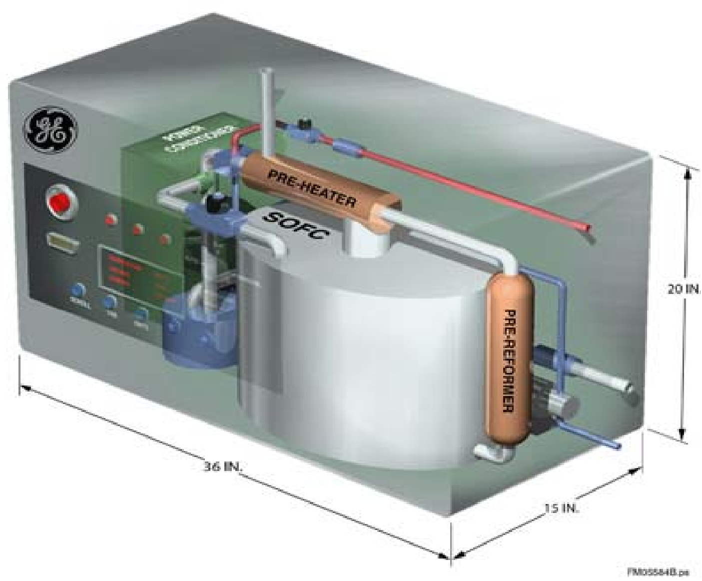

Figure 2.1. SECA System Concept

The key components include a low-cost, lightweight SOFC and a compact, fuel flexible fuel processor, along with thermal management and advanced control subsystems.

The general features of the SECA SOFC program are summarized in Figure 2.2. The Phase I will culminate in a demonstration of a modular SOFC system suitable for operation under different conditions. A specified application will be selected at the beginning of Phase II. Phase II will result in a demonstration of a packages system for the specified application. Phase III will result in field testing of a packaged system for the specified application for extended periods to demonstrate operating characteristics required for commercial power plants.

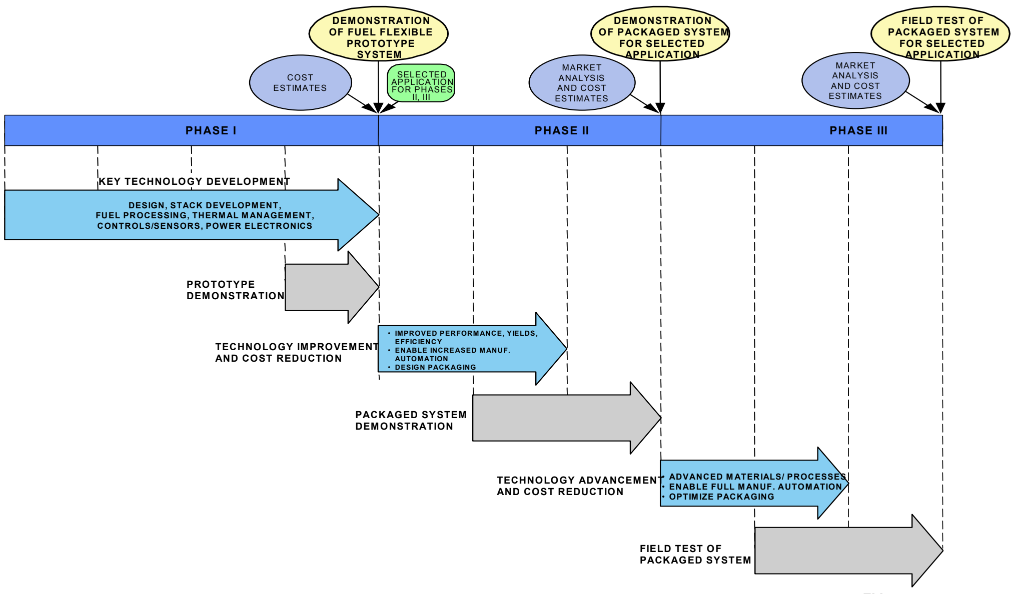

Figure 2.2. Key Program Features

EXPERIMENTAL APPROACH, RESULTS AND DISCUSSION BY TASK

3 SYSTEM DESIGN AND ANALYSIS

Highlights of the system design and analysis task include the following:

- A six-sigma performance analysis for a Phase III target of 40% was performed including required variabilities from 13 major subsystem parameters
- A performance variability analysis of the Phase I conceptual system was performed including estimated variabilities from 11 major subsystem parameters

- Four concepts were compared to the baseline system
- The baseline system concept was selected for the conceptual system design
- Subsystem cost allocations were revised to meet the Phase I target of $800/kW
- A failure modes and criticality effects analysis (FMECA) for most of the subsystems has been performed
- Part load models for the fuel processor, stack, and inverter have been developed to be incorporated into a system part-load performance model; this will be used to predict the most efficient operational point and the maximum power rated operational point
- Preliminary analysis of a prototype system efficiency was estimated at the 5-kW design point if some "off-the-shelf" subsystems were utilized and the effects on efficiency evaluated

3.1 SYSTEM DEFINITION AND ANALYSIS

The system analysis task after SECA Rebaselining planning consists of the following major subtasks:

- Design for Six Sigma (DFSS) Conceptual System Design (CSD)
- DFSS Prototype System Design

The major program milestones resulting from the system analysis efforts remain the same:

Milestone #2:	Design of SOFC System Concepts	Completed
Milestone #6:	Optimization of System Design	due 10/2003
Milestone #11:	Definition of Design of Prototype System	due 8/2004

Milestone #2 was accomplished and reported in a prior report[1] and reviews[2]. This effort used DOE Phase III goals for the design basis.

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[1] Honeywell, Report 01-71698 (12)-2, SOLID STATE ENERGY CONVERSION ALLIANCE (SECA) - SOLID OXIDE FUEL CELL PROGRAM, Performed under DOE/NETL Cooperative Agreement, DE-FC26-01NT41245, Semi-Annual Report, April 2002 – September 2002

[2] Semi-Annual Review, SECA 2003-1-29; SECA *Technical Assessment (audit) at GE Hybrid Power Generation Systems, January 16-17, 2003*

3.1.1 DFSS Conceptual System Design

This task culminates with program milestone #6: An optimized conceptual system design using GE's DFSS process. This effort is aimed at reaching the Department of Energy's (DOE) Phase I goals.

- Performance: existing and projected
- Cost: existing and projected
- Availability: existing and projected.

The output of the process is a validated DFSS CSD, validated by a design a review. While some data is expected by the end of the process (scheduled for 10/2003) to verify the CSD, the design and operation of the prototype system in 2005 will be a more complete verification of the system concept.

3.1.1.1 Define

The DOE established minimum requirements by Phase as given in Table 3.1.1. These requirements form the program targets. The targets are used to derive customer level critical-to-quality (CTQ) attributes as given in Table 3.1.2 for the CSD effort for Phase I. As a result of a meeting with the DOE[3], further clarification of the targets are as follows:

- The minimum system efficiency requirement for the Phase I prototype is 35%; the prototype can be demonstrated at a power level different from the maximum rated power and/or at conditions different from the design points but consistent with the operating conditions for the application will be defined in the test plan.
- Various approaches/modifications can be employed to improve system efficiency of the prototype. However, any cost impact must be taken into account.
- The Phase I prototype system (projected at large volume production) target is $800/kW and calculated at the system's rated power or maximum power.
- Any material or component estimated or projected cost requires rationalization.
- Material cost ($/kg) will be "standardized", and material cost "standards" will be forwarded to the SECA industrial teams.
- Cost estimate for Phase I will not include excess packaging materials (e.g., insulation) and other components included in the prototype solely for test monitoring and diagnostic purposes (e.g., certain sensors not actually used for controls, thermocouples, etc.).

[3] SUMMARY OF DISCUSSION, Meeting at Department of Energy/National Energy Technology Laboratory (DOE/NETL), Morgantown, WV, September 3, 2003

An assumption has been made that costs required for energy storage, such as batteries, do not have to be included in the cost estimate. However, they will not be included in calculating the maximum power rating of the system.

A stationary system is the primary application with natural gas as the fuel. A preliminary “SECA Program Phase I Product Specification” was created to include the DOE targeted requirements for a grid-connected, natural gas application. However, testing could be done using methane or a natural gas surrogate; other fuels to be tested are to be determined at a later date, with propane as a surrogate for a Liquefied Petroleum Gas (LPG)-fueled system.

3.1.1.2 Measure

The conceptual system design will address three major requirements: performance (or system efficiency), estimated cost ($/kW for manufactured costs at 50,000 units/year), and availability (time available for power production during a test sequence). Models identified for development to estimate the ability to meet the requirements include performance, cost, and reliability models, which are described below in the Design section.

An initial SECA Phase I Program Product Specification, revision A, was created to include the DOE requirements for Phase I to include system level targets, lower specification limits (LSLs) and upper specification limits (USLs).

3.1.1.3 Analyze

The Analyze step includes developing conceptual designs allocating performance, cost, and availabilities to subsystems, initiation of variability analyses, and performing risk analyses.

Phase III conceptual system design performance: analysis of a conceptual system design to meet the targeted efficiency for phase III was performed. The conceptual system design (CSD) is targeted at meeting the minimum efficiency requirement (or lower spec limit, LSL), of 40% for the primary application. The design assumes that technologies currently under development in SECA would achieve significant performance improvements and reduction of performance uncertainties. A target system efficiency is chosen here to insure that the 40% efficiency is achieved. The system is composed of the following major elements:

- SOFC Stack
- Fuel Processor (FP)
- Thermal Management (TM)
- Controls
- Power Electronics (PE)
- Reactant Delivery

Phase III Component Assumptions and Performance Analysis: Required component performances to meet the Phase III system efficiency have been analyzed and the resulting system performance calculated.

Key performance assumptions for the stack, fuel processor, thermal management, power electronics, and air delivery components and the effects on system efficiency have been evaluated in terms of "influence coefficients", or the change in system efficiency /change in the selected parameter.

The stack performance sensitivity parameter can be used in development to trade one parameter vs another. For example, if the stack delta-T is found in development to be too difficult to achieve, it can be lowered while increasing the average cell voltage and fuel utilization. Various combinations of cell voltage and fuel utilization can still achieve the targeted efficiency of 41% while reducing the stack temperature increase.

The thermal management components include heat exchangers and insulation for the purpose of heating the reactant streams to the necessary stack temperature level by recovering heat from the hot exhaust streams while minimizing heat losses. The heat transferred has been evaluated for each component.

Design for Six Sigma (DFSS) methodology is used in design to optimize the utilization of available resources in achieving the design goals. In applying DFSS, one metric utilized is a "z-score" for system goals, where z-score is defined as follows:

$$Z = \frac{x - \mu}{\sigma}$$

where X = either the upper spec limit (USL) or the lower spec limit (LSL), μ = the mean of the measurement, and σ = the standard deviation of the measurement.

The specification limit can be either a USL or LSL, or both. The z-score definitions for LSL and USL are defined as follows:

$$Z_{LSL} = \frac{\mu - LSL}{\sigma} \qquad Z_{USL} = \frac{USL - \mu}{\sigma}$$

In applying this z-score to the CSD, the SECA development program is, effectively working on improving the μ and reducing the σ values. For SECA Phase III, the system LSL of 40% is defined by the DOE Requirements. In order to achieve this LSL with a good probability of meeting it, a higher target has been set. Assuming a normal distribution, then if a Z_{LSL} value of 1 is targeted and achieved, then there is an 84% probability of exceeding the 40% LSL system efficiency; if a Z_{LSL} value of 3 is targeted and achieved, then there is a 99.9% probability of exceeding the 40% LSL system efficiency. Such analysis has been performed to insure that the down-selected system design will be capable, with further development, of achieving the Phase III performance goal.

TECHNOLOGY GAPS AND RISKS: This report primarily addresses system and component performance requirements for the Department of Energy's Phase III Requirement of 40% system efficiency. Other important requirements, including cost, design lifetime and performance degradation are not addressed here but will be in the Phase I developmental effort. It should be noted that these requirements are challenging and represent significant risks.

Median performance and variabilities of several components are considered high-risk areas that need development. These parameters form the focus of technology development efforts at GE.

PHASE I Performance Variability Study: For the baseline CSD, analysis was performed to indicate the probability of meeting the system performance goal using a system an ASPEN program model and a Monte Carlo simulation to vary the parameters shown in Table 3.1.1. These estimates were done at the request of DOE for an independent technical audit.

Table 3.1.1 Revised Audit Parameter Assumptions (July 2003) As ASPEN Inputs

SUBSYSTEM/COMPONENT	REVISITED AUDIT ASSUMPTIONS (July 2003)
	PARAMETERS VARIED
A -----SOFC STACK	H2 UTIL
	STACK DT
	ANODE CH4 INTER REFORM. BYPASS FR_0703
B -----FUEL PROCESSOR	STEAM-TO-CARBON RATIO_0703
	C/O Ratio (T calcualted _0703)
C -----THERMAL MANAGEMENT	AIR HEX - cold side dp-psi_0703
	AIR HEX-hot side dp-psi_0703
	FUEL/AIR PREHEATER-hot side dp-psi_0703
	STEAM GENERATOR-Hot Side dp-psi_0703
D -----AIR DELIVERY -	COMPRESSOR ISENTROPIC EFFICIENCY_0703
G -----POWER ELECTRONICS	INVERTER EFFICIENCY_0703

The variabilities of the above parameters were estimated based on expert opinions of those within the HPGS development team. These estimates were done for a system designed to reach 35% efficiency at a 5-kW rated system design point. As noted above, the SECA efficiency goal has been identified to be at an appropriate operational point, which may or may not be 5kW.

Concept brainstorm sessions were held to develop system ideas that increased the probability of meeting the DOE program goals. Many ideas were generated and an evaluation criterion was developed to screen the ideas and compare them to the baseline concept.

After the criteria were established, a six-sigma tool, called a "Pugh Matrix" evaluation tool was utilized to down select to four concepts. The four concepts were analyzed, and the baseline concept was down-selected. The other concepts either offered no performance advantage, or it was concluded that they added unacceptable levels of technical and/or programmatic risk to be implemented as part of Phase 1.

Performance Assumptions (allocations): In order to meet the overall system efficiency goals, each subsystem must perform to a capability. These capabilities have been flowed down to the subsystems.

Cost Allocations: The system level requirement is a manufactured cost of $800/kw. Cost targets have been allocated to the subsystems.

Availability Allocations: The phase I availability apportionment to the major subsystems was determined.

Risk Assessment: A failure modes and criticality effects analysis (FMECA) was performed as outlined in MIL-STD-1629A is being followed. The objective of a FMECA is to identify all modes of failure within a system, the impact to the system if the failure were to occur, and the risk mitigation plan. Over 100 failure modes have been identified and mitigation actions to minimize the risks are being evaluated at this time. Many of the mitigations have resulted in actions such as adding additional sensors or recommended procedures.

3.1.1.4 Design

The design step includes construction of appropriate system and subsystem models required to perform the CSD. Subsystem models for the SOFC stack, fuel processor, heat exchangers and inverter require development beyond that of the generic capabilities in the system model platform, ASPEN PLUS. Other component models within ASPEN are deemed adequate for the CSD.

Subsystem Model Development:

Stack: A stack model was developed that is adequate for system analysis and design. Other more detailed models are being developed both for cell and stack designs. The output is the average cell voltage. This model is incorporated in a “User-Block” in the ASPEN system model.

Fuel Processor: Efforts are focused on four areas: carbon deposition, methane conversion, pressure drop and thermal heat loss. The objective is to develop simple correlations that can be validated with experimental data and integrated into the overall system model.

One of the critical issues of interest in fuel processor design is the effect of carbon formation. Traditionally, equilibrium calculations have been performed to determine the carbon deposition boundary. ASPEN and a National Aeronautics and Space Administration (NASA) equilibrium routines were used to identify carbon prediction regions as a function of temperature, pressure, steam/carbon (S/C) ratios and carbon to oxygen (C/O) ratios. Equilibrium predictions indicate that carbon should not form at the normal operating condition. But it is known that in practical situations, the boundary is determined more by reaction kinetics. Efforts are under way in developing reaction kinetic models and incorporating these models to develop predictive capabilities for carbon deposition boundary. Preliminary results using this approach show that kinetic information could provide a better estimate of the carbon deposition boundary. However, data is required to validate this approach.

Pressure drop through the fuel processor is being developed for an integrated heat exchanger and catalyst as described below in the fuel processor section.

A methane conversion model was developed based on data collected. Inputs to the model include catalyst volume, reactant flow rates, temperatures, pressures and compositions. Outputs include reformate flow rates, temperatures, pressures and compositions plus a temperature profile and warning if the catalyst could reach a temperature that could damage it.

Heat exchangers: A model is required to predict the thermal performance and pressure drops for the heat exchangers. This model will use correlations to predict heat transfer and pressure drop deviations from a selected design. The correlations will be input into ASPEN heat exchanger models that will predict output temperatures and pressures as a function of input flow rates and conditions.

Inverter: A significant parasite on the system is the inverter, which converts the dc power to the desired ac voltage. A simple model, based on vendor data, was constructed to give a predicted efficiency of conversion as a function of outlet ac power produced as shown in Figure 3.1.19.

System Performance Model Development: A system model has been developed for the baseline CSD and is continually being updated and improved. System model results for given subsystem and component performance show a system achieving 35% system efficiency at the design level, 5 kW net ac power. However, as noted above, the minimum system efficiency requirement for the Phase I prototype is 35% which can be demonstrated at a power level different from the maximum rated power and/or at conditions different from the design points but consistent with the operating conditions for the application. Hence, the model is presently being updated to include subsystem models as described above to be capable of predicting part load performances system performances for at least the following operational points:

- The system design operational point
- A maximum efficiency operational point.
- A maximum power operational point which will be defined as the “system rated power’

Part of the design process includes understanding the critical performance factors. Sensitivity analyses for the following parameters were performed for the Phase I CSD.

Stack: The effects of varying the following parameters on system efficiency have been evaluated:

- Cell voltage
- Fuel utilization
- Stack temperature rise
- Pressure drop
- Fuel leakage from anode to cathode
- Fraction of methane feed internally reformed in the stack

Cell voltage, fuel utilization, temperature rise and internal reforming fractions have major impacts on the system efficiency.

Fuel Processor: The effects of varying the steam-to-carbon (S/C) and carbon-to-oxygen (C/O) ratios have been evaluated.

Thermal Management: The effects of varying the pressure drop and heat loss have been evaluated.

Air Compressor: The effects of the air compressor efficiency have been evaluated.

3.1.1.5 Optimize

System trade studies have been performed to optimize the conceptual system design.

3.1.1.6 Validate

The CSD will be validated by performing design reviews, both an external (with DOE) and an internal (GE) review; in addition, a preliminary test plan will be formulated for the PSD to demonstrate key features of the design.

3.1.2 DFSS PROTOTYPE SYSTEM DESIGN

This effort is to commence after the external CDR review is accomplished, scheduled for mid October 2003.

4 COST ESTIMATE

Highlights of the cost estimate task are as follows:

- The stack model was modified to include a capability of specifying the total cell area required of the stack
- A detailed fuel processor model is under development based on a detailed parts-list of the fuel processor to be used in the prototype system

4.1 BACKGROUND AND APPROACH

As previously reported, a thorough, detailed, flexible and modular stack cost model and analysis tool has been developed. A dedicated cost model of the fuel processor has also been created in concurrence with the fuel processor development task; likewise, a dedicated cost model for the thermal management heat exchangers is under development. For the system balance-of-plant (BOP), including air delivery, fuel delivery, water delivery, controls and power electronics sub-systems, cost estimates related to off-the-shelf products or referenced costs have been gathered from vendors or literature and will be used as the basis for a top-level BOP cost model.

4.2 STACK COST MODEL

The stack cost model is a complete cost estimation tool that uses a series of performance inputs and design assumptions and generates a breakdown of materials, equipment, labor and facilities costs associated with stack manufacturing. It includes a stack performance module which converts the performance inputs, i.e. the thermodynamic conditions under which the fuel cell operates, into a polarization curve, which in turn, is used to compute the total electrochemical area needed to fulfill the power and voltage requirements. Along with the design assumptions, this total area is used by the model to calculate stack manufacturing costs. The performance inputs this model requires as assumptions are among those generated in the ASPEN performance model. (A complete description of this model and its capabilities is available in previous reports).

Several steps are used in determining how the materials costs of the stack are calculated: knowing the system power target, the assumption as far as cell performance (represented by a polarization curve) and the operating point on this curve (voltage), allow the user to calculate the total electrochemical area needed for the system. Coupled with the stack and cell designs, this area is used to compute the overall dimension of the system, in terms of number of cells. In parallel, the cost of a cell is calculated knowing the cell composition and its physical characteristics (thickness of the different ceramic layers, cell size,…) and the cost of each of its constituent (obtained as quotes from vendors). For high-volume production, the unit cell cost is coupled with a manufacturing yield projection to generate the overall cell materials cost for a system. Similarly, the stack size computed earlier is used to generate the cost of the remaining items in the stack, knowing, from identified suppliers, the cost references for these ancillary parts.

The manufacturing plan, when coupled with the intended production volume (50,000 units per year) and the system power (5 kW), allows the user to generate the actual manufacturing processes, the equipment requirements and the facility requirements, which in turn allow the calculation of the labor, equipment and facility costs.

The stack cost model that has been created has been designed to accommodate sensitivity analyses through flexibility, modularity and user-friendliness. It is therefore an easily modified tool, where progresses can be recorded as the design gains maturity. The stack concept that is being generated in the scope of Phase I of this program will be the subject of various analyses when the individual costs of its components, related to its specific design, will be completely assessed and understood.

In parallel to this work, different manufacturing approaches are currently being investigated on the basis of the newly generated stack design. These different options will allow the identification of the equipment needed to complete the consecutive manufacturing steps. The costs associated with these pieces of equipment will then be generated based on quotations obtained from vendors.

Ultimately, a manufacturing cost, including equipment, labor and facility costs, is generated and is added to the materials cost to form the total stack costs.

4.3 FUEL PROCESSOR COST MODEL

A detailed fuel processor cost model is under development by GE's GRC-West personnel, who are also constructing the fuel processor to be used in the prototype system. It will include

- A detailed parts list of the existing fuel processor to be used in the prototype system
- An estimate of the required labor to produce the unit
- A scaling methodology to estimate the cost for mass production (50,000 units per year)

The model will be available for use by the end of October 2003.

4.4 THERMAL MANAGEMENT COST MODEL

The thermal management cost model is under development. It should be available for use by the end of October 2003

4.5 BALANCE-OF-PLANT COSTS

The cost references used have been quotes received from vendors for off-the-shelf components or from literature sources. A methodology to scale costs of a component has been adopted for which the performance requirements do not match the ones of a referenced item. A generic top-level transfer function was created based on key performance parameters.

4.6 SUBSYSTEM COST ALLOCATIONS

As given in the System Analysis section above, the subsystem cost allocations to meet the system goal of $800/kW were revised.

5 STACK DEVELOPMENT

5.1 STACK DESIGN DEVELOPMENT

In this reporting period, the task of the stack design development has focused on the design of flow fields and stack test modules to support the development and validation of the circular half-sealed stack concept. The flow fields were designed with computational fluid dynamic (CFD) analysis to achieve cell-level flow uniformity and the required pressure drop for cell-to-cell flow uniformity. A single-cell test module was designed for validation of the flow field design and cell perimeter seal design and the fabrication of the interconnect. A two-cell stack module was designed to validate the compliant manifold design and sealability. An N-cell stack test module design was designed for generic multi-cell stack design up to 1 kW for validation of the stackability and stack performance evaluation.

CFD analysis was conducted to evaluate the flow field designs to achieve flow uniformity and desirable pressure drop, and minimize temperature gradient in the cell, and potentially reduce airflow requirement for higher system efficiency.

5.1.1 SELECTED GO-FORWARD CONCEPT

As reported in the last report period, a stack concept was selected as the go-forward concept. This concept has many attractive features which will enable it to reach the SECA performance levels required.

5.1.2 FLOW FIELD DESIGN

Some requirements for flow field designs are:

- Uniform flow to minimize the hot spot

- Desirable air and fuel pressure drop for cell-to-cell flow uniformity
- Minimized cell temperature gradient

A very promising flowfield design has been generated for the stack concept.

5.1.3 INTERCONNECT DESIGN

The interconnects have been designed for the stack concept.

5.1.4 SINGLE-CELL STACK TEST MODULE DESIGN

Single-cell test modules have been designed to validate the flow field design and the cell seal concept.

5.1.5 TWO-CELL STACK TEST DESIGN

A two-cell test stack was designed to validate the external manifold design.

5.1.6 N-CELL TEST STACK DESIGN

The N-cell stack was designed to be a generic stack for up to 1 kW power generation at the design point.

5.1.7 FLOW AND THERMAL MODELING

Thermal and flow analysis of the downselected stack design are in progress. 3D CFD models for single cell stacks have been built to conduct the analysis.

5.2 STACK AND MODULE TESTING

5.2.1 SOFC Performance with Simulated ATR Fuel

During this reporting period, the composition of simulated ATR fuel was analyzed at different temperatures (600 to 850°C) by using GC (Gas Chromatograph). The test results indicate that an appropriate composition was formed in module tests. There are some small deviations from the ATR fuel composition defined at the nominal system operating point. The simulated ATR fuel has low hydrogen and CO_2 concentration, but relatively high water and CO concentration.

A single cell module with baseline anode was tested at 800°C with diluted hydrogen (64%) and simulated ATR fuel that mimics the expected reformate produced by an ATR fuel pre-processor for the SECA system (a mixture of H_2, N_2, CO_2, H_2O, and methane). The simulated ATR fuel does show some impact on cell performance at these test conditions during the test (see Figures 5.2.1 and 5.2.2). There is about 5% performance loss after switching 64% diluted hydrogen to ATR fuel, which is different comparing with modified anode tested before. There is no significant impact on the performance of modified anode cell with ATR fuel. One possible reason for this is the effect of the microstructure of the anode that may play an important role for the methane internal reforming since there is no methane reforming in the fuel-heating coil.

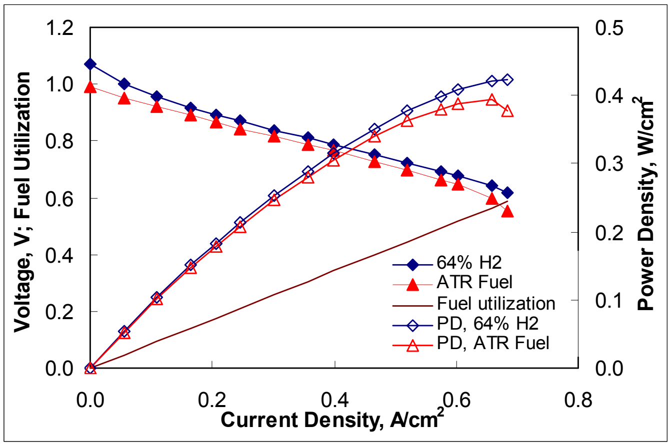

Figure 5.2.1 Performance of single cell module with baseline anode at 800°C with 1 SLPM diluted hydrogen fuel (64% hydrogen balanced with nitrogen) and ATR fuel under ambient pressure.

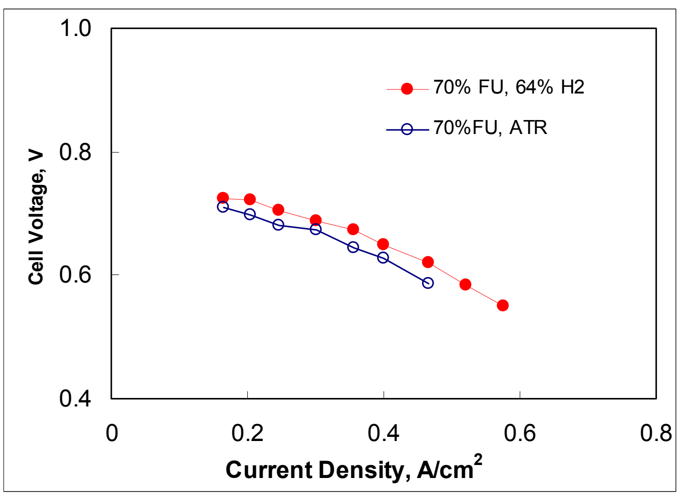

Figure 5.2.2 Performance of single cell module with baseline anode at 800°C under fixed fuel utilization with diluted hydrogen fuel (64% hydrogen balanced with nitrogen) and ATR fuel under ambient pressure.

5.2.2 Cell Performance as a Function of Temperature and Fuel Concentration

During this reporting period, SOFC cell performances as a function of temperature were explored by using a single cell module. The purpose of this test is to repeat the test performed in last report and confirm the effects of temperature on the cell performance with simulated ATR fuel which is critical in evaluating expected SECA stack performance, since significant temperature gradients are expected across the active area of the cell. As shown in Figures 5.2.3 and 5.2.4 the cell performance is a strong function of temperature that is similar comparing the performance data reported in last report. Cell performance (peak power density) decreased about 65% from 378 mW/cm^2 to 133 mW/cm^2 when cell-operating temperature drops from 800°C to 650°C. A 100°C temperature gradient will still cause about 23% performance loss @ 0.4 A/cm^2 and 35% FU with simulated ATR fuel.

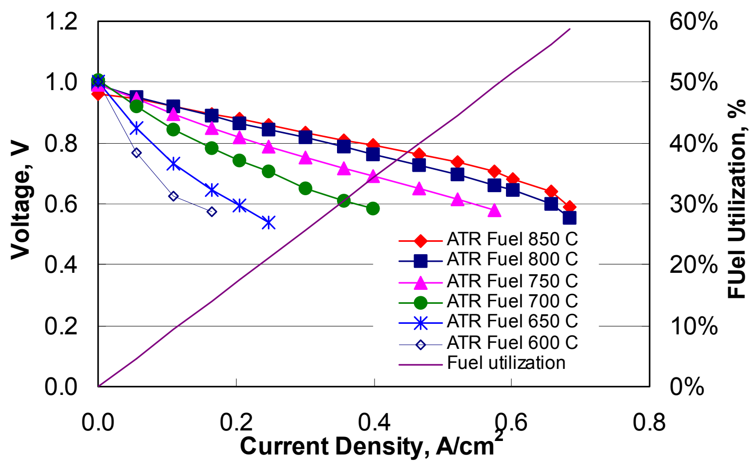

Figure 5.2.3 Performance of single cell module as a function of temperature (from 600 to 850 °C) with simulated ATR fuel and 2.5 SLPM air.

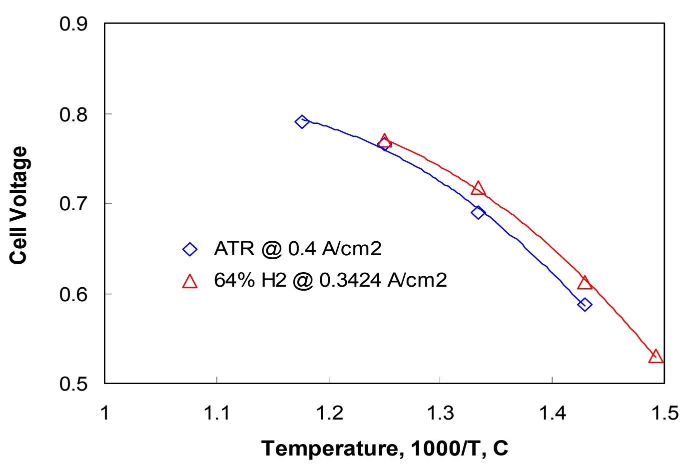

Figure 5.2.4 Performance of single cell module as a function of temperature (from 700 to 850 °C) with diluted 64% hydrogen (30% FU) or simulated ATR fuel (35% FU) and 2.5 SLPM air.

5.2.3 Module and Stack Testing

During this reporting period, several single- and two-cell stack modules were tested to validate the stack design concept. In particular, the results of single-cell modules S201 and S211, and two-cell stack S206 will be reported here.

Single-cell module S211 was tested at 800°C, initially in dilute hydrogen (64% H_2/36% N_2). The fuel-side leakage of the module was tested at temperature with a flowmeter on the fuel exhaust line, and found to be negligible. Polarization curves obtained from this module (and from module S201, which was tested before S211) are shown in Figure 5.2.5. A maximum stable fuel utilization was achieved of 95%, certainly the best ever achieved in a GE module or stack. Note that module S201 achieved a stable utilization of 93% at a very similar performance level, a result which S211 repeated. At this utilization, reasonable performance was achieved: 0.6693 V at 0.3556 A/cm^2, for a power density of 0.238 W/cm^2. At conditions closer to the target operating point of the SECA system, performance was extremely close to the goal. At 80% fuel utilization and a current density of 0.429 A/cm^2, the cell voltage was 0.6898V, for a power density of 0.295 W/cm^2. This compares favorably with the goal performance of 0.300 W/cm^2 at this operating point, when considering that this performance was achieved with a baseline cell. Cells with improved anode and cathode are being developed and will be available for testing in the next reporting period.

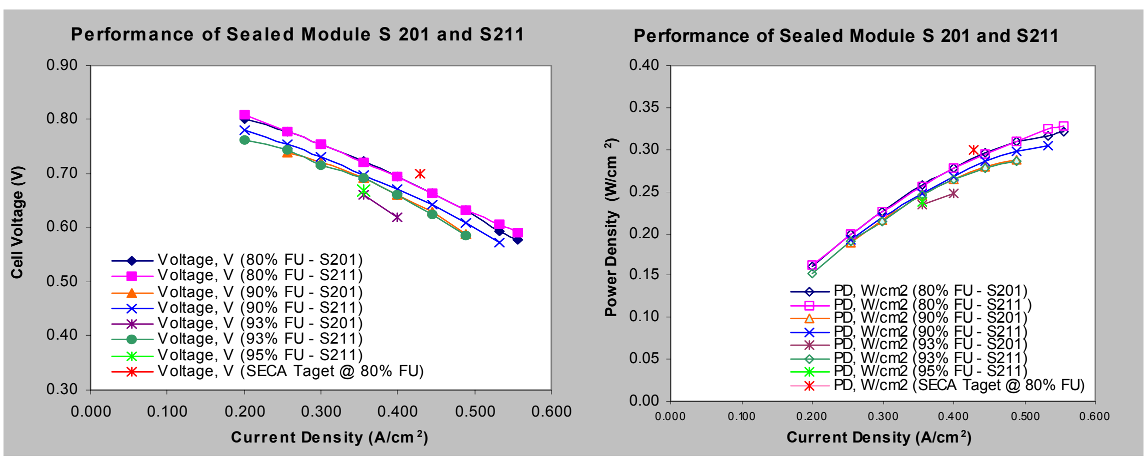

Figure 5.2.5: Polarization curves of square test modules S201 and S211.

Module S211 was also tested in simulated ATR fuel (as described in section 5.2.1) and simulated steam reformate fuel (produced by a similar means). Unfortunately, performance was limited by back pressure from the fuel exhaust line: the water knock-out was poorly positioned and water was condensing in the exhaust, causing severe performance fluctuations at high utilization levels. Some performance data was obtained at 80% fuel utilization in each fuel, and is shown in Figure 5.2.6. The drop-off in performance from dilute hydrogen can be seen, and was more severe than that previously observed in sealless radial modules. The drop in performance was approximately 10% near the target performance level. Modules to be tested in the next reporting period will test this result with a better exhaust line.

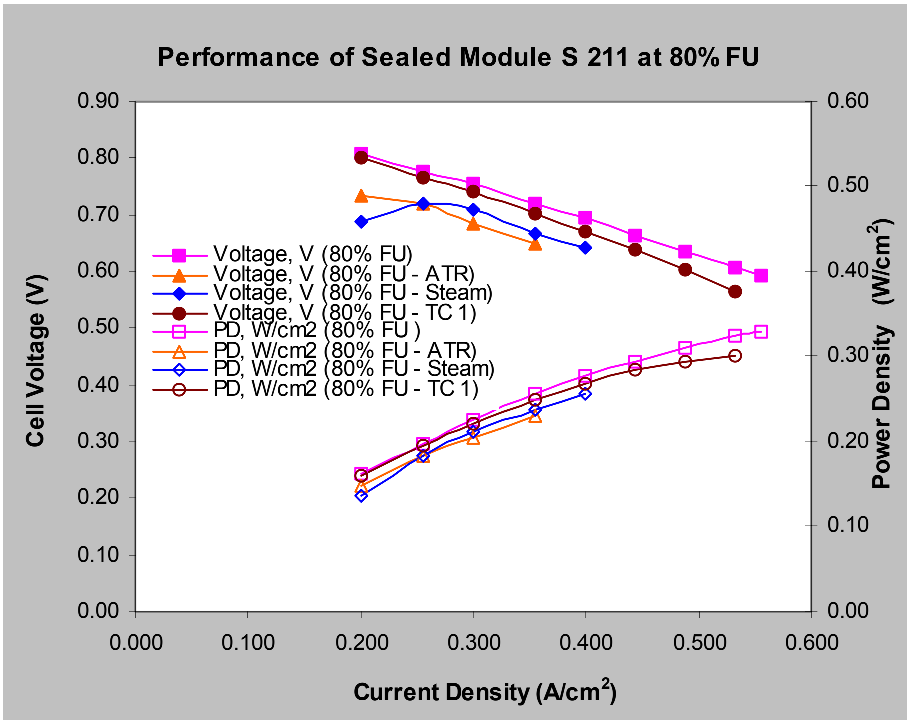

Figure 5.2.6: Performance of module S211 at 80% fuel utilization in various fuels.

A power outage prevented significant thermal cycling of module S211. Module S201, however, survived 10 thermal cycles and could still achieve stable performance at 88% fuel utilization. Cycling degradation was high, close to 1% per cycle; improvements in the seal tape are expected to decrease this value in future tests.

A 2-cell stack, S206, was also tested, with mixed results. The interconnect plates were found to be somewhat warped, which, as it turned out, prevented adequate sealing of the manifold. Despite substantial leakage, 75% fuel utilization could be maintained, although the stack performed poorly (see Figure 5.2.7).

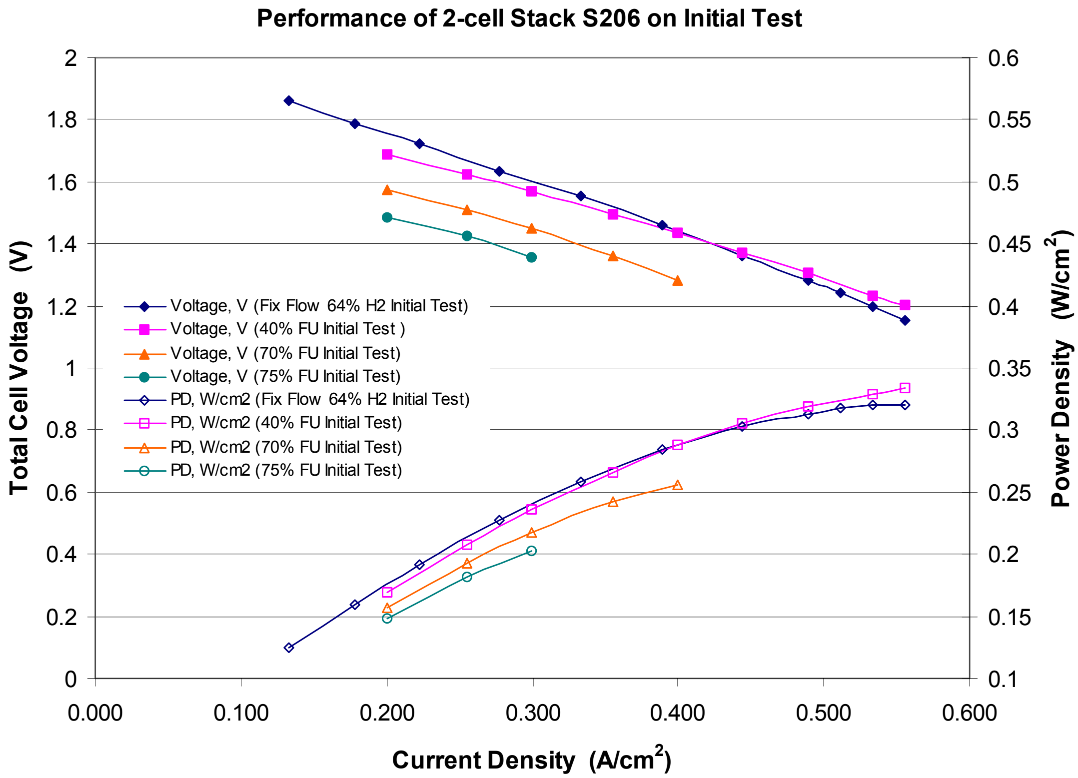

Figure 5.2.7: Performance of 2-cell stack S206.

The results of these modules are very promising to date. In the next reporting period, round half-sealed modules ranging from 1-cell to 1 kW in size are planned to be built and tested.

5.3 CELL DEVELOPMENT

5.3.1 Analysis of Cell Microstructure

Cell microstructure has a strong effect on the performance of anode-supported SOFCs. In order to optimize cell microstructure, increase the robustness of cell manufacture processes therefore improving cell performance and fuel utilization, microstructures of some tested cells were analyzed by using SEM and EDS during this reporting period.

5.3.2 Cathode Development

The objective of this task was to optimize the microstructure of an LSM/YSZ cathode for a low ASR at 800 °C. The single atmosphere air cathode polarization measurement was used to evaluate the performance of modified cathode. The cathode polarization ASR was measured with no bias and a model was developed to extrapolate to the polarization ASR at 0.42 A/cm^2. This method was also used to estimated the cathode ohmic ASR. The advantages of the measurement are that it isolates the performance of the cathode, it has high precision, and it is capable of measuring 3 samples per day in a fully automated mode. The limitations are that the cathode cannot be fully conditioned and the ASR must be extrapolated to 0.42 A/cm^2. Therefore the measurement was used for screening microstructural changes and estimating the magnitude of the effects. The optimized microstructures will be validated in 1 inch button or 4-3/8 inch cell tests.

The single atmosphere air polarization measurement used a symmetric cathode specimen with 1.44 cm^2 of cathode on a 150 μm yttria-stabilized-zirconia (YSZ) substrate. The AC impedance was measured between frequencies of $1x10^5$ Hz and 0.01 Hz. The polarization ASR was determined from the difference between the high frequency and low frequency intercepts with the real impedance axis on a Nyquist plot. The high frequency intercept with the real impedance axis was taken to measure the ohmic resistance of both cathode pads and the YSZ substrate. The cathode ohmic resistance was determined by subtracting the resistance of a typical YSZ substrate. A measurement system analysis showed that there was a relative standard deviation of 2.5% for 6 repeated measurements on the same sample and a relative standard deviation of 4.5% for measurements of 6 identical samples.

Several processing factors such as cathode thickness, sintering temperature, surfactant incorporation, and particle size, were examined in order to reduce the polarization resistance of the cathode.

As a result of the identification of critical processing parameters, a set of designed experiments was planned and will be performed for the next reporting period.

5.3.3 Low Cost Cell Materials

In this reporting period, work has been focused on two areas: impact of the low cost materials on fabrication scale-up and initial performance. Long term performance stability is planned in the future.

5.3.3.1 Fabrication Scale-up

One concern with low cost YSZ in the anode is the fabrication ability because the low coat YSZ usually contains higher impurity and the particle size is rather larger. Typical impurity species and levels (wt), and particle size from one of the low cost alternatives are listed below:

SiO_2: 200 ppm
Fe_2O_3: 600 ppm
TiO_2: 1100 ppm
Al_2O_3: 3900 ppm
Particle size (d50): 8.9 micron

Bilayers with low cost YSZ in the support anode were made and scaled-up to 4"3/8 and the sintering rate and cell flatness are comparable to those cell made with baseline materials with low impurity and fine and controlled particle size.

5.3.3.2 Performance Verification

Design of experiments were performed. Single cells performance with low cost materials were evaluated. Statistically, the results indicate that low cost materials have no impacts on 1” single cell performance in the tested periods. For this reporting period, effort has been focused on performance verification with larger cells with 4”3/8 footprint. Two cells have been tested. Shown in Figure 5.3.1 are the polarization curves of two cells with low cost anode in comparison with a baseline cell tested under constant air and fuel flow rates. While the long term performance needs to be evaluated, the initial performance is very good.

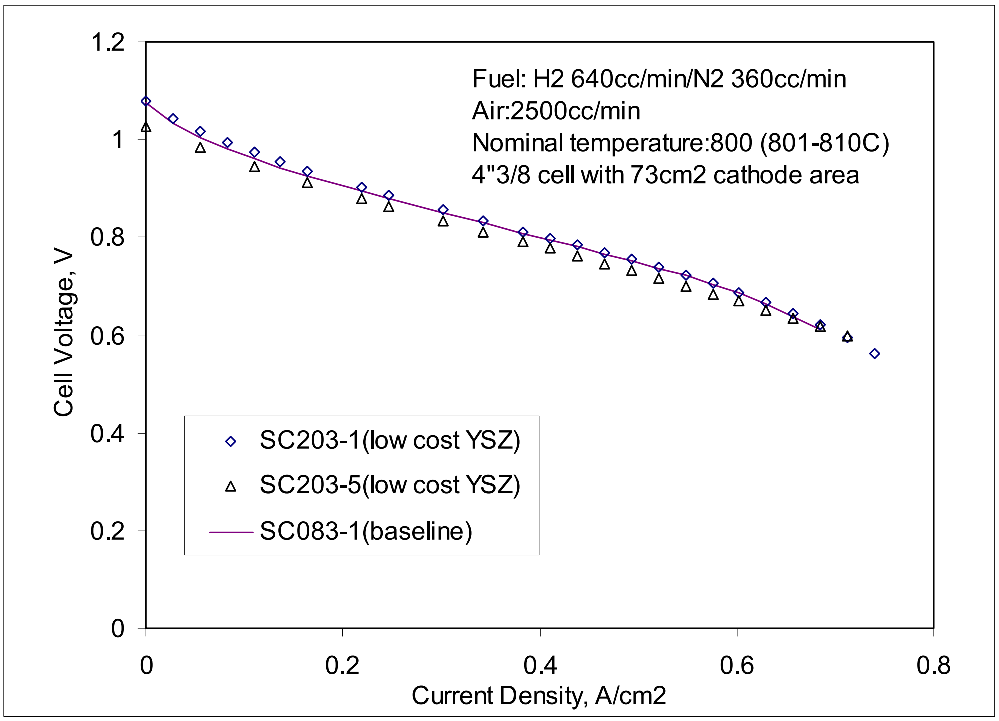

Figure 5.3.1: Polarization curves of low cost cell in comparison to baseline cell.

Those cells with low cost YSZ in anode were also characterized under different fuel utilization. Shown in Figure 5.3.2 are polarization curves under constant fuel utilizations of those two modules with low cost anode. Again, the performance is comparable to baseline cells.

While the initial performance was good, slight performance decay was observed in these modules. More module tests and post-test analysis are in progress to identify the potential causes.

In addition to the electrochemical performance evaluation, samples were also prepared for mechanical strength measurement. Those results will be available in the next reporting period.

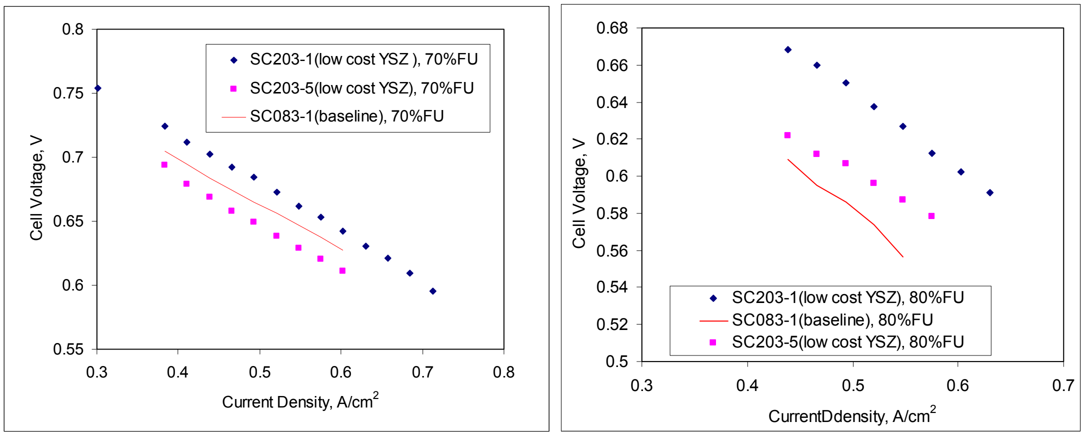

Figure 5.3.2: Cell performance under constant fuel utilization.

5.3.3.3 Mechanical Strength Improvement

Effect was also put to improve the mechanical strength of the cells. Since anode supported cell will be used, the anode mechanical strength is critical to the overall cell strength.

5.4 STACK MATERIALS DEVELOPMENT

In this reporting period, progress has been made in seals and interconnect materials development.

- Seal materials have been down-selected and seal capability is being established. Temperature and pressure capability was also characterized. The down selected seal was also applied to stack module tests which achieved the gas tightness and high fuel utilization.
- Several alloys have been down selected for SECA application. Cr transport, oxidation behavior and ASR change with time were characterized. Based on ASR data, three selected alloys showed much better oxidation resistance than baseline materials. Coating approaches were also initialized.

5.4.1 Sealant

In this reporting period, the seal denoted as NS7 was down-selected as the seal material for the SECA stack design. A series of sealing leakage and thermal cycle tests on 1” cells have been conducted and all met or exceeded the design leakage specification requirements. Properties of NS7 glass were characterized by a variety of techniques. The seal was also used on the single cell modules, in which the seal achieved complete gas-tightness during heating-up and the following two thermal cycle operations. The modules were able to reach 93~95% fuel utilization, another indicator of gas tightness.

5.4.1.1 SECA Sealing Requirements

The primary sealing requirements are:

- Low leakage rate
- Thermal cyclability
- Chemical stability
- Electrical Insulating

The leakage rate requirement depends on stack design, stack efficiency requirement, and location of the seal materials.

5.4.1.2 Seal Materials Down-Selection

Several sealing approaches were considered and evaluated for SECA stack application. Based on the test results, NS7 was down-selected as the sealing materials to be further studied for SECA stack sealing solution.

5.4.1.3 NS7 Sealant Development and Characterization

In order to better understand the sealing behavior of NS7, a series of chemical and physical characterization was conducted on the seal.

5.4.1.4 Sealing Temperature Capability Study

The temperature capability (maximum allowable operating temperature) of current NS7 seal has become a critical parameter for stack and system design,

In summary, NS7 glass seal, which seals 1” cell anode to ebrite, successfully demonstrated acceptable pressure holding capability at 850^{o}C for the test time without obvious pressure decay.

5.4.1.5 Fuel Cell Test with NS7 Seal

Two single cell modules with NS7 seal were tested (see Section 5.2 for more details).

Both tests achieved 100% anode gas-tight sealing for two thermal cycles and maximum fuel utilization was 93~95%. Prolonged tests revealed some leakage in the seal, which was later determined to be caused by metal deformation rather than seal itself. Testing of sealed fuel cell performance with modified cell module design is in plan, and long-term stability test of NS7 in wet hydrogen is in progress.

5.4.2 Interconnect

For interconnect materials, efforts have been focused on evaluating ferritic stainless steels and coatings on metals.

5.4.2.1 Alloy Development and Evaluation

Improvements have been made in oxidation-driven ASR degradation behavior through ferritic stainless steel alloying. This includes both experimental alloys and semi-commercial alloys Crofer22APU (VDM Thyssen), ZMG232 (Hitachi), and 20Cr-5W steels (Sumitomo). Evaluation includes the Cr volatility measurement, oxidation resistance test, and ASR measurement.

In the Cr volatility evaluation, Cr evaporation rates as a function of humidity was characterized.

Oxidation resistance and ASR of candidates were evaluated in air. The metal was first oxidized for times ranging from 400 to 1300 hours. The samples were then characterized with ASR measurement, oxidation thickness, oxide scale composition and morphology analysis. In all the cases, the candidate alloys performed better than the baseline alloy, especially after oxidization at higher temperature, 850°C.

Evaluation on these alloys suggests acceptably low ASR values may be achievable in the 700-850°C temperature range under SOFC cathode-side environment in 1500 hours operation.

6 FUEL PROCESSING

Considerable progress has been achieved in the area of fuel processing during this reporting period. Work in this area has been performed in the development of the external fuel processor and internal reformation within the SOFC stack, as well as further improvement of test capabilities within GE. At the beginning of this reporting period, commercially available autothermal reforming (ATR) catalysts were tested in support of the design of the external fuel processor. Based upon the results of these evaluations, various performance models that were constructed from these evaluations, and the requirements of the SECA system, a preliminary design for the external fuel reformer hardware was developed. Subsequent to this process, a formal design review was held in which the hardware design was evaluated relative to the functional requirements of the SECA system. The design passed this review successfully and the hardware is in fabrication as this report is being prepared.

In the area of internal reforming, a number of measurements were initiated in this reporting period with the goal of a better understanding of the inherent methane reforming capability of the HPGS anode and the SOFC cell architecture. Tests were designed and performed that probed both the inherent reforming capability of the anode and the kinetics surrounding this reformation. These determinations were performed initially using a standard packed bed geometry and ground anode catalytic materials. Further work in this area culminated recently in a determination of the internal reforming capability of an actual operating fuel cell that possessed the GE SOFC cell architecture using a surrogate ATR reformate formulation. In addition, modeling work was initiated during this period to better understand the potential thermal side effects of efficient on-anode reformation.

6.1 EXTERNAL FUEL PROCESSOR DEVELOPMENT

As has been reported, an external fuel processor based on autothermal reforming is being developed for the 5 kWe Prototype System. Performance requirements for the unit are influenced by a number of drivers including overall system design, specific needs of the SOFC stack, and the targeted application for the system.

To expedite and facilitate the hardware development process, the unit is being developed using GE's Design for Six Sigma (DFSS) process. Initially, various requirements for the processor based upon the needs of the drivers were tabulated and ranked using DFSS. Next, the requirements were analyzed to identify the design variables that affect them to the highest degree

Armed with the knowledge of the most important requirements of the unit and the most important variables that influence them, candidate catalyst materials were identified and evaluated for the ability to satisfy the performance requirements. A hardware design was developed subsequently based upon the results of the catalyst experiments and the unit requirements. Performance models were developed for the new design and were used to validate the ability to reach required operating points.

6.1.1 Fuel Processor Catalyst Evaluation

In order to verify the performance of the catalyst and to obtain experimental data for the model development, a number of lab-scale catalyst tests were performed on candidate catalyst materials.

Samples were evaluated in a bench scale reactor. The process gases were monitored by mass flow meters. A small accumulation tank was used to prevent pulsation in the steam flow. A thermocouple placed ½'' in front of the catalyst monitored the inlet gas temperature, while a furnace was used to maintain the catalyst at a constant temperature. A gas chromatograph was used to measure the reformate composition and independent infrared monitors for carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4) were used to confirm the gas chromatographic results.

Once the effect of design variables on the performance requirements was established, the catalyst was operated at a single point for 100 hours to determine if there were any short-term degradation effects at the target operating point. An inspection of the level of hydrogen produced during this time indicates that no severe degradation of the performance has occurred over the duration of the test.

Overall, the bench scale catalyst testing demonstrated that the candidate ATR catalyst can meet the performance requirements of the prototype system.

6.1.2 Fuel Processor Conceptual Design and Modeling

A successful design of the fuel processor is one that can utilize system inputs and provide the requisite outputs that enable the overall SECA system to function at the desired operating point and at the desired level of efficiency. Based upon system calculations, a set of component input and output specifications was derived for the fuel processor, and these specifications were used to drive the primary design of the unit. Many of these specifications were listed in the previous SECA semi-annual report.

Once the requirements were fully defined, design variables that affect the requirements were identified and a model of the fuel processor was created. The model facilitated a number of important design operations including: 1) the engineering analysis for the detailed design of the fuel processor; 2) the analysis of the effects of design variables on requirements, and; 3) the creation of a detailed process operations map. Primary design variables implemented by the model are gas hourly space velocity (GHSV), O/C, S/C, and inlet gas temperature into the processor. Primary requirements described by the model are methane slip in the output reformate stream, product gas temperature from the fuel processor, and the maximum temperature of the ATR catalyst.

The model was developed using MATLAB software. The ATR model did not account for coking processes or other mechanisms of catalyst deactivation. Reaction coefficients used in the model will be adjusted after prototype testing.

The ATR process consists of partial and complete oxidation reactions of methane, which are fast and strongly exothermic, and steam reforming reactions involving methane, which are slow and endothermic. The fast oxidation reactions can produce a temperature spike inside the catalyst that is significantly higher than the exit gas temperature. The design and control of the fuel processor must take this into account.

6.1.3 External Fuel Processor Design

Based upon the results of the catalyst testing and the information obtained fro the modeling studies, a design for the external fuel processor was developed.

A fabrication shop that has extensive experience with sheet metal and Inconel fabrication was chosen to build the first prototype of the external fuel processor. The fabrication of the prototype fuel processor is currently scheduled for completion in October 2003.

6.2 INTERNAL REFORMING

The ability to harness and utilize excess waste heat from the SOFC stack is one of the key requirements of a high efficiency SOFC power generation system. Relocation of the reformation process (the endothermic steam reformation process) from an external fuel processing unit to within the intimate boundary of the SOFC stack is one method by which the excess heat can be exploited directly, thereby reducing the need for excess air flow and increasing the overall efficiency of the SOFC system. Thus, the development of materials, approaches, and technologies that enhance and support internal reformation are highly desirable and, indeed, are necessary for a commercially viable SOFC system.

There are a number of different methods for carrying out internal reformation. One of the most straightforward and deceivingly simple is to carry out the reformation reaction directly upon the anode of the SOFC. This is possible since the primary component of the anode is nickel, and nickel is a highly efficient and inexpensive catalyst for steam reformation.

In this reporting period, various aspects of on-anode steam reformation have been examined. Experiments pertaining to the kinetics of the reaction have been performed with the goal of understanding the magnitude and nature of the rate constant to be used in detailed fuel cell models. Tests that measure directly the efficiency of methane conversion over an actual operating cell were performed during this reporting period. Finally, the localized cooling of the fuel cell, was examined in detail to better understand one of the potential challenges of internal reformation.

6.2.1 Measurements of Reformation Kinetics

For this work, experiments were performed with the specific objective of obtaining chemical kinetic information for use in subsequent studies on internal reformation and in performance models generated for the SOFC. One of the most critical uses for such models is in the design and optimization of the SOFC anode so that the final optimized anode microstructure can satisfy numerous cell and stack requirements simultaneously including cell electrochemical performance, cell reliability, and overall cell and stack efficiency. During the past six months, an existing experimental setup was modified and calibrated for studying reformation kinetics.

6.2.1.1 Results of Kinetic Measurements

For the parametric tests, the total flow rate was kept constant and nitrogen flow was used to compensate for the change in pressure. The tests showed the high sensitivity of rate of reforming to methane partial pressure as has been reported in literature. The steam and hydrogen partial pressures had a lower order influence on the rate.

6.2.2 Measurements of Methane Conversion Efficiency

A cartoon depicting the major steps of the methane reformation and conversion process is presented in Figure 6.1. As this figure would tend to indicate, the reformation process is comprised of a number of individual steps, each of which possesses its own set of associated kinetics and governing equilibria. As mentioned in the previous section of this report, studies were initiated during this reporting period to better understand some of these processes in order to lay a foundation for fundamental modeling as well as establish baseline performance levels.

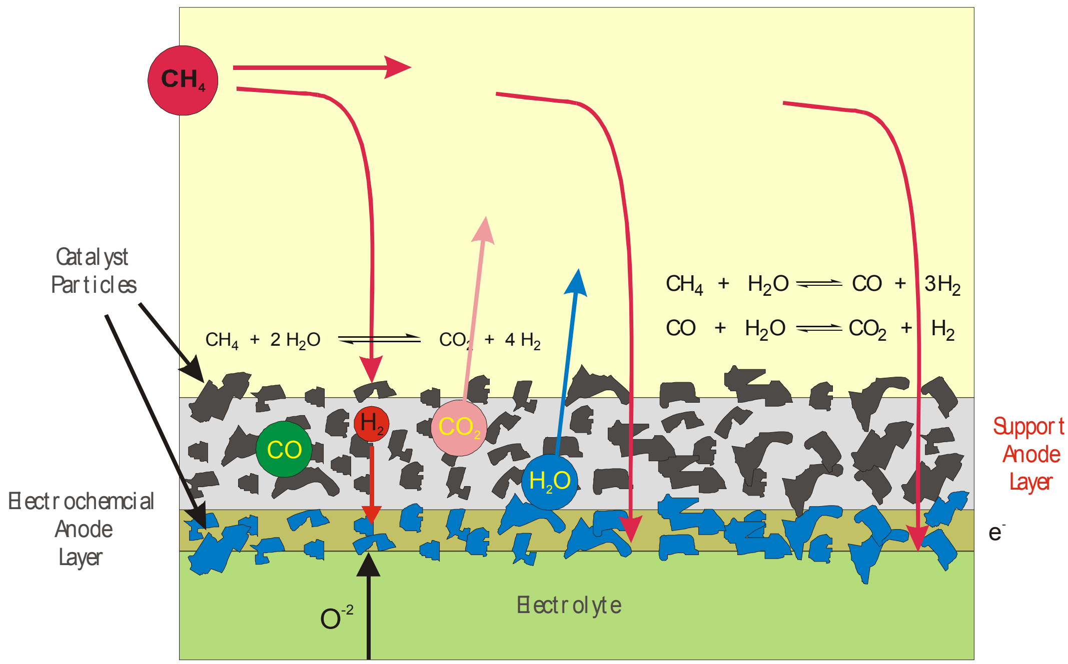

Figure 6.1. Diagram of the Methane Reformation and Conversion Process.

In this section, methane conversion measurements are discussed which explore the capability of the nickel-based anode and support anode materials. Results are reported for experiments performed on ground support anode samples and on an operating SOFC.

6.2.2.1 Evaluation of Anode Materials

To better understand the methane conversion capability of the anode, initial experiments were conducted.

Figure 6. shows the level of methane conversion as a function of time using the surrogate ATR gas stream. After an initial 2 to 4 hour period of drift, the methane conversion was stable at approximately 95% for over 90 hours as shown in the figure. It is suspected that the initial drift was due to an unstable supply stream.

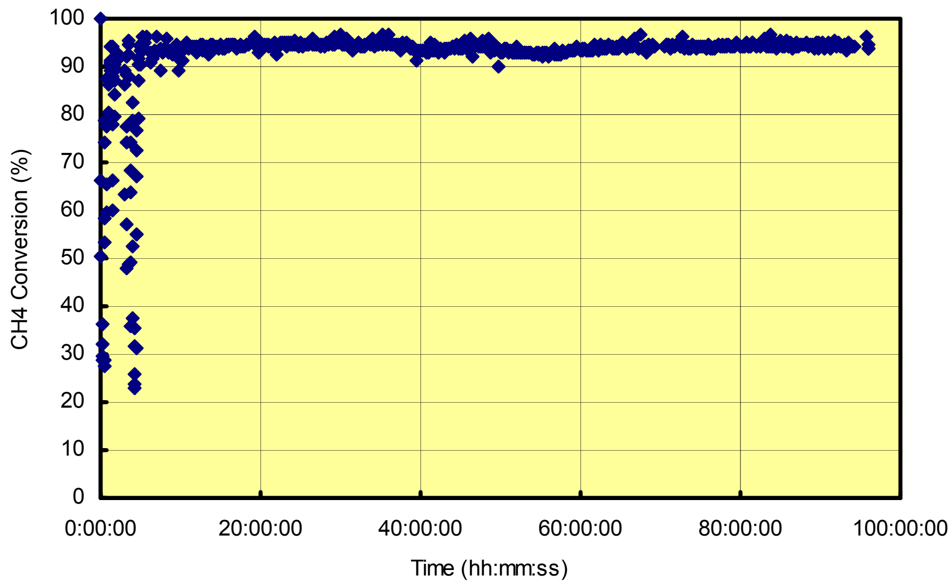

Figure 6.2. Methane Conversion with the Simulated ATR Reformate Stream.

Immediately following this experiment using the ATR surrogate, a gas stream with a significantly higher methane content was introduced into the cell in order to evaluate the potential for on-anode reformation. For this experiment, the gas stream consisted of only methane and steam at a S/C ratio of 1.5. A temporal plot of these conversion data is provided in Figure 6.1. Stable methane conversion (approximately 90%) was also measured for this stream for up to 100 hours. The results of this experiment with the high methane content imply that no external reformation may be necessary for the system running on methane and that a high level of internal reformation can be achieved with fuel streams of high methane content the on-anode approach.

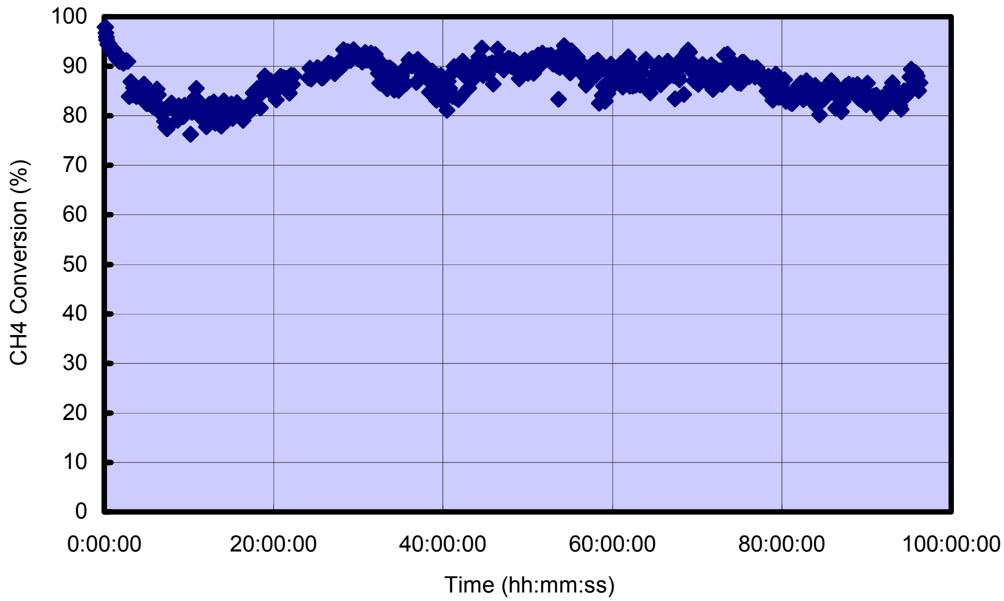

Figure 6.1. Methane Conversion with a Fuel Stream Having High Methane Content.

6.2.2.3 Methane Conversion Measurements on Cells

Toward the end of the reporting period, a series of methane conversion measurements were made on a working single cell, SOFC that utilized on-anode reformation. Measurements were only made with the cell operating at open circuit (no current flow). This case should represent a worst case scenario in terms of methane conversion as no water is formed locally on the anode and no hydrogen is consumed via the oxidation electrochemistry. The cell was a sealed single cell module with an active area of 90 cm^2. Tests of methane conversion were conducted using an ATR surrogate fuel mixture having various methane contents. Flow rates for the fuel mixture fed to the cell were calculated based on an assumed operational current density and fuel utilization although no current was drawn from the fuel cell. Gas samples were drawn immediately before and just after the fuel cell and analyzed using a gas chromatograph. Methane conversion measurements were confirmed both through a direct measurement of the methane loss through the cell (using nitrogen as an internal reference) and through carbon balance calculations. Agreement was found typically to be within 1%. The results of this experiment and the level of methane in the test mixture are provided in Table 6.1 below.

Table 6.1. Methane Conversion in an SOFC at Open Circuit.

CH_4 mole percentage in the reformate stream	7.3	10.6	13.9
CH_4 conversion (%) , through N_2 as internal reference	96.3	96.9	96.0
CH_4 conversion (%), through carbon balance	95.3	96.1	95.2

It is clear from Table 6.1 that the methane conversion through the anode compartment of the single cell SOFC module is over 95% (i.e., 95% of the methane entering anode flowfield is converted into carbon monoxide and hydrogen). The 96% methane conversion at relatively high methane mole percentage (13.9%) in the reformate stream indicated in Table 6.1 implies that the anode layer within the SOFC module may be able to process high levels of methane in the reformate stream successfully, thereby yielding a higher degree of internal reforming and overall system efficiency.

6.2.3 Thermal Modeling Associated with On-Cell Internal Refomation

The highly endothermic nature of the steam reforming reaction, especially if the reaction occurs within a small reaction zone on the fuel cell, poses a potential problem via the generation of a highly localized “cold spot” on the cell that could lead to significant thermal stress within the ceramic. This effect can be particularly acute at open circuit conditions when the SOFC does not generate current and there is no exothermic electrochemical reaction to offset the endothermic reformation reaction.

To better understand the magnitude and breadth of this potential issue, a series of calculations was performed to determine the anticipated temperature decrease on the cell.

Ultimately, the temperature profile experienced across an SOFC that utilizes internal reforming will be the result of a number of operating factors including current density, fuel and coolant air flows, the temperature of fuel and air flows, and the configuration of fuel and air flows (i.e., co-flow versus counterflow). These calculations, while preliminary, do indicate the potential for localized thermal stresses on the fuel cell and they suggest that further computational and experimental work should be performed to better understand both the potential temperature differential on the cell and the level of thermal stress that can be tolerated by the ceramics.

7 CONTROL AND SENSOR DEVELOPMENT

In Q2 and Q3 of 2003 the control system development team completed the conceptual control system design phase for the conceptual and prototype systems. The startup and shutdown strategies for the system were defined and further detail included for the normal operating mode for the system.

In order to determine the controllability of the conceptual system design being studied for the SECA program, a conceptual control system design was developed. This design must accommodate numerous constraints throughout the system and handle disturbances during normal operation, as well as regulate the system through startup, shutdown and emergency shutdown scenarios.

The high level requirements for the design are:

- Safety
- Performance
- Cost
- Reliability

These flow down to specific requirements, which are noted in Table 7.1.1.

7.1 DESIGN AND ANALYSIS METHODOLOGY

The development and evaluation of the control design is accomplished by constructing dynamic models of the downselected SECA conceptual system design and the proposed control algorithms in the Matlab/Simulink modeling environment.

The plant model is then assembled from component models in the proprietary HPGS Dynamic Model Component Library.

Next, the controller is constructed. This allows the dynamic system model to be verified versus the steady state model results. It also permits the control architecture and detailed algorithms to be exercised in the various operating modes. The primary exercise mechanism for the plant and controller is the standard load profile, which provides a variety of step-wise load changes to disturb the system. The results of this testing are then used to modify the controller tuning or algorithm logic as appropriate.

Given reasonable approximations of component performance data, information from the model can be used to identify significant dynamic interactions, such as the affect of thermal lags, within the plant. The simulation data is also used to evaluate the effectiveness of the overall system component layout in terms of controllability. If significant issues in this area exist, they are flowed back to the system design team as part of the “design for control” methodology. By identifying both dynamic interactions and controllability issues early in the design process in an iterative fashion with the system design team, the “design for control” methodology seeks to minimize development costs. These costs could be significant if a major system redesign were necessary later in a program to accommodate control issues not properly addressed at the preliminary development stages.

Some key modeling assumptions include:

- Mass flow propagates from inlet to outlet
- Pressure states propagate from outlet to inlet

- The pressure/flow characteristics for each component (excluding valves and compressors) are linear
- Reverse flow conditions are not allowed
- Heat loss to the environment through splits, merges and valves is negligible
- All water entering the steam generator is vaporized

Effort was also expended to verify the accuracy of the models with respect to the steady state analysis. An overview of the results for the overall system model is shown in Table 7.1.1. It should be noted that improvements to the stack and reformer models have been recently implemented. These changes have resulted in improved accuracy compared to the steady-state models. Comprehensive data regarding the improvements was not available at the time of this writing.

Table 7.1.1: Preliminary percent differences between steady state and dynamic models.

Variable	Stack	Combustor	Air Preheater	Cathode Blower	Steam Reformer	Fuel Preheater	Merge	Natural Gas Compressor	Steam Generator	Pump
Temperature	9.00	7.00	16.0	4.00	33.0	17.0	2.00	3.78	13.0	0.01
Mass flow H2	100.0	-	-	-	42.0	-	-	-	-	-
Mass flow O2	-	0.00	0.00	0.00	-	0.00	0.00	-	-	-
Mass flow H2O	24.0	0.00	0.00	0.00	4.00	0.00	0.00	-	0.06	0.06
Mass flow N2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-	-	-
Mass flow CO2	63.0	0.00	-	-	100.0	-	-	-	-	-
Mass flow CH4	0.00	-	-	-	99.0	0.00	0.00	0.02	-	-
Mass flow CO	1060	-	-	-	257.0	-	-	-	-	-
Pressure	14.0	12.8	17.5	2.17	77.3	11.1	18.6	0.77	62.8	0.41

7.2 REQUIREMENTS

The requirements for the control system design flow down from the high-level customer requirements and flow up from the various component design teams. One of the primary challenges has been translating the customer requirements for safe, reliable, cost-effective operation into measurable goals for controller performance. The other significant challenge was establishing the constraints for system components that do not exist. Data from experiments, steady state analysis and engineering judgment were combined to develop a preliminary list of key component variables, targets and specification limits. Note that different constraints were often needed in each of the three primary operating modes: startup, normal operation and shutdown.

7.3 GENERAL ARCHITECTURE

The general controller architecture consists of a supervisory algorithm that determines setpoints based on user settings and system conditions. These setpoints are provided to a set of active controls that handle setpoint tracking, disturbance rejection and trim.

7.3.1 Supervisory Controls

The supervisory controls serve the function of coordinating system operation, providing the structure for the various operating modes of the system, handling the sequencing and transition between operating modes, monitoring the health and safe operation of the system, and optimizing system efficiency. Various elements of the supervisory controls are discussed below.

Key Independent Variables - In the current system design there are five key independent variables that govern the operation of the system. These key independent variables will be set by the supervisory controls to maximize system efficiency and stability while meeting the required power command. These key variables will then be interpreted and driven down to the lower level control loops as individual actuator setpoints.

7.3.1.1 Operating Modes

There are three primary operating modes and several sub-modes that need to be addressed by the supervisory controls. These modes are:

- Startup
- Normal Operation
  - Increase Power
  - Hold Power
  - Decrease Power
- Shutdown
  - Normal
  - Emergency Shutdown

A state transition diagram of these modes is shown in Figure 7.3.1. This diagram is actually a state machine that is used by the supervisory controls as a set of rules to determine what operating mode the system is in or should be in and what steps are appropriate to take to change system settings in response to user commands, load changes or disturbances.

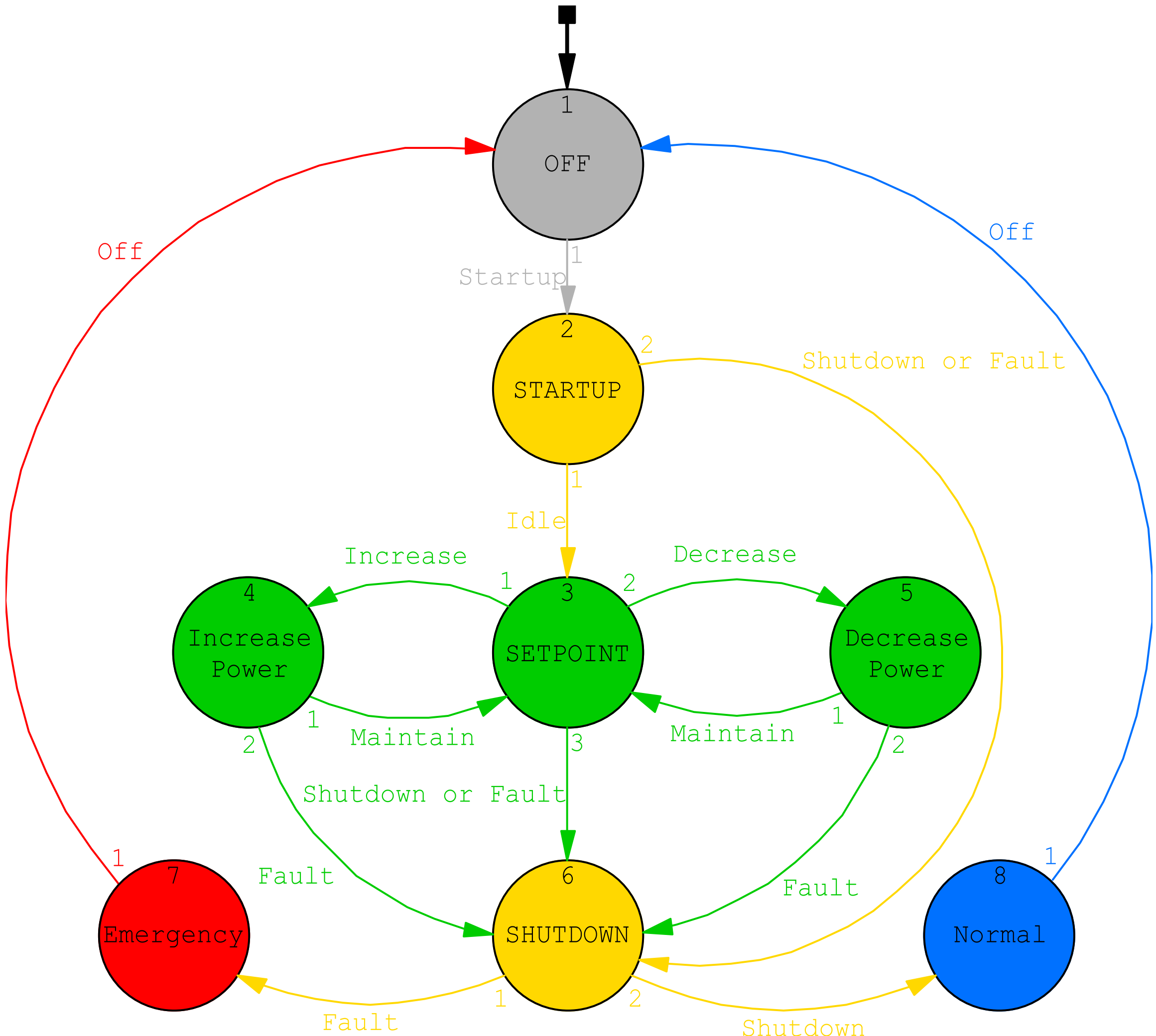

Figure 7.3.1. State transition diagram.

7.3.2 Active Controls

The active controls translate setpoint commands from the supervisory controls into signals that ultimately drive individual actuators throughout the system. The control design combines the output of feedforward and feedback algorithms to realize the benefits of both.

7.3.2.1 Feedforward

The feedforward algorithms speed up the system response to setpoint changes and take advantage of the a priori knowledge of system operation to improve controller performance. These algorithms utilize the setpoint information, either by itself or coupled with sensor data from the system, along with a map. The map transforms the system level setpoint targets and any feedback signals into a setpoint that is recognizable by the individual actuators e.g. speed, valve position, etc. The maps are currently based upon tabulated data, but may be updated to include transfer functions or more sophisticated Model Predictive Control techniques if warranted in the detailed design phase.

7.3.2.2 Feedback

This control approach employs single loop proportional-integral (PI) type compensation for improved tracking and disturbance rejection. The PI controllers also incorporate an anti-windup feature to prevent saturation problems. Although not currently in use, the gain levels provided to the controllers may be scheduled so that different sets of gains can be used by the controller if warranted by a particular operating condition. 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 can later be investigated to determine an approach that best suits the performance requirements for the system.

7.4 STARTUP

The main focus of the startup design is to control the various key system variables to their setpoints in a manner that does not subject the SOFC to undue thermal stresses or other potentially damaging or unsafe conditions. In doing so, the startup algorithms contribute to promoting the reliability of the SOFC system. The specific performance requirement of start time has an effect not only on availability, but also on the utility of the product to a potential customer and on market size.

7.4.1 Development

The synthesis of the startup strategy began by the controls team assembling customer requirements and component operating parameter data along with lessons learned from the stack and fuel processing teams. This information was used to brainstorm and evaluate four concepts (A-D).

Initial analysis was performed by constructing dynamic models of the candidate systems to provide a quantitative overview of the performance of each strategy. The team also evaluated the four concepts using a Pugh matrix. When assessed against the customer requirements, concept C was found to have the most favorable combination of cost, startup time, and general controllability. Improvements will continue to be implemented as needed during subsequent development phases.

7.5 NORMAL OPERATION

During normal operation, the primary tasks of the controller are to hold the stack to its power setpoint while maintaining component constraints, to accommodate load increases and load decreases, and to reject disturbances.

7.5.1 Development

Although the above tasks seem reasonably straightforward, several design issues need to be addressed. During long-term system operation, it is anticipated that the cell voltage output for a given operating point will degrade to a certain extent. This leads to either a decrease in power or efficiency and the need to compensate for that variation. For the case of holding a power setpoint, understanding of customer requirements was required to determine what power trim control concept should be used:

- Maintaining efficiency while decreasing power output
- Maintaining power output while decreasing efficiency

For this application, holding efficiency was determined to be the most important. A PI controller & logic to handle trim and bound the range of the trim amount will be implemented in the detailed design phase.

Holding the multiple system variables to their targets was determined to be a significant challenge in that there are only limited variables available for the controller to adjust.

7.6 SHUTDOWN & EMERGENCY STOP

The key focus of the shutdown strategy is to control the stack temperature decrease to prevent damage to the stack and other system components. This requires active control of the system from operating conditions down to a temperature where the stack heat loss to the environment does not cool the stack faster than the temperature decrease rate limit. An additional requirement is to be able to quickly remove fuel from the system in an emergency situation. Whereas the normal shutdown strategy seeks to protect the stack, fuel processor and other components from damage, the primary consideration of the emergency stop design is to protect people from potentially dangerous situations, even if the stack or system are damaged as a result. Shutdown time is one of the key performance requirements as it impacts system availability. Another key issue is to minimize the capital cost of the shutdown process.

7.6.1 Development

The synthesis of the shutdown strategy began with the controls team assembling customer requirements and component operating parameter data along with lessons learned from the stack and fuel processing teams. This information was used to brainstorm and evaluate the four candidate concepts.

The team then evaluated the four concepts using a Pugh matrix. When assessed against the customer requirements, Concept D was found to have the most favorable combination of cost, reliability, and performance.

7.7 SENSORS & ACTUATORS

The conceptual control system will require sensors and actuators to measure and enact system requirements. Sensors include flowmeters, thermocouples, and pressure transducers. Actuators include valves, both manual and motorized, regulators, and fluid delivery components.

7.7.1 Valve Selection

Valve selection is critical to control of high temperature fluid systems. Manufacturers offer various types of valve configurations, ball, gate, globe, butterfly, etc. — each suited for particular fluid control applications. Some valves are designed for leak tight shut-off, others for throttling or flow diversion. In general, a valve is selected based both on its configuration and flow resistance. Most valve manufacturers define a valve's flow resistance using a valve flow coefficient: the *Cv* value. The *Cv* is defined as the flow of water at 60 °F, in gallons per minute, at a pressure drop of 1 psi. This is a straightforward way to size a valve for incompressible liquid flow. The *Cv* value can be extended to compressible, non-choked flow by the relation (Fluid Control Institute, **FCI 68-1-1998)**

$$Q = 16.05Cv\sqrt{\frac{P_1^2 - P_2^2}{S_g T}}$$

where Q is the flow in SCFM (14.7 psia, 60 °F), P_1 is the upstream pressure, P_2 is the downstream pressure, S_g is the fluid specific gravity with respect to air, and T is the fluid temperature in Rankine.

Some application characteristics of the most common fluid control valves:

<u>Butterfly</u>

Control: Linear or equal percentage
Uses: Fully open/closed, throttling, frequent operation
Advantages: Low cost/maintenance
High capacity
Good availability for high temperature applications
Good throttling control (*Cv* profile)
Low pressure drop
Disadvantages: High torque required for control
May not seal leak-tight (especially in high temperature applications)

<u>Ball</u>

Control: Linear and/or quick opening
Uses: Fully open/closed, limited throttling
Advantages: Low cost/maintenance
High capacity
Low leakage
Low pressure drop
Tight sealing
Disadvantages: Poor throttling characteristics when throttling small pressure drops

Solenoid

Control: Quick opening
Uses: Fully open/closed
Advantages: Low cost/maintenance
Moderate capacity
Low leakage
Low pressure drop
Tight sealing
Disadvantages: Poor throttling characteristics

Electromagnetic actuator can be wasteful for parasitic power consumption

Globe

Control: Linear or equal percentage
Uses: Throttling, flow regulation, frequent operation
Advantages: Accurate flow control
Excellent throttling control (*Cv* profile)
Disadvantages: High torque required for control
Expensive
High pressure drop

Gate

Control: Quick opening
Uses: Fully open/closed, infrequent operation, low fluid trapped volume
Advantages: Low cost/maintenance
High capacity
Low leakage
Low pressure drop
Tight sealing
Disadvantages: Poor control
Cannot be used for throttling
Non-repeatable *Cv* at other than fully open/closed positions

Based on the above valve characteristics and the SECA system control needs, valve recommendations have been made.

Both fuel and airflows are critical parameters that must be measured and controlled in the SOFC system. The requirements for each fluid vary and will be looked at separately in the following sections.

7.7.1.1 Fuel Flow

The SOFC will operate at very specific levels of fuel utilization dictated both by stack longevity and efficiency requirements. Thus, it will be very important to have fast, accurate, and precise control of fuel flow to match the power demanded of the SOFC system. Some of the options for measurement on the Conceptual System are:

Coreolis Meter

Measures: Mass
Advantages: Moderate pressure drop
Good turn down

High accuracy
Low susceptibility to gas composition changes
Disadvantages: High cost

Calibrated Orifice
Measures: Volumetric
Advantages: Good accuracy
Good turn down
Disadvantages: High cost
Some susceptibility to gas composition changes
High pressure drop

Laminar Flow Element (LFE)
Measures: Volumetric
Advantages: Good accuracy
High capacity
Good turn down
Low pressure drop
Disadvantages: Some susceptibility to gas composition changes

Thermal Mass Flow Meter
Measures: Mass
Advantages: Moderate accuracy
Low pressure drop
Disadvantages: High susceptibility to gas composition changes

Characterized Metering Valve
Measures: Position vs. Flow relation
Advantages: Low pressure drop
Low cost
Disadvantages: Some susceptibility to gas composition changes
Low accuracy

Recommendations for fuel flow meters have been made.

7.7.1.2 Air Flow

The largest parasitic loss in the SOFC system will be the pumping requirement for system air. Therefore, any pressure drop added to the airflow circuit will have a direct effect on system efficiency. While it is important to know how much air is flowing while under normal operation, the accuracy of the measurement can be less than that for fuel flow. This is because the SOFC nominally operates with greater than three times the airflow required to supply its electrochemical reaction—the balance necessary to cool the SOFC stack.

Coreolis Meter
Measures: Mass
Advantages: Moderate pressure drop
Good turn down
High accuracy
Disadvantages: High cost

Calibrated Orifice
Measures: Volumetric

Advantages: Good accuracy
Good turn down
Disadvantages: High cost
High pressure drop

Laminar Flow Element (LFE)
Measures: Volumetric
Advantages: Good accuracy
High capacity
Good turn down
Low pressure drop
Disadvantages: Moderate Cost

Thermal Mass Flow Meter
Measures: Mass
Advantages: Moderate accuracy
Low pressure drop
Disadvantages: Moderate Cost

Compressor/Characterized Metering Valve
Measures: Position vs. Flow relation
Advantages: Low cost
Disadvantages: Additional pressure drop on air system
Low accuracy
Low controllability

Characterized Blower
Measures: Corrected Flow vs. Blower Speed
Advantages: Moderate accuracy
No additional pressure drop
Disadvantages: Moderate Accuracy

A recommendation has been made on the approach.

7.8 BUILT-IN TEST AND HEALTH MONITORING

The inherent need for safe and reliable system operation requires that feedback data be used not only for control of actuators, but also for monitoring so that variables throughout the plant are maintained within acceptable limits for the current operating mode.

7.8.1 Key System Constraints

Even though the system design is still changing, a preliminary list of key system constraints has been compiled to aid in the control system development and trade studies. The values of the various constraints will definitely change as the component and overall system designs mature, but the constraints on the identified system variables should be maintained with any control system designed. These constraints will be used as evaluation criteria for various trade studies that will be conducted with alternative system and control system designs. As the system and component designs mature, this list of constraints will grow and develop into the basis for the built-in test (BIT) that will ultimately monitor system health.

As noted above, the basis for system health monitoring is the table of system variable constraints. By comparing the measured or derived data returning from the system with the ranges established for each operating mode, the controller is able to determine if the system is operating within acceptable limits. Two limit levels will be used for the BIT evaluations. A warning threshold will be set at a level that provides a safety margin away from the specification limits. The specification limits themselves set the range for the hazard limit levels. Another factor that affects the establishment of system health is the duration of deviant signals since outside influences may temporarily give false readings. For signals with an out-of-specification value that lasts for a prescribed period of time, the system will report a warning to the user via the human-machine interface. In most cases, the active controls will function to negate the deviation. However, for situations when the warning persists or the error grows and exceeds the maximum threshold level, a hazard signal will be reported to the user and either a normal or emergency shutdown will be initiated by the supervisory controls. A sequencer will set the data retrieval schedule for each individual built-in test comparator with more critical data points being sampled at a higher frequency.

8 THERMAL MANAGEMENT SUBSYSTEM

The thermal management subsystem is defined as those components downstream of the stack (i.e. burner & heat exchangers) whose primary tasks are to; 1) react any remaining combustibles in the anode exhaust and, 2) to preheat the various streams that eventually find their way to the stack inlet (anode & cathode inlets).

The challenges to this subsystem primarily relate to burner and heat exchanger design. HX-01 must be capable of handling temperatures that are well beyond the capabilities of most off-the-shelf equipment. The burner, on the other hand, must be capable of burning an ultra-lean mixture of H_2 and CO, with concentrations that are close to the flammability limits of H_2.

Work within the past 6 months has been directed towards addressing the challenges previously mentioned. One of the first tasks that was completed was the evaluation of burner concepts for the combustion of ultra-lean mixtures of H_2/CO.

For the heat exchanger design, two concepts were evaluated. The first concept integrates the functions of both heat exchange and combustion and is termed the Integrated Recuperator/Gas Burner (IRG). The second concept uses a more conventional approach.. Both concepts are expected to provide the required performance. To this extent, an IRG unit has been fabricated and is currently awaiting testing. Similarly, a vendor has prepared a preliminary design for the conventional heat exchanger concept.

A test rig has been recently constructed to allow performance testing of the IRG. The test rig has the capability of providing preheated air at temperatures equivalent to those likely to be seen in the stack exhaust. Testing of the IRG is scheduled to take place at the end of October.

9 ELECTRICAL SYSTEM

The electrical system design effort is composed of the balance of plant electrical subsystem design and the power electronics subsystem design.

9.1 BALANCE OF PLANT

The balance of plant (BOP) electrical system includes the electrical power supplied to BOP components, the excitation power supplied to instrumentation, the command signals to actuators, the signals from sensors, all of the component wiring, and the controller hardware. During this reporting period, the electrical system design for the Conceptual System Design (CSD) was completed and work began on the electrical system design for the Prototype System Design (PSD).

9.1.1 Conceptual System Design

The conceptual electrical system design for the CSD was completed during this reporting period. This design effort developed the basic architecture for the electrical system and requirements for the subsystems and components. A component level FMEA was completed to identify and address critical failure modes.

To minimize cost and parasite power, the system controller will also serve as the inverter controller for CSD. Additional benefits of a single controller for the entire system are:

- Simplify configuration management
- Lower development cost
- Lower hardware cost
- Simplify mechanical/electrical layout

The controller will be a custom design based on proven processors and technologies with rugged technology similar to those used in engine control units (ECU) in automobiles. The benefits of the custom design are:

- Low cost for high volume
- Simplify mechanical packaging
- Simplify mechanical design
- High software/controls flexibility

With this approach, high volume costs for the controller unit can be very low.

9.1.2 Prototype System Design

Based on the balance of plant electrical system design for the conceptual system, a design for the prototype system is being developed. This design will take into account the differences between the conceptual system design and the prototype systems. The primary differences between the two designs will be the inclusion of extra instrumentation for monitoring component performance in the system and additional sensors and actuators for added system safety and controllability.

At the conclusion of Q3, initial block diagrams were developed for the prototype system with the additional components and instrumentation identified. The initial parasite loads have been identified and submitted to the system analysis team for use in their system optimizations. Current efforts are focused on sourcing the electrical components that meet the required performance specified by the system design.

9.2 POWER ELECTRONICS

The power electronics development efforts have been focused on developing requirements, vendor identification and evaluation, and design down-select for the prototype and conceptual systems.

9.2.1 Power Electronics Requirements

In previous reporting periods, analysis was done to correlate stack voltage, inverter efficiency targets, and grid connection considerations. This work concluded in Q2 with the release of a power electronics specification to prospective vendors and the SECA core teams in Power Conditioning Module Specification, Revision D.

CONCLUSIONS

Significant progress has been made in GE's SECA program over the last reporting period. The conceptual system design task has been completed, with a design review to be held in October. Multicell stacks have been designed and assembled, with significant scaleup planned in the near future. A stable fuel utilization of 95% was achieved on a test module, which produced 0.238 W/cm2 at 0.669 V under this condition. Sealant and interconnect materials have been identified which have demonstrated the capability of meeting or exceeding the stack thermal cycling and degradation targets. The external fuel processor was designed and is being fabricated. The startup, shutdown and normal operation control strategies were defined for the conceptual system. Several other advances have been made, and as the focus now turns to the design and fabrication of the SECA prototype unit, the GE team is well-positioned to meet the goals of the program.

REFERENCES

None.