SECA Phase 1 Final Report

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Summary Page

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1. Revision 0History

Revision	Date	By	Revision Details
A	November 15, 2007	Charles Vesely	

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1 Executive Summary

The following report documents the progress of the Cummins Power Generation (CPG) SECA Phase 1 SOFC development and final testing under the U.S. Department of Energy Solid State Energy Conversion Alliance (SECA) contract DE-FC26-01NT41244. This report overviews and summarizes CPG and partner research development leading to successful demonstration of the SECA Phase 1 objectives and significant progress towards SOFC commercialization.

Significant Phase 1 Milestones:

- Demonstrated:
    - Operation meeting Phase 1 requirements on commercial natural gas.
    - LPG and Natural Gas CPOX fuel reformers.
    - SOFC systems on dry CPOX reformate.
    - Steam reformed Natural Gas operation.
    - Successful start-up and shut-down of SOFC system without inert gas purge.
    - Utility of stack simulators as a tool for developing balance of plant systems.
- Developed:
    - Low cost balance of plant concepts and compatible systems designs.
    - Identified low cost, high volume components for balance of plant systems.
    - Demonstrated high efficiency SOFC output power conditioning.
    - Demonstrated SOFC control strategies and tuning methods.

The following table illustrates the results achieved for the SECA Phase 1 test:

Table 1.1 – Performance Results

RESULTS AGAINST PHASE 1 METRICS		
REQUIREMENT	***TARGET***	***Actual***
Power Rating (Net DC@ NOC)	3 – 10 kW	3.2 kW (4pt. Ave.)
Efficiency Mobile (DCnet/LHV)	25 %	37.1 % (4pt. Ave.)
Steady State Degradation	2 %/500 hrs	1.7 %/500 hrs
Transient Degradation	1 %/10	1 %/10
Total Degradation (1500h + Tran.)	7 %	6.3 %
Availability	>80 %	99 %
Peak Power (Net DC)		4.6 kW
Fuel Type	Commercial Commodity	NG Pipeline

The Phase 1 performance test was carried out at the Cummins Power Generation facility in Minneapolis, Minnesota starting on October 2, 2006. Performance testing was successfully completed on January 4, 2007 including the necessary steady-state, transient, efficiency, and peak power operation tests. Further detail can be accessed in the "SECA Phase 1 Test Report" document number TR-CPG-PH1-PUB-R01.

2 Reference Documents

- Semi-annual reports:
  - 41244R01.pdf
  - 41244R02.pdf
  - 41244R03.pdf
  - 41244R04.pdf
  - 41244R05.pdf
  - 41244R06.pdf
  - 41244R07.pdf
  - 41244R08.pdf
  - 41244R09.pdf
  - 41244R10.pdf
- Test Report TR-CPG-PH1-PUB-R01
- Minimum requirements (Appendix A)

3 Definitions and Acronyms

BOT	Beginning of Test
cBOP	Cold Balance of Plant
CPG	Cummins Power Generation
DIR	Direct Internal Reforming
DOE	U.S. Department of Energy
EOSS	End of Steady State
ETS	Energy Technology Services LLC
FCV	Flow Control Valve
FRU	Field Replaceable Unit
GC	Gas Chromatograph
hBOP	Hot Balance of Plant
HEX	Heat Exchanger
Hot hold	Condition with system at operating temperature and stack at 0 A DC
IT	Current Transducer
LHV	Lower Heating Value
M1	Mission 1 (system), or SECA Phase 1 system
mlpm	Milliliters per minute
MTI	McDermott Technology, Inc.
NETL	National Energy Technology Laboratory
NOC	Normal (or Nominal) Operating Conditions
P&ID	Piping & Instrumentation Diagram
PCU	Power Conditioning Unit
PDT	Pressure Differential Transducer
PMP	Pump
SECA	Solid State Energy Conversion Alliance
SLD	Single Line Diagram
slpm	Standard liters per minute (1 atmosphere, 70°F (21.1°C))
SOFC	Solid Oxide Fuel Cell
SOFCo	SOFCo EFS, formerly McDermott Technology, Inc.
SP	Set-point
0SS1	Steady State #1 consisting of the first 1000 hour steady state period
SS2	Steady State #2 consisting of the last 500 hour steady state period
SV	Solenoid Valve
Ua	Air (oxidant) utilization
Uf	Fuel utilization
VPS	Versa Power Systems Ltd. / Inc.

4 Background

With the release of the US Department of Energy's Request for Proposals (RFP) in 2001, Cummins Power Generation (CPG) recognized the potential for Solid Oxide Fuel Cell (SOFC) technology in serving a number of CPG markets. The SECA RFP was particularly well aligned with CPG interests in its focus on the 3-10 kW modular conception which is a good fit to a number of consumer markets that value the very low noise, exhaust emissions, and vibration potential of the SOFC. CPG conducted a survey of available SOFC technology partners for stack and hot zone technologies and engaged in discussions with a number of developers, settling on McDermott Technology Inc. (MTI) as a promising combination of technology development capability and commercial fit with CPG's aims. In 2001 MTI's ceramic interconnect structure appeared to offer a number of significant advantages compared to the state of metallic interconnects which characteristically suffered from a number of durability related problems. CPG subsequently formed a SECA team with MTI (later re-incorporated as SOFCo) and were successful in receiving a SECA Cooperative Development Agreement for SOFC development on September 30, 2001.

Upon receipt of the award, detailed planning and development work started and the program began ramping up in early 2002. Early work included development of product technical objectives that would guide the design and development of the stacks, Balance of Plant (BOP), Controls, Power Electronics, and system integration. Development of product technical objectives produced a number of insights into practical product requirements for SOFC's that greatly enhanced understanding of the range of technical challenges inherent in the effort to commercialize the technology.

During the period from January 2002 through early 2005 CPG and SOFCo made significant progress against the objectives of both the SECA program and the requirements for commercialization. A dry CPOX fuel reformer was developed to operate on LPG fuel, and successfully converted to pipeline natural gas. A kilowatt scale system (C1) was constructed and operated to develop valuable data leading to an enhanced understanding of requirements for controls and BOP, and a 5 kW system was constructed in preparation for the SECA test regime planned for the second half of 2005. Simple and robust control strategies and algorithms were developed and implemented. Suitable low cost components based on high volume commercially available components were identified and integrated into the BOP. SOFCo stack technology development produced consistent progress in the performance and degradation of the all ceramic stack. Unfortunately, that progress, though consistent, was diminishing as the required targets for stack performance were approached. Development testing of the SOFCo hot zone in the Phase 1 deliverable (C2) system revealed a number of shortcomings in hot zone performance at the same time that testing of the stacks was indicating problems in reaching the targets for stack performance required to support the system operational objectives.

Recognizing the rapid progress in commercially attractive lower cost metallic interconnect technology, in 2005 CPG engaged the DOE in discussions regarding the possibility of changing the stack supplier for the CPG effort. These discussions culminated in the selection of Versa Power Systems, Inc. (VPS) as the new stack partner for the CPG effort, and a one year Phase 1 extension to allow for the transition from SOFCo to VPS stacks.

Cooperative development with VPS was extremely productive and effectively combined CPG developed understanding of commercial requirements, lower cost BOP components, and high efficiency power electronics with VPS high performance stack, fuel reformer, and system integration expertise to produce and successfully test the Phase 1 deliverable (M1) system.

The finale of the Phase 1 test occurred on January 4, 2007 and completed demonstration of the performance objectives of Phase 1 of the SECA program for CPG and VPS.

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    - Successful start-up and shut-down of SOFC system without inert gas purge.
    - Utility of stack simulators as a tool for developing balance of plant systems.
- Developed:
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5 Stack Development - Overview

The CPG SECA Phase 1 stack development began with a ceramic interconnect-electrolyte supported cell construction and transitioned to a metallic interconnect-Anode supported cell. The initial all ceramic stack provided useful characteristics including: higher stack temperature operation, lower cathode flow rate and pressure requirements (with 100% cathode cooling), and Monolithic structure (shock and vibration robustness). These, plus the possibility of combining the stack and manifold as a single unit, provided an appealing package. However, overall stack performance and potential progress toward meeting the phase 1 metrics was not sufficient, primarily in stack cost, ASR, and degradation. Progress on metallic interconnected stacks had improved substantially and surpassed the all ceramic technology near the end of the phase 1 program. It was apparent that to meet the phase 1 metrics within a reasonable period CPG would have to shift to the metallic interconnect technology.

While there has been significant progress in the development of the SOFC subsystems that can support meeting the program Phase 1 goals, the SOFCo ceramic stack technology had progressed significantly slower than plan and CPG considered it unlikely that the systemic problems encountered would be overcome in the near term. SOFCo had struggled with a series of problems associated with inconsistent manufacturing, inadequate cell performance, and the achievement of consistent, durable, low resistance inter-cell connections with reduced or no precious materials. A myriad of factors have contributed to these problems, but the fact remains that progress had not kept pace with the SECA program. In view of the situation, CPG conducted an independent assessment of the state-of-the-art in planar SOFC’s stacks and concluded that existing alternative technologies offered the specific performance, durability, and low cost needed to meet the SECA objectives. We further concluded that there was insufficient evidence to reliably predict that SOFCo would be able to achieve the SECA performance and cost goals on a schedule consistent with SECA or CPG commercialization goals. CPG believes SOFCo had made a good faith effort consistent with the available resources, but fell short of achieving the programs scheduled targets.

CPG initiated a process of application for extension of Phase 1 of our SECA program with the intent of transitioning to an alternative stack supplier with more mature SOFC technology, and demonstrated a system meeting the SECA Phase 1 goals by the end of calendar 2006. We identified an alternative supplier and reported the progress on the transition and program planning in monthly technical reports, reviews, semi-annual report, and final topical report.

A major SOFCo shortfall was the achievement of target cost value for stacks, and the associated cost impact on the SOFC module. The stack cost miss was driven by a combination of higher-than-target ASR (thus requiring additional stack material to meet power requirements) and failure to successfully replace precious metals at the cathode to interconnect junction.

SOFCo made significant progress against degradation targets during the reporting period, but repeatable degradation progress is cross-linked to replacement of precious metals at the cathode to interconnect junction, which remained to be accomplished. A further concern was stability of the interconnection junctions under transients, which remained to be explored following the material set replacements for precious metals. This was considered a high risk area due to the ridged nature of the ceramic/ via assembly.

5.1 Stack Development – SOFCo Ceramic Interconnect Technology

During the Phase I effort, SOFCo performed more than 200 individual stack tests, with most of these using 2-5 cell short stacks. The majority of the early tests were performed using 3YSZ electrolyte-supported cells, and were aimed at establishing repeatable stack assembly procedures and validating the SOFCo "all-ceramic" stack design using the multi-layer ceramic interconnects. The work demonstrated effective cell-to-interconnect and stack-to-manifold sealing, and showed that high fuel utilization (>80%) could be achieved. In 2004, SOFCo began using ScSZ electrolyte-supported cells for stacks, and shifted emphasis toward achieving the stack performance (power density and degradation rate) required for the C2 system demonstration.

In 2004, SOFCo demonstrated that the required initial stack power density could be achieved, but degradation rates were too high. An internal "Tiger Team" performed an extensive study and developed a fundamental understanding of the primary sources for stack degradation; key mechanisms were identified and corrective actions were defined. As a result of this effort, short stack degradation was reduced from 10-20% per 500 hours to less than 4% per 500 hours (from peak power). More important, the contributions to stack degradation associated with the interconnects and the various electrical contacts within stacks were substantially eliminated. With subsequent refinements, particularly with the addition of compliant connections, a stack ASR of 0.6 $\Omega\text{-cm}^2$ was demonstrated using externally supplied ScSZ cells. Stack performance now appears to be largely driven by the cell behavior, for which degradation rates are on the order of 2% per 500 hours. At the end of this reporting period, SOFCo conducted two short stack tests using reformed natural gas as the fuel. Both of these stacks were operated for >1000 hours and demonstrated power degradation rates of 2-3% per 500 hours, approaching the Phase I SECA target.

Figure 5.1 illustrates the ASR improvements SOFCo accomplished during the period. Although the ASR and degradation demonstrations approached the Phase 1 targets the material sets were inconsistent. This along with the inability to bring the stack cost within reach of the Phase 1 target lead CPG to form a new partnership utilizing a proven metallic interconnect technology. (Ref. 41244R01 to R08).

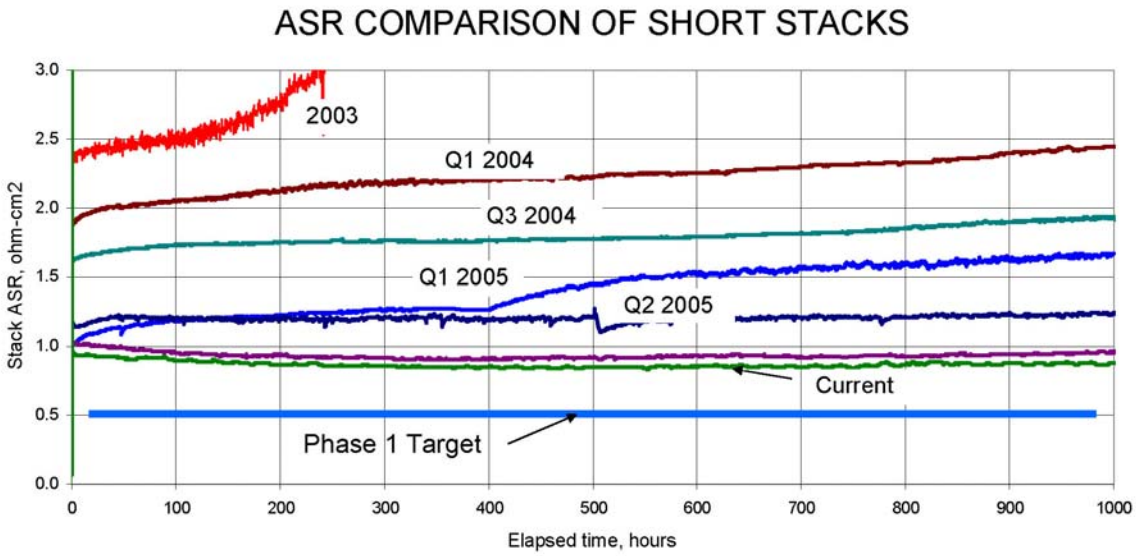

Figure 5.1 SOFCo ASR Improvements vs. Time (Ref. 41244R08 fig. 7)

5.2 Stack Development – VPS Metallic Interconnect Technology

The CPG-VPS SECA Phase 1 system stack effort was designated the PCI2 (ref. 41244R09). This stack is a variant of the baseline PCI stack. The PCI2 development included revised seals to reduce stack leak rates and provide for better manufacturability. The results of this change were also in improved electrical isolation, lower pressure drops, reduced cell-to-cell performance variation and stack size.

(Ref. 41244R09 and R10).

6 Reformer Development – Overview

Propane was the initial fuel type for the Phase 1 development due to the availability onboard the targeted commercial application. Due to SECA program initiatives to create a simplified comparison structure between industrial teams the C1 test unit was converted to operate on Natural Gas. The C1 and C2 system utilized a SOFCo developed gaseous CPOX reformer which was controlled with CPG systems and electronics. The later M1 System incorporated a steam reformer. Natural gas, water, and thermal energy from the waste streams are combined to steam reform the natural gas into a $CH_4/CO/H_2$ reformate that is electrochemically combined with oxygen from the air to produce DC electrical power. Reducing gas was used for reliable and safe system start-up and shutdown, as well as to protect the fuel cell anode.

6.1 Reformer Development – SOFCo Natural Gas CPOX

Development of the natural gas CPOX reformer resulted in the characterization of performance versus time and temperature. This allowed for the development of key software and control systems which provided operation based on cost effective control devices. The basic system of operation was to calculate the desired operational inlet and outlet conditions based on accumulated hours and throughput and utilize these results in a feedback control that maintains the desired CPOX operation via the outlet temperature. The desired outlet temperature is function of accumulated past operating conditions and desired mass flow rates to properly fuel the stack. Unfortunately this implementation was not demonstrated for Phase 1 due to the change to steam reforming for the final M1 test unit. (Ref. 41244R01 to R08). [ ]

6.2 Reformer Development – VPS Natural Gas Steam Reforming

The steam reforming VPS “integrated module” was modified for the CPG M1 system to provide less methane slip than in previous VPS systems. This was implemented to demonstrate system operation closer to the target application were direct internal reforming (DIR) would not be available due to the characteristics of diesel fuel reforming. The Phase 1 test reforming samples indicated that the level of DIR was significantly reduced. However, the CH_4 levels attained for the reformate were greater than the original target. (Ref. 41244R09 and R10). [ ]

7 System Development – Overview

The original SOFCo partnership system design was based on a CPOX reformer and a pressurized hot box that contained the fuel cell stacks, manifolds, and post process combustor. The controls and power electronics for these early systems was entirely a CPG effort. The later system was based on steam reforming with an atmospheric hot zone were some combustion and leakage gasses were routed to a separate exhaust from the stack cathode/anode streams.

7.1 System Development – SOFCo Sealed hBOP Full Recuperator

The CPG-SOFCo SECA Phase 1 C1 system (Figure 7.1) was the first complete SOFC system operated at CPG. It was designed for an output of 1000 Watts.   Approximately 600 hours of development operational time was accumulated on the C1 systems first set of functional stacks. Prior to functional stacks the C1 was operated on a pair of simulated stacks to provide software development and calibration tuning of the BOP. The controls, software, and power electronics were complete CPG design and development content. After development testing of the C1 system was completed a second, C2, development system was fabricated and began testing with improved simulated stacks for controls and software development. [[redacted]]

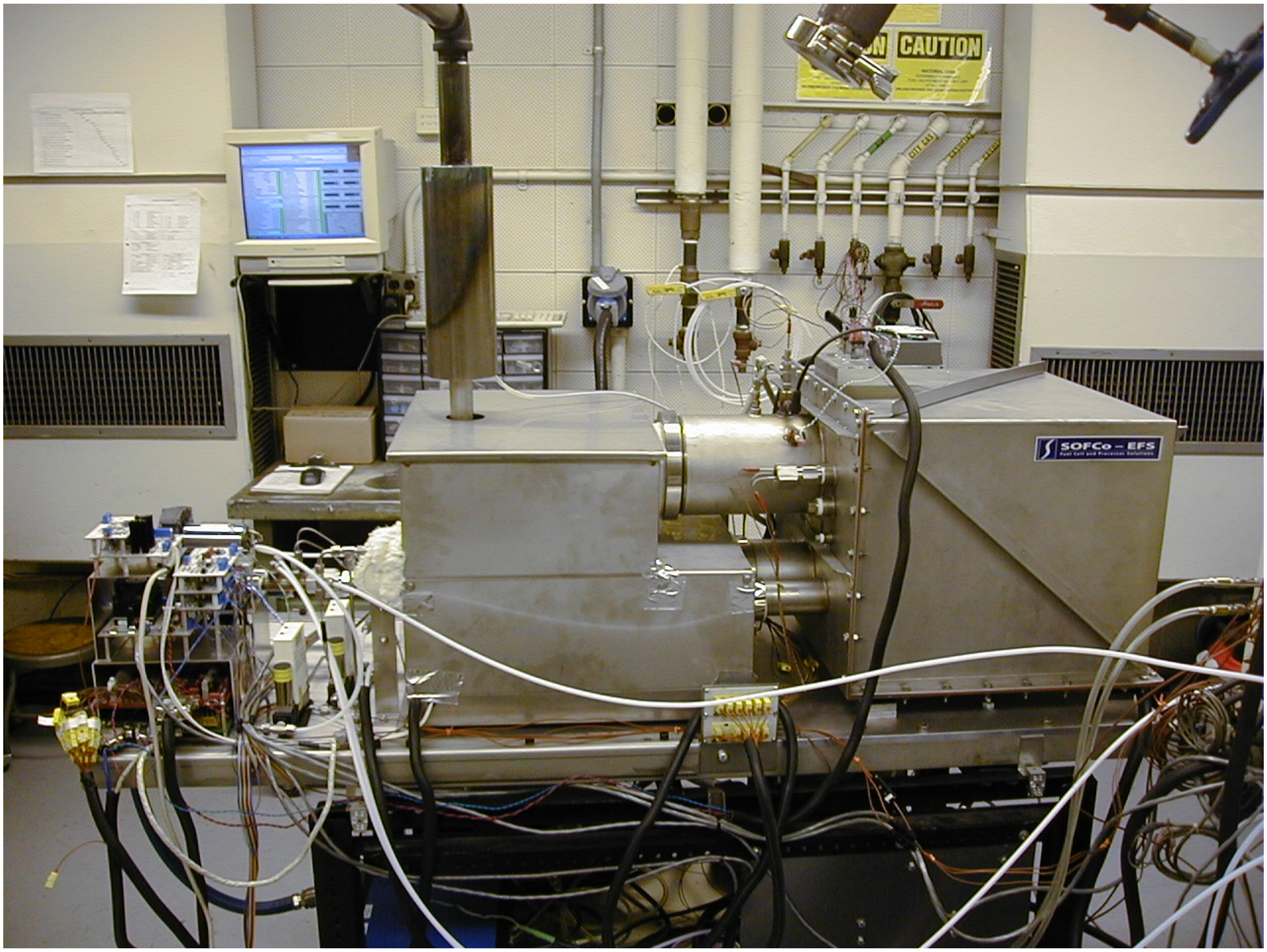

Figure 7.1 C1 Test Unit at CPG

7.1.1 System Development – SOFCo

The CPG-SOFCo SECA C2 system (Figure 7.2) was designed to be a natural gas-fueled 5kW$_{net}$ prototype for the SECA program, produced by the CPG-SOFCo team. The system incorporated CPG designed subsystems, including Cathode air supply, Reformer fuel and air supply, Burner fuel and air supply, System thermal control, and all power electronics. (Ref. 41244R01 to R08). [redacted]

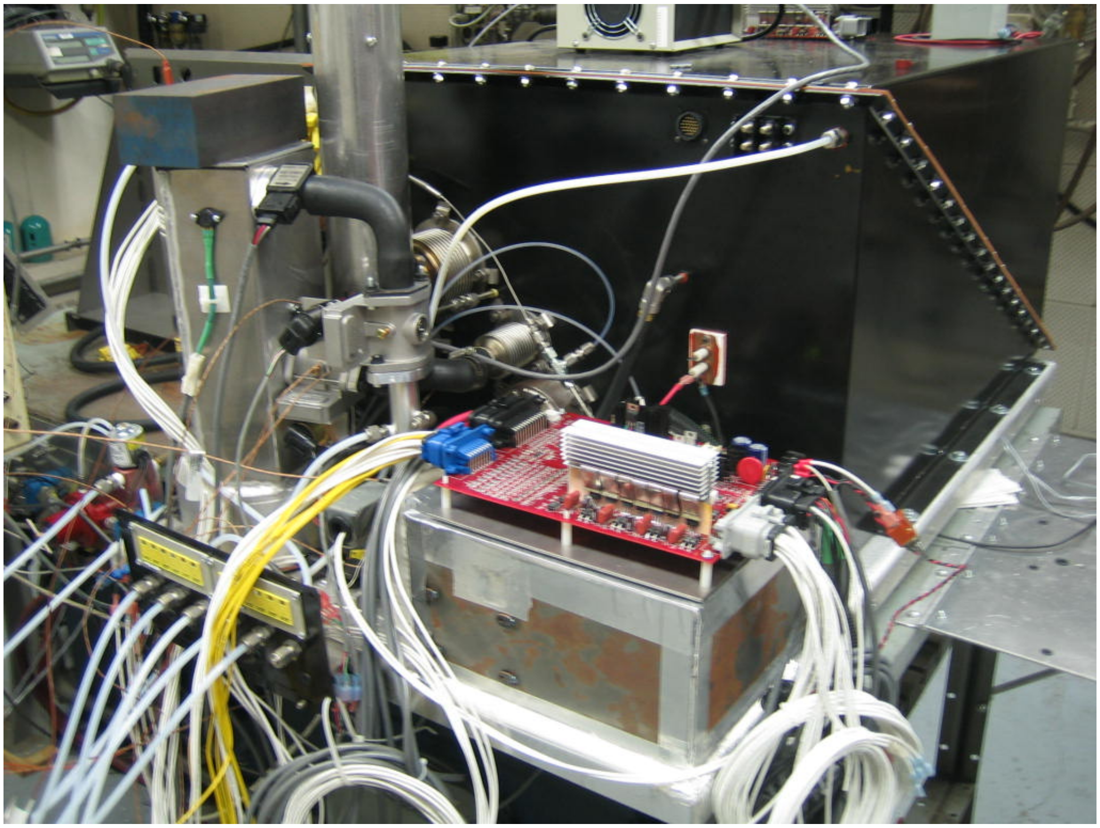

Figure 7.2 C2 Test Unit at CPG Utilizing Simulated Stacks

7.2 System Development – VPS Open hBOP, Manifolded Cathode Outlet

The CPG-VPS SECA Phase 1 system (Figure 7.3) has been termed the Mission 1 or M1 system. The M1 system is natural gas-fuelled $3kW_{net}$ prototype for the SECA program, produced by the CPG-VPS team. The system incorporates VPS and CPG designed subsystems, including VPS' planar Solid Oxide Fuel Cell (SOFC) technology.

System inputs include natural gas, water, air, and reducing gas (4% H_2, balance N_2). Natural gas and water are mixed to steam reform natural gas into a CO/H_2 reformate that is electrochemically combined with oxygen from the air to produce DC electrical power. Reducing gas is used for reliable and safe system start-up and shutdown, as well as to protect the fuel cell anode.

The M1 system is divided into 2 major areas: the Hot Balance of Plant ("hBOP") and the Cold Balance of Plant ("cBOP").

Figure 7.3 Phase 1 Test Article at CPG

<u>Hot Balance of Plant</u>
High temperature processes occur in the hBOP, including fuel reforming, fuel and air preheating, fuel cell power generation, steam generation, and fuel cell exhaust combustion. The Integrated Module ("IM") is a component that houses the steam generator, afterburner, reformer, and air pre-heater in a single thermally integrated unit. The afterburner supplies heat to the 3 incoming process streams occurring in the IM. Cathode air is preheated, steam is generated by vaporizing water, and then the steam – natural gas mix is steam reformed to create the CO/H_2 reformate. The M1 system reformer is a redesign of a previous VPS reformer to allow for near-complete conversion of the natural gas into H_2 and CO. This will supply the stacks with a reformate that is representative of a fuel feed created by future diesel reformers.

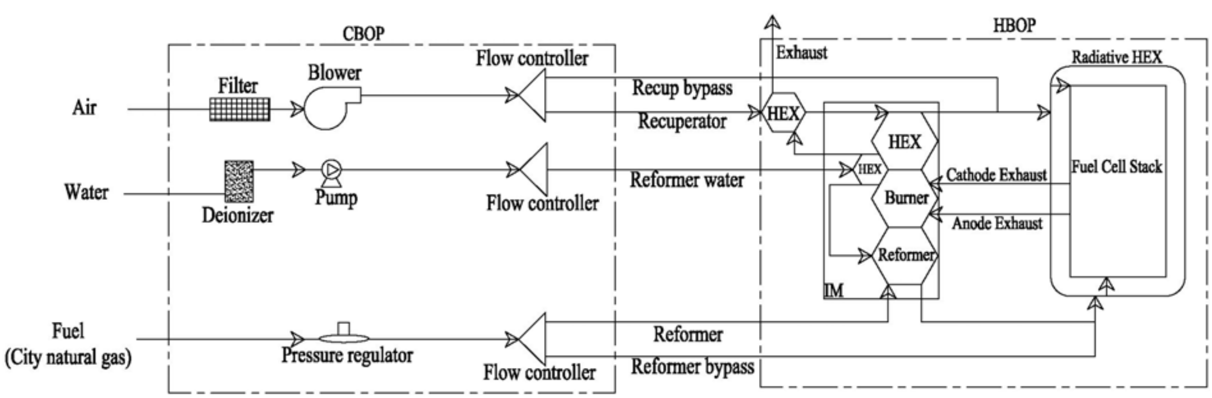

Figure 7.4 Phase 1 System Schematic

The stack zone is located in the hBOP, and includes the stack tower, a vertical column of 4 stacks, totaling 112 cells. Each stack has 28-cells and the gas distribution is internally manifolded. The stack support (or base manifold) is located at the bottom of the stack tower and combines the anode inlet, anode outlet, cathode inlet, cathode outlet distribution ports into 1 unit. The stacks are surrounded by a radiative air heat exchanger, which takes advantage of the high heat transfer rate available through thermal radiation, to cool the stack tower while under power load. The incoming cathode air flows through the radiative air heat exchanger. The stack zone also includes a ring burner at the bottom of the tower that supplies hot gas for start-up. A small radiative fuel heat exchanger (U-tube) in the stack zone also provides some pre-heating to the anode inlet gas.

The hBOP is encapsulated by thermal insulation to minimize heat loss. The insulation takes the form of shaped insulation components or insulation blankets. [[redacted]]

Cold Balance of Plant

The cBOP contains the flow control, electronics that are necessary to operate the system, and power conditioning.

The fluid delivery system controls the flow of natural gas, water, and air through the various process streams. The fluid delivery system also controls the flow of reducing gas during start-up, shutdown, and emergency shutdown sequences. [[redacted]]

The electronics in the cBOP include the CAN-bus controller that controls the fluid delivery system, DC-DC boost power converter, and control algorithms for operation of the overall system. The controller also provides data logging of all the monitored inputs and an interface to an operator. The DC-DC boost provides a high voltage out of the SOFC system at approximately 200 VDC. An inverter, external to the system, is used in CPG's ultimate product-level implementation.

Other components

The system also includes many small components and sensors for measurement of temperature, pressure, current, and voltage.

External to the system is a desulfurizer that removes sulfur compounds from the raw incoming natural gas stream. A Gas Chromatograph ("GC") is used to analyze the raw natural gas composition and stack inlets and outlets.

A facility power meter is also used external to the system to measure the draw from parasitic loads on the system and this information is used in the calculation of the system efficiency.

(Ref. 41244R09 and R10).

8 Controls & Power Electronics Development

The controls for the C2 unit were designed, programmed, and tuned at CPG. This was accomplished with a single imbedded control module (fig.8.1) designed by CPG.

The M1, Phase 1 test, unit controls were primarily a VPS design that worked in conjunction with CPG power electronics peripherals via a CAN network.

8.1 Controls Development - CPG

The C1 and C2 control loops were tuned by performing a series of system ID experiments on the hot system simulator to determine the system dynamics and gains. Simple dynamic models were then fitted to the data gained from these experiments, and the models were used to tune the controls. The control simulation and tuning was done with Simulink modeling software.

In addition to the control system tuning and validation software in the MCU to export the control sensor signals to the external data acquisition system was add to reduce the number of redundant sensors in the system and was pivotal in the control system tuning.

An overview of the control algorithms for the C2 system is summarized below;

Stack temperatures: The stack temperatures are controlled by controlling the Cathode inlet air and outlet temperatures; this also effectively controls the stack average temperature. The stack Cathode inlet air temperature (fig. 8.2) is cooled by regulating the amount of Cathode air flow that is bypassed around the recuperator heat exchanger. In addition the inlet air temperature can be further regulated by controlling the energy transferred across the recuperator by controlling the inlet exhaust temperature to the recuperator. The stack Cathode outlet temperature, and thus stack delta T, is controlled by the amount of Cathode air mass flow that is driven through the system. Increasing the Cathode mass flow rate decreases the Cathode outlet temperature, and vice versa.

Cathode Mass Flow; In the C2 design the Cathode mass air flow is regulated by a closed loop routine that controls the blower speed in concert with an automotive based mass air flow sensor (MAF).

CPOX outlet temperature; The CPOX outlet temperature is controlled by a closed loop routine that regulates the CPOX air flow.

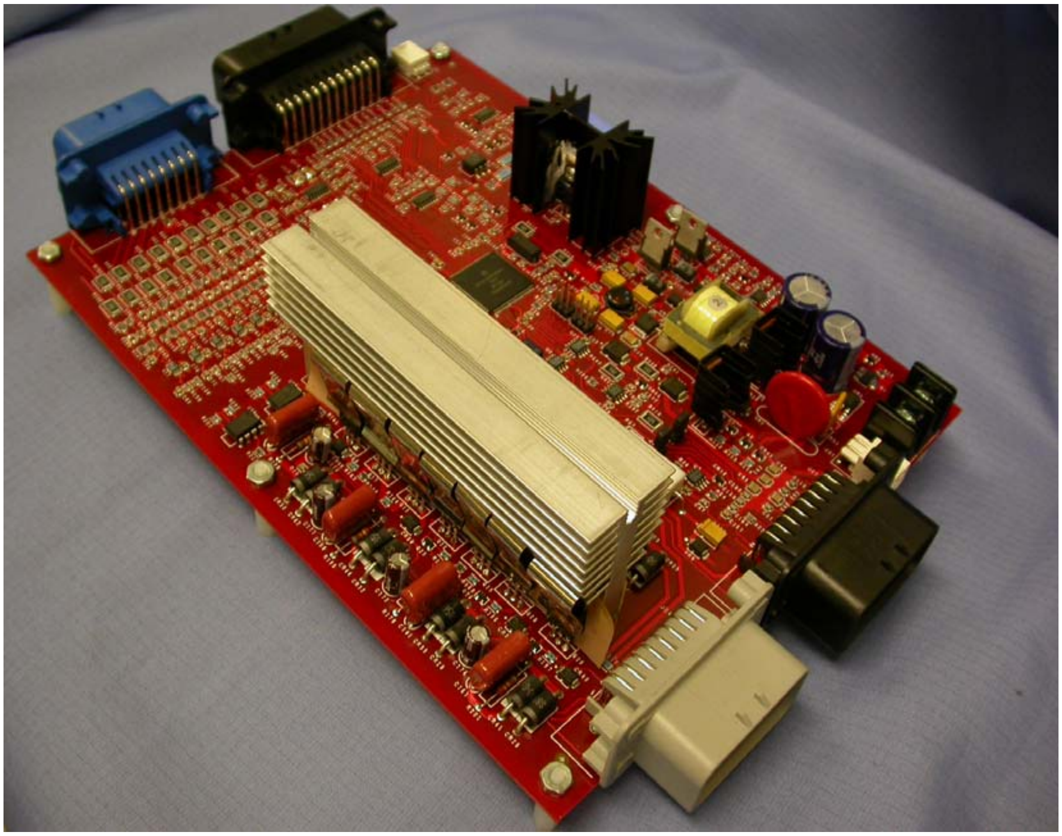

Figure 8.1 C2 Control Module Developed at CPG

Recuperator control; In the C2 design the recuperator exhaust inlet temperature is regulated with a feed back loop by controlling the burner air flow and the system makeup fuel. The control over recuperator inlet temperature is a means by which the thermal energy input to the balance of plant can be precisely controlled. Consequently, controlling the recuperator inlet temperature is an integral part of the start up process and is critical in maintaining hot idle conditions. If during stack loaded operation the recuperator inlet temperature needs to be reduced, quench air passed through the startup burner is utilized. If during stack loaded operation the recuperator inlet temperature needs to be raised, make up fuel is added to the combustor flow.

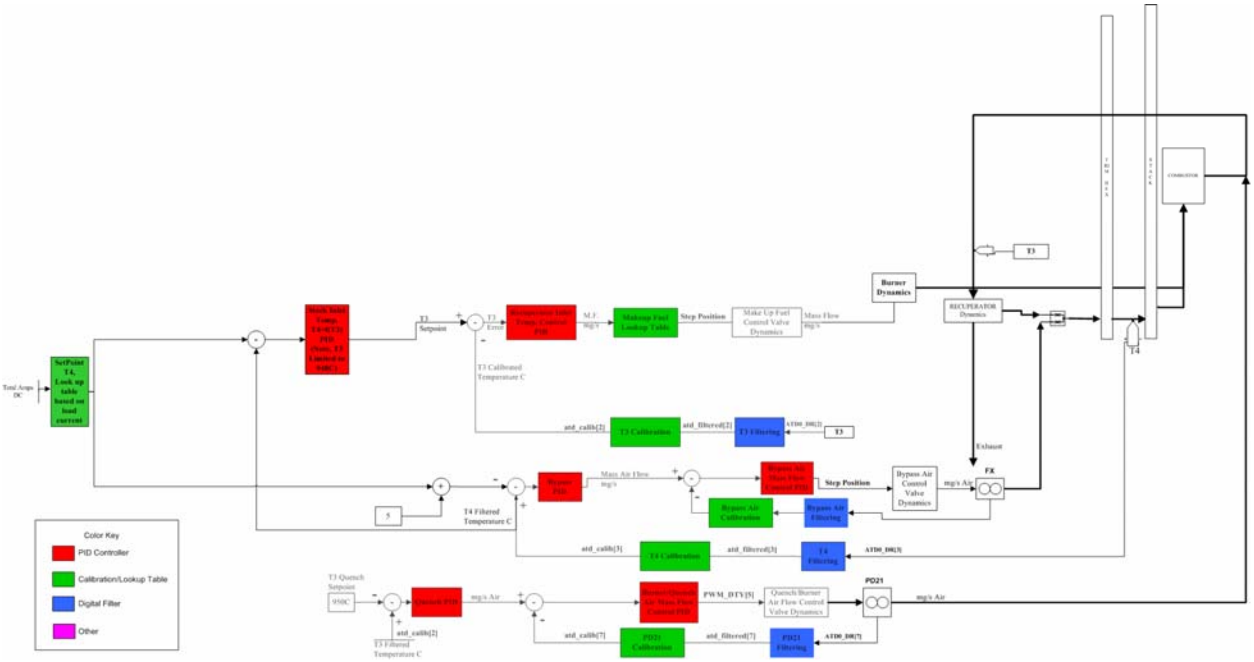

Figure 8.2

C2 Stack Inlet Temperature Control Loops. (Ref. 41244R08, Fig. 90)

In order to tune the system a series of step command experiments were performed on the various mass flow controls, while the resulting temperature transients were recorded by a data acquisition system. The data gathered was then used to construct a dynamic model of the open loop plant dynamics. This dynamic model in turn was used to simulate the closed loop system within Simulink (fig. 8.3). The gains derived from this modeling were used directly in the actual control system and the resulting performance matched the simulated results.

For example, to tune the recuperator inlet temperature control loop, an experiment was performed where by a step change was made to the make up mass flow of fuel and the resulting recuperator inlet temperature response was recorded by the data acquisition system. A dynamic system model was fit to this data and the resulting model was used to tune the closed loop control system via a Simulink software model.

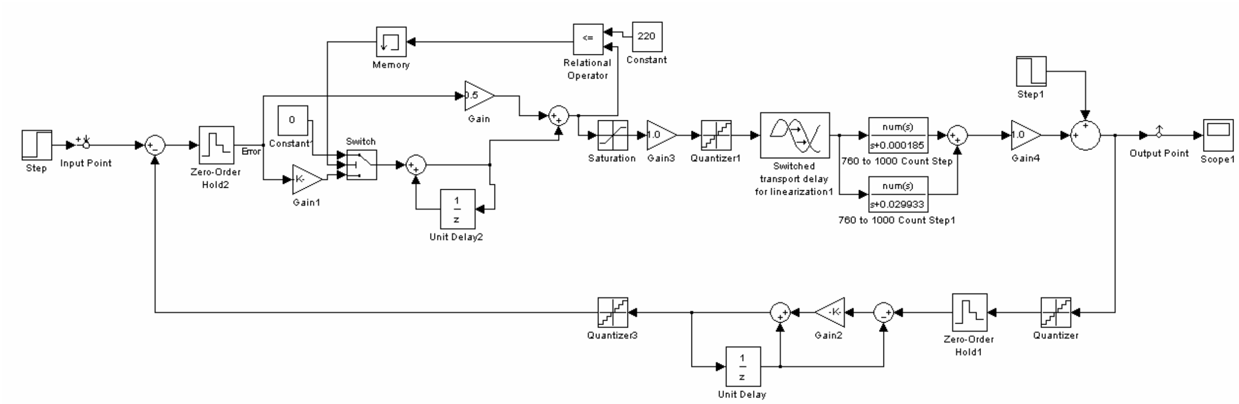

Figure 8.3

Simulink Model of C2 Recuperator Temperature Control (Ref. 41244R08, Fig. 91)

The model derived in this way was accurate enough such that the gains derived could be used directly in the actual system without further tuning. In addition, other control techniques, such as feed-forward, could be tested before implementation with the actual hardware.

The above tuning example was repeated for each individual control loop, starting with the inner most loops and then working outward to the farthest outer control loop. In addition, these tests were also repeated at a number of operating conditions in order to verify the veracity of the modeling. [[redacted]]

8.2 Power Electronics Development

Initial work in this area centered on the review and interfacing of CPG's existing DC-DC boost (Fig. 8.4). In February, a review of DC-DC boost performance, minimum input voltage requirements, and stack compatibility were completed.

CPG was provided a packaging envelope from the baseline system cold balance of plant enabling the DC to DC booster to be located.

Also finalized during the period in joint discussions was the proposed DC loading scheme for system testing. The system will be operated in the constant stack current mode. CPG has selected a water-cooled Amrel DC load for their test facility. During initial testing in Calgary, an alternate VPS load by Torkel will be used.

Fuel Cell Boost Development

The fuel cell boost had to be slightly modified from the design used with the previous systems. A major concern was with boost cooling, the previous system used Cathode air flow to cool the boost prior to induction into the stack, but the VPS stack used much less cathode air flow consequently there would be reduced air flow for boost cooling. In addition, there were concerns about achieving the required cathode blower pressure, with the addition of the heat from the fuel cell boost into the air stream; thus it was decided to separate the boost cooling air from the cathode flow stream. As such a new heat sink design was tested utilizing a separate muffin fan for cooling air flow. This new design was mocked up, tested and found to work well.

The fuel cell boost packaging and internal buss bar connection were also redesigned to fit into VPS packaging envelope. The cooling system and packaging performed well and the efficiency was even slightly improved over the previous package design. The fuel cell boost efficiency versus output load can be seen in Figure 8.5. [[redacted]]

Figure 8.4 CPG DC-DC Boost Tested in M1

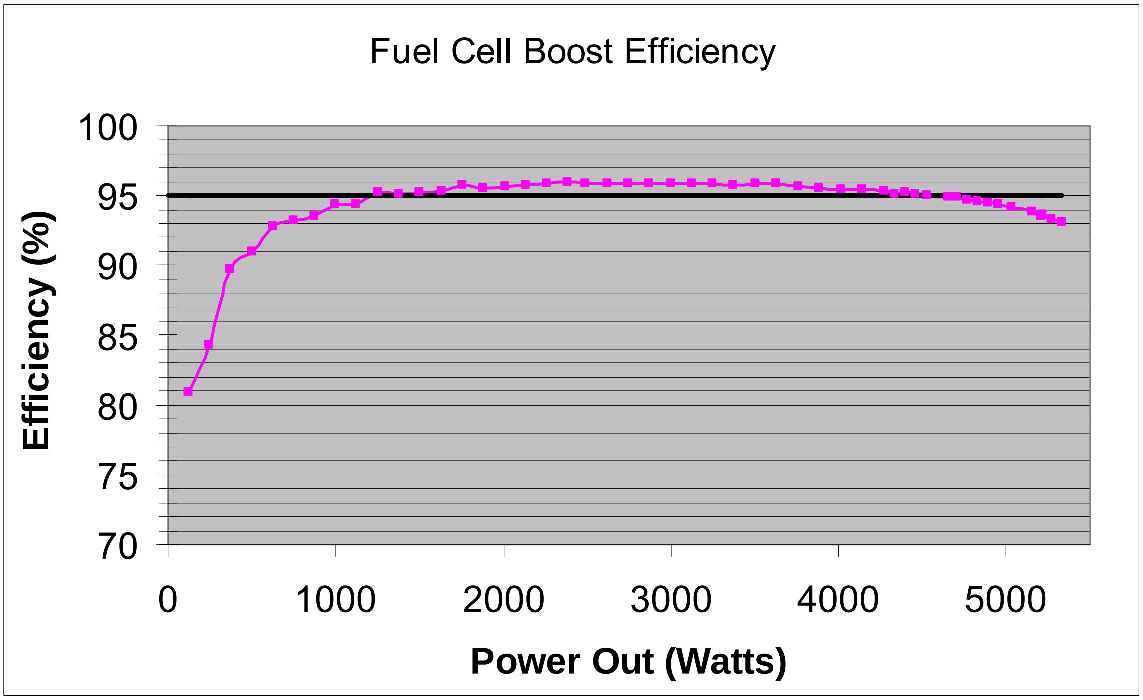

Figure 8.5 M1 Fuel Cell Boost Efficiency versus Load

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9 Phase 1 Test Results

The following section details the results of the M1 Phase 1 test. It is shown that the M1 unit met the performance requirements for the SECA Phase 1 demonstration (Table 9.1). These results were compared to the daily information available from the gas supplier (Ref. TR-CPG-PH1-PUB-R01).

Table 9.1 – Performance Results

RESULTS AGAINST PHASE 1 METRICS		
REQUIREMENT	***TARGET***	***Actual***
Power Rating (Net DC@ NOC)	3 – 10 kW	3.2 kW (4pt. Ave.)
Efficiency Mobile (DCnet/LHV)	25 %	37.1 % (4pt. Ave.)
Steady State Degradation	2 %/500 hrs	1.7 %/500 hrs
Transient Degradation	1 %/10	1 %/10
Total Degradation (1500h + Tran.)	7 %	6.3 %
Availability	>80 %	99 %
Peak Power (Net DC)		4.6 kW
Fuel Type	Commercial Commodity	NG Pipeline

9.1 M1 Phase 1 Test Article

Figure 9.1 is the M1 test article during the Phase 1 evaluation in cell 137 at CPG.

Figure 9.1 Phase 1 Test Article at CPG

10 Outlook

At the end of the Phase 1 program the technology is seen to be approaching the necessary requirements for creating a successful commercial implementation in the core CPG Recreational vehicle power generation market in the five to ten year range. Key technical obstacles are Diesel fuel reforming without water (including Sulfur handling), Cost/Performance, and Durability. Other issues are related to manufacturing process control, start-up times, turndown, and, load management. After some experience in control full SOFC fuel cell systems it is apparent that proper mechanical system design would allow for the utilization of relatively low cost sub-system components and reduce part counts. We are targeting a system response rate of 10 Watts per second and a minimum turn down of five to one. This is a function of balancing the overall power generation system requirements with supplemental battery capacity. The durability/degradation requirement continues to be a function of the start-up time. If start-up is under 15 minutes the system may only require a 2000 hour design life. However, if the star-up time is significantly longer this will become a 20,000 hour design life.

11 Summary

It has been shown that all of the DOE SECA Phase 1 requirements have been met. Performance of note is the DC net efficiency that exceeds both the mobile and stationary requirements. This was achieved with the PCU in the system and taking the additional efficiency hit for an assumed AC inverter loss for the parasitic loads (actual production high level parasitic loads would be powered directly from the DC bus). The system availability was virtually 100% during the required run time. The only shutdown during the steady state, transient, and peak power periods of the test was due to a facility fault and not the system. Table 11.1 re-iterates the results achieved:

Table 11.1 – Performance Results

RESULTS AGAINST PHASE 1 METRICS		
REQUIREMENT	***TARGET***	***Actual***
Power Rating (Net DC@ NOC)	3 – 10 kW	3.2 kW (4pt. Ave.)
Efficiency Mobile (DCnet/LHV)	25 %	37.1 % (4pt. Ave.)
Steady State Degradation	2 %/500 hrs	1.7 %/500 hrs
Transient Degradation	1 %/10	1 %/10
Total Degradation (1500h + Tran.)	7 %	6.3 %
Availability	>80 %	99 %
Peak Power (Net DC)		4.6 kW
Fuel Type	Commercial Commodity	NG Pipeline

The test profile followed the test plan with the minor exception of one unintentional shutdown that lasted for about 4 hours.

An independent auditor (ETS) reviewed the following data to confirm its accuracy:

1. Stack voltage (EE590) at the 4 test points and peak power
2. Stack current (IT580) at the 4 test points and peak power
3. Boost voltage (EE510) at the 4 test points
4. Boost current (IT510) at the 4 test points
5. Parasitic power (WT510) at the 4 test points and peak power
6. Fuel flow rate (F201) at the 4 test points and peak power
7. Lower Heating Value (LHV) at the 4 test points and peak power
8. DC gross efficiency at the 4 test points
9. DC net efficiency at the 4 test points
10. Degradation at the 4 test points (1st point excluded)
11. Peak power at peak power

The performance demonstrated by the CPG/VPS Phase 1 test article was a success relative to the SECA Phase 1 requirements.

Appendix A – Minimum Requirements

MINIMUM REQUIREMENTS			
	PHASE I	PHASE II	PHASE III
POWER RATING (NET)	3kW - 10 kW	3kW - 10 kW	3kW - 10 kW
COST	$800/kW	$600/kW	$400/kW
EFFICIENCY (AC or DC/LHV)	Mobile - 25%	Mobile - 30%	Mobile -30%
	Stationary -35%	Stationary - 40%	Stationary - 40%
STEADY STATE TEST @ NORMAL OPERATING CONDITIONS	1500 hours	1500 hours	1500 hours
	80% availability	85% availability	95% availability
	Δ Power≤2% degradation/500 hours at a constant stack voltage with R≥0.95.	Δ Power≤1% degradation/500 hours at a constant stack voltage with R≥0.95.	Δ Power≤0.1% degradation/500 hours at a constant stack voltage with R≥0.95.
	R-Linear Correlation Coefficient	R-Linear Correlation Coefficient	R-Linear Correlation Coefficient
TRANSIENT TEST	10 cycles	50 cycles	100 cycles
	Δ Power≤ 1% degradation after 10 cycles at a constant stack voltage.	Δ Power≤0.5% degradation after 50 cycles at a constant stack voltage.	Δ Power≤0.1% degradation after 100 cycles at a constant stack voltage.
TEST SEQUENCE	1) Steady State Test -1000 hours 2) Transient Test 3) Steady State Test - 500 hours	1) Steady State Test -1000 hours 2) Transient Test 3) Steady State Test - 500 hours	1) Steady State Test -1000 hours 2) Transient Test 3) Steady State Test - 500 hours
FUEL TYPE	For the complete duration of the Steady State and Transient Tests, operate the Prototype on either a commercial commodity, natural gas, gasoline, or diesel fuel (s) or a representative fuel based on respectively methane, iso-octane, or hexadecane corresponding to the proposed primary application (s). Utilize external or internal primary fuel reformation or oxidation. If multiple applications using different fuels are proposed split the total test time equally among the different fuel types.	For the complete duration of the Steady State and Transient Tests, operate the Prototype on either a commercial commodity natural gas, gasoline, or diesel fuel (s) corresponding to the proposed primary application (s). Utilize external or internal primary fuel reformation or oxidation. If multiple applications using different fuels are proposed split the total test time equally among the different fuel types.	For the complete duration of the Steady State and Transient Tests, operate the Prototype on either a commercial commodity natural gas, gasoline, or diesel fuel (s) corresponding to the proposed primary application (s). Utilize external or internal primary fuel reformation or oxidation. If multiple applications using different fuels are proposed split the total test time equally among the different fuel types.
MAINTENANCE INTERVALS	Design aspects should not require maintenance at intervals more frequent than 1000 operating hours.	Design aspects should not require maintenance at intervals more frequent than 1000 operating hours.	Design aspects should not require maintenance at intervals more frequent than 1000 operating hours.
DESIGN LIFETIME	Not less than 40,000 operating hours for stationary applications and 5,000 hours for transportation applications for military uses.	Not less than 40,000 operating hours for stationary applications and 5,000 hours for transportation applications for military uses.	Not less than 40,000 operating hours for stationary applications and 5,000 hours for transportation applications for military uses.