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Program Area of Interest: Fuel Transformer Solid Oxide Fuel Cell

Abstract
The following report documents the technical approach and conclusions made by Acumentrics Corporation during latest budget period toward the development of a low cost 10kW tubular SOFC power system. The present program, guided under direction from the National Energy Technology Laboratory of the US DOE, is a nine-year cost shared Cooperative Agreement totaling close to $74M funded both by the US DOE as well as Acumentrics Corporation and its partners. The latest budget period ran from January of 2006 through June 2006. Work focused on cell technology enhancements as well as BOP and power electronics improvements and overall system design. Significant progress was made in increasing cell power enhancements as well as decreasing material cost in a drive to meet the SECA cost targets. The following report documents these accomplishments in detail as well as the layout plans for further progress in next budget period.

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INTRODUCTION

Acumentrics Corporation has focused during the latest six-month budget period of the SECA program on the design and manufacture of micro-tubular SOFC power systems approaching twice the power density now achieved from state of the art anode supported tubular designs. By developing a common stack design with high power density cells capable of meeting the SECA cost targets, a number of markets will be opened to this technology. Present markets being focused upon include telecommunication, remote residential, and military markets. Operation on fuels including natural gas and propane will be developed for the telecommunication and remote residential markets. These fuels will be developed and demonstrated during Phase I of the program. Operation on liquid fuels, including diesel and JP-8, will be developed for the military markets. These fuels will be developed and demonstrated during Phases II and III of the program.

The overall goals of Phase I of the program, which represents three years of development, include:

1. Design of a common low cost generator to meet all chosen markets.
2. Development of an anode supported micro-tubular cell capable of twice the power density presently achieved.
3. Prototype testing of a natural gas or propane fueled unit meeting and exceeding SECA goals.

The research and development to achieve the above goals can be listed in three major sub-tasks:

1. **System development and integration** – In this task work is focused on the functionality and cost reduction of major BOP components. Thermal hydraulic components are being developed and tested as well as the necessary control strategies. Power electronics and control hardware is being refined and cost reduced to meet the goals of the program. Work is also concentrating on thermal recovery and burner designs for stationary and mobile applications.

2. **Cell Technology Development** – In this task work is focusing on improvements in cell power density through material changes and refinements. Composition and morphology of the anode, electrolyte, and cathode are all being addressed to increase cell power.

3. **Stack Technology Development** – In this task work is focused on generator design and assembly to reduce cost and improve reliability. Connections to the anode and cathode for current collection are being optimized. Casting of insulation to net shape or near net shape is also a focal point for cost reduction.

EXECUTIVE SUMMARY

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During this past budget period, a number of accomplishments were made. They include:

- **Ceramic Interconnection Stack Test Exceeds 1400 hours of Operation:** The first small stack test incorporating ceramic interconnections has exceeded 1400 hours of operation and completed thirteen thermal cycles. To date, there has been no noticeable degradation. Further testing will be completed in the next six month period.

- **Ceramic Interconnection Stack Test Exceeds 2400 hours of Operation:** The first small stack test incorporating ceramic interconnections has continued to operate in the latest reporting period and has now exceeded 2400 hours of operation and completed fourteen thermal cycles. There still has been no noticeable degradation.

- **Prototype Assembly:** A prototype system has been fabricated to complete SECA Phase I testing. This system incorporates the latest cell technology advancements as well as generator and BOP enhancements. The unit will be tested in the next few months according to the outlined SECA test plan.

- **Commencement of the SECA Phase I Machine Prototype Testing:** The SECA Phase I machine commenced testing on June 27, 2006. The unit was started from room temperature to net operating power in approximately 1 hour and started to supply power to the local grid. Initial data was taken on temperatures and power conditions and the first stage 1000 hour run was commenced.

Task 1.0 - System Development and Integration

Subtask 1.1 – Prototype Stationary System Design

A 264-cell version of a horizontal stack, chromite cell, generator CAD model was prepared. Each stack will consist of 11 cell manifolds (6 cells per manifold, a single cooling injector and two end of cell support manifolds. The stacks contain end of cell supports as described in Section 3.3 to support the cells at both ends rather than having them cantilevered from the manifolds.

Differences between this design and the earlier single ended current collection design are:

- The fuel cell module is 3 inches wider to accommodate the longer cells
- Fuel Cell Module height reduced
- The plenum is wider to distribute air uniformly under cells
- The downcomer transitions from existing recuperator to wider cells
- End of cell stack supports added
- End of cell shipping lock down feature added
- Offgas flame shield added
- Silver rod power leads
- Power lead cooling
- Thermocouple lengths adjusted to match interconnect spacing

Methods of delivering the off gas collected in the off gas chamber of the stack manifolds to the down comer have been evaluated. This configuration is being evaluated to eliminate the over heating of the upper stack cells from the combustion of the off gas in the cathode air stream between the stack and recuperator, and to improve the low power operating efficiency through the direct use of the off gas to raise the temperature of the cathode air.

Several of the design changes associated with triple chromite cells that are being incorporated into the Stationary System Prototype were built and tested in a pre-prototype generator. The results of this testing is described in Section 3.0

Final thermocouple and voltage sense maps along with interconnection schematics were prepared for the prototype generator.

Subtask 1.2 – Prototype APU System Design

No work to report this period.

Subtask 1.3 - Control Strategy Development

The new fuel cell control board design was completed in January. Software development of a new real time operating system (RTOS) for both the fuel cell controller and inverter controller has commenced.

Updates to the current generation control system have been made for the testing of higher power cell bundles.

The current control system has been modified to allow the control of two power converters (in parallel) between the fuel cell and balance of plant. This is necessitated by the increase in output current of our cells, which has driven the output current of existing generator designs beyond 200 Amps (the limit of our existing converter design).

New ideas were explored to improve the reliability of control system connections and to further improve the reliability and cost of the fuel cell electrical systems. The most promising involves the replacement of substantial parts of the wiring harness with mass-terminable cable assemblies, and integrating the fuse requirements onto a printed circuit board.

The present wiring scheme is shown in Figure 1 and requires 8 connector assemblies at the bulkhead and hundreds of individual connections. The interim scheme shown in Figure 3 makes use of mass-termination cable assemblies between the control board and bulkhead routing board. The bulkhead routing board has connectors on the reverse side for GUM and cell voltage connections and handles all of the point-to-point connections required. The bulkhead board only requires a single penetration through the bulkhead, replacing 7 connectors in the existing scheme. The separate fuse block was integrated onto the bulkhead board. Further analysis will be made of the interim scheme as well as an advanced solution to remove all cabling between the control board and the bulkhead board, migrating to a board-to-board connection.

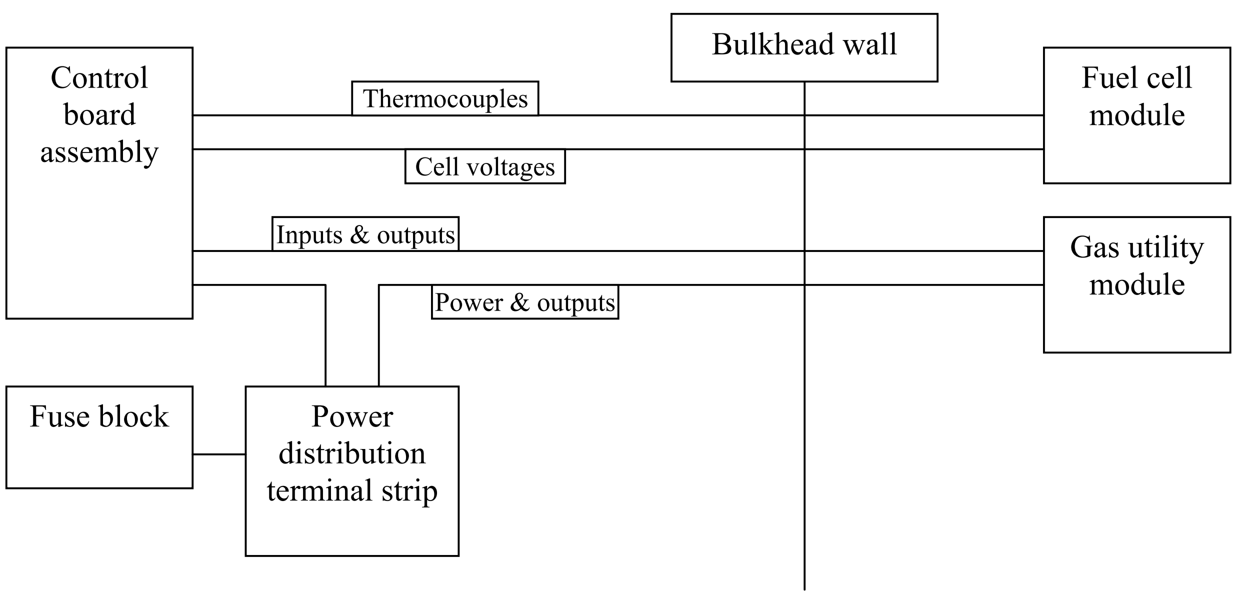


Figure 1: Existing wiring scheme

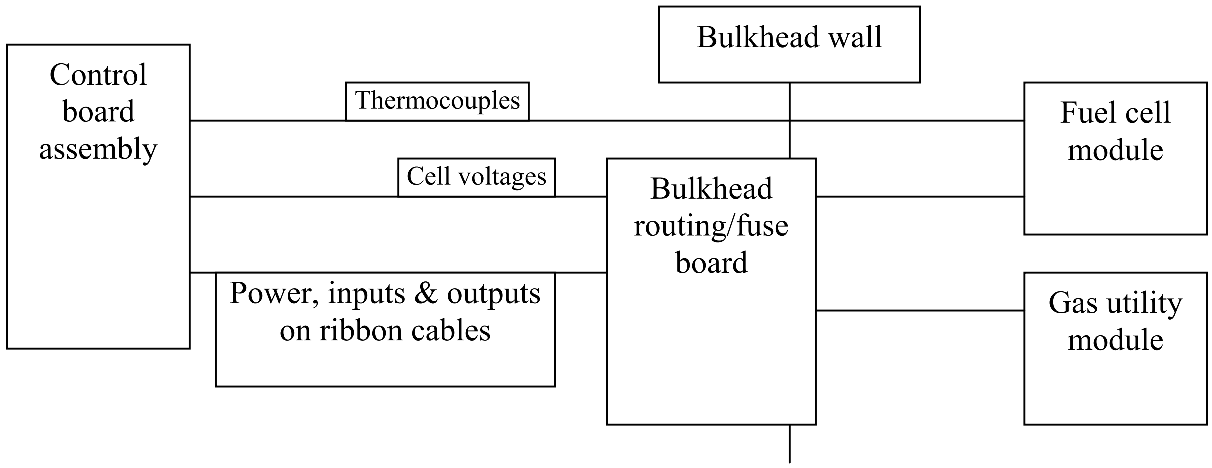


Figure 2: Interim wiring scheme

The new control board has been debugged and basic functionality of the control algorithms has been established. Paralleling of power converters has been achieved to allow operation beyond 200 Amps.

A new printed circuit board to streamline the assembly of the communications interconnections has been developed, built and tested.

Calibration algorithms for the new control board have been implemented for the phase-1 test unit. The algorithms will be refined and the calibration process streamlined to allow for automation. The communications routing circuit board is being used on the phase-1 test unit.

New firmware has been developed for the phase-1 test unit to allow for the developments in the gas handling equipment and additional monitoring requirements.

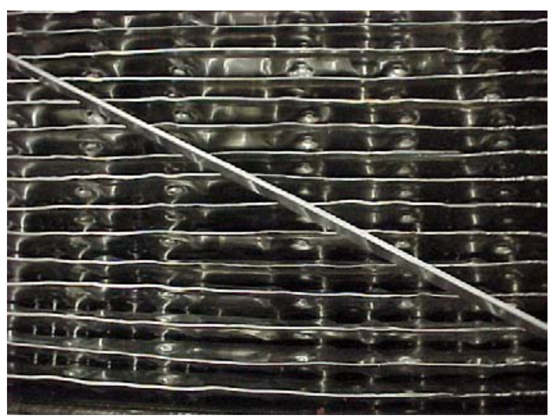
Subtask 1.4 – Heat Recovery

Contractual arrangements were finalized and fabrication of a folded sheet plate recuperator has been completed. The design of the unit was modified to fit the footprint of the vertical stack geometry.

A company completed fabrication of the folded sheet, counter flow recuperator. Airside inlet and outlet headers were also fabricated and the unit was installed in the recuperator test stand. Exhibits 1 and 2 show the assembled unit with the air outlet plenum installed. The plenum is sized to permit incorporation of the unit with the standard 5 kW downcomer duct and burner. Also included are photos of the air and exhaust side heat transfer surfaces. The exhaust outlet port shows the folded sheets and the air inlet port shows where there sheets are crimped and resistance welded together to from two separate, air tight flow compartments on either side of the folds. Also visible in the photos are the dimpled features stamped into the sheets to provide the proper sheet spacing as well as extended surface area.

Exhibit 1: Folded Sheet Counter Flow Recuperator

Exhaust Outlet



Air Inlet

Exhibit 2: Recuperator Construction Details

Exhibit 3: Unit Installed in Recuperator Test Stand

Pressure drop and leakage measurement were made on the unit prior to installation into the test stand. As shown in Figure 3 the unit has extremely low-pressure drop with the pressure drop essentially equal on both the air and exhaust sides. At 5" (w.c.) the unit had a leakage rate of 20 lpm, which is probably attributable to the plenum gaskets and sealing gaskets rather than an actual leakage across the heat exchanger surface. Also shown, in Exhibit 3, is the unit installed in the recuperator test stand prior to final insulation installation. The recuperator was sized with a vertical stack configuration in mind and therefore the width of the unit is much narrower than the horizontal stack/cross flow recuperator test stand configuration. A refractory transition piece was made to direct the exhaust flow to the exhaust inlet. Shakedown testing of the test stand was completed and performance operation will be conducted during the next reporting period.

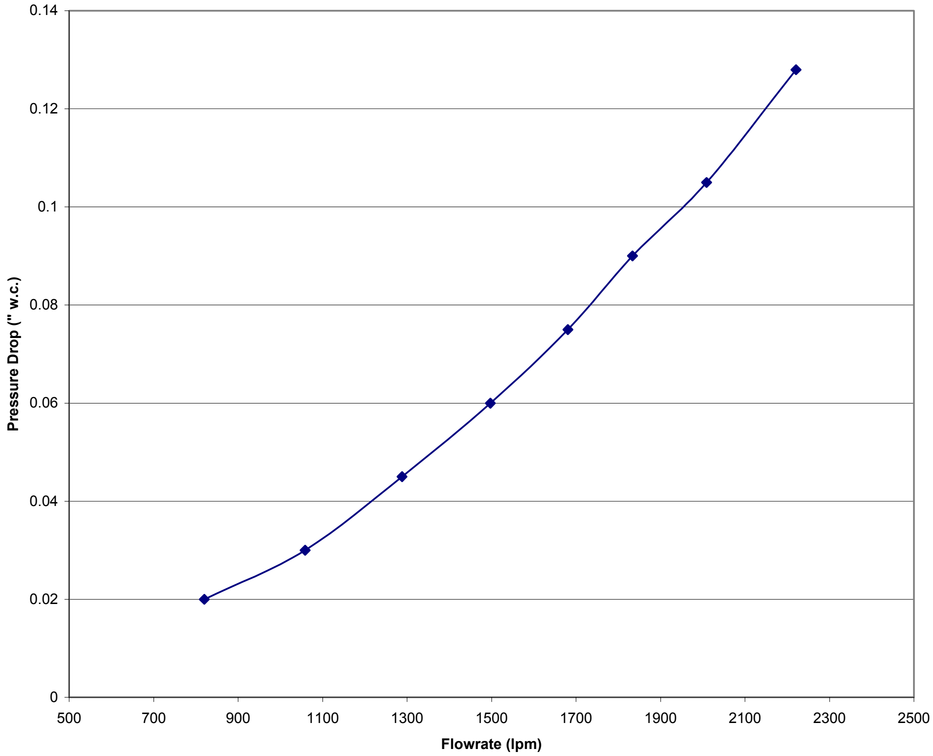


Figure 3: Measurements Prior to Installation

In general, the recuperator did not meet the required effectiveness of approximately 86%. The effectiveness at the design flow rate was approximately 68% based on the temperature measured at the inlet plenum of the recuperator.

It appears that there is significant short-circuiting or bypass of the flow on both the air and exhaust sides. This is illustrated by a thermal image of the casing during operation as shown below. Further indication of this temperature gradient is the condition of the casing after operation as shown in Exhibit 4.

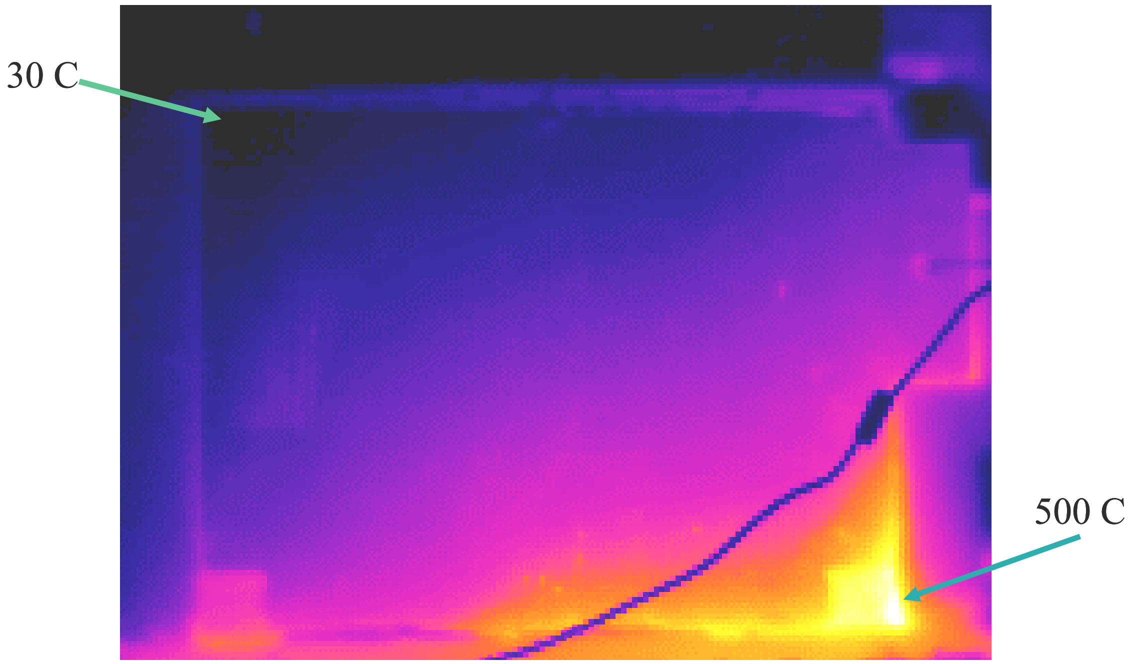


Exhibit 4: Thermal Image of Casing

Exhibit 5: Casing Discoloration After Operation

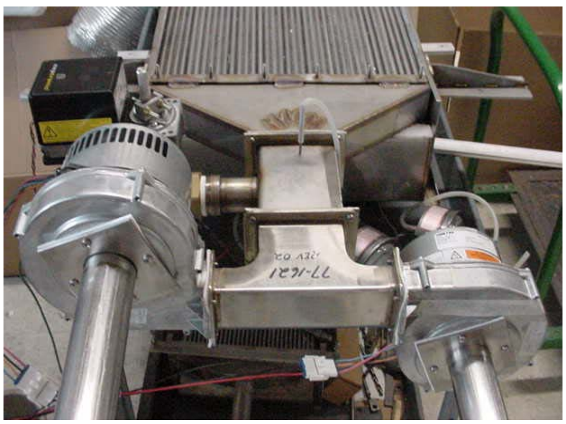
Further evidence of non-uniform flow is the vertical temperature gradient at the air outlet plenum measured at approximately 150 C. For example, at the horizontal centerline, the air preheat temperature at the base of the plenum was 637 C, 50 mm up the air temperature was 553 C and another 50 mm up the temperature was 509 C. Because of this wide vertical distribution in the plenum, the air preheat temperatures measured in the outlet duct (down comer) were felt to be the most accurate since the flow had a chance to mix and a truer average temperature was therefore measured.

Exhibit 6 shows the exhaust outlet plenum with internal insulation and thermocouple installed. Even with this restricted flow opening, the measured exhaust outlet temperature was very sensitive to the vertical position of this thermocouple.

Exhibit 6: Exhaust Outlet Plenum

In order to improve the contact zone between the air and exhaust streams, a block of insulation was placed in the air outlet plenum of the recuperator as well as the air outlet transition piece. At the air inlet, a piece of ceramic fiber paper was glued to the perforated sheet. The air inlet port was restricted to a width of 300 mm and the air outlet port was restricted to a height of 50 mm. This was done to force the bulk of the air flow to regions of the metal plates that were adjacent to the exhaust flow and to restrict the air flow away from areas where the exhaust flow was short circuiting the heat transfer surface. The exhaust outlet port remained the same as at the end of the previous test, restricted to a height of approximately 50 mm. The test results with these modifications are given in the summary table above (Test Conditions 4 –6). In general, there was only a slight improvement in the performance for each of the test conditions. At the design flow rate of approximately 1060 slpm the performance improved from 68.2% to 70.3% effectiveness based on the exhaust inlet temperature.

The prototype generator recuperator was received from the manufacturer and modifications were made to enable cathode air bypass, support the offgas manifold and locate thermocouples below the exhaust side entrance. Flow testing was conducted to determine the baseline (ambient temperature) pressure drop on the airside. This testing also verified the ability to operate with dual or single fans. Orifice tubes were designed and manufactured for measuring the cathode airflow at the blower inlets. The photos (1&2) below show the cathode air blowers and associated recuperator inlet transitions and orifice inlet tubes as well as the third pass bypass air inlet.



(Photo 1)

(Photo 2)

Recuperator with Cathode Blowers and Bypass Inlet

Subtask 1.5 – Burner Design

Burner operating hours have continued to be accumulated on bundle testers and stack testers.

A new burner was installed in Stack Tester #1. It was found that insufficient primary was being delivered to the burner and carbon build up in the burner ports was resulting in temperature non-uniformity in the cathode air reaching the bundle.

Subtask 1.6 - Gas Utilities

Valves

Over the past year, valves have been utilized on test stands to regulate the burner fuel. The valves have continued to be plagued with sticktion and the maintenance required to ensure the valve retains good burner performance has become problematic, especially on test stands that are conducting long-term tests. For this reason, two alternative valves are currently being tested on the burner lines of two Stack Test stands. The two proportional valve were installed on two Stack Test Stands and have operated flawlessly for more than 1000 hours. Due to slack in the valve gearing, the rotary valve creates a small continuous oscillation in the temperature data and consequently voltage data. This characteristic does not appear to affect the performance of the components under test, but does mean some averaging is required to compare data points.

Two samples of a linear actuator have been obtained. A control board was purchased so as preliminary testing can proceed. These actuators may provide a means to developing a viable alternative to the bulky valves, which are currently used to control various airflows in the 5kW generators. Testing will define control and mechanical operating characteristics, which will assist in designing multi-airflow manifolds and air bypass configurations. Using these actuators will reduce the size, weight, power consumption and price of the airflow control components.

Trial Generator P&ID

As part of the design process the pressure drop through the GUM components with flow was calculated. At 40 LPM the pressure drop through the GUM is calculated to be 2.7”, neglecting losses from fittings and the flex line, which is used to connect the cabinet bulkhead fitting to the GUM. The pressure-flow calculations will be verified against experimental measurements. Measurement of actual subsystem and component pressure/flow characteristics are underway.

Gas Utility Modules

Two gas utility modules has designed and built for the SECA phase 1 generator test requirements. SECA generator 1 is being designed using a horizontal stack geometry, with enhanced gas utilities. Mass flow controllers operating on bottled methane will be used to rule out issues related to variable natural gas quality, and ensure accurate flow measurement. The P&ID for this generator is shown in Figure 4.

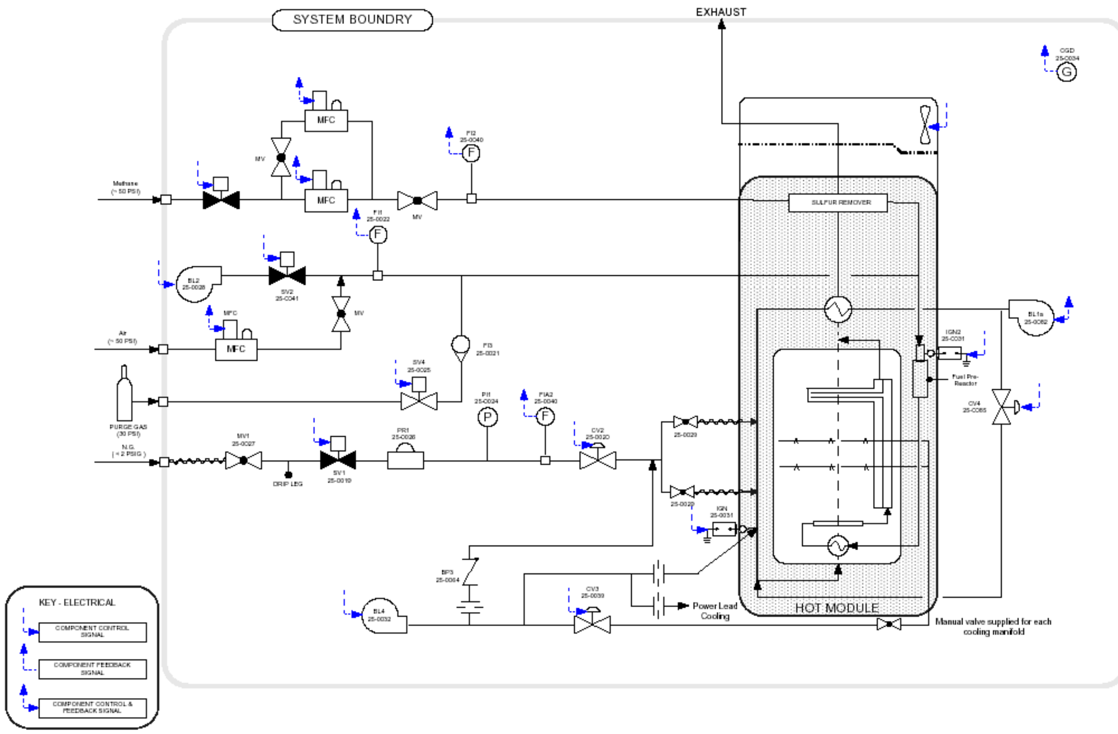


Figure 4: P&ID for SECA Generator 1 test layout

SECA generator 2 represents an alternative geometry, with a vertical cell stack configuration, operating with gas utilities more representative of the current 5kW products. The P&ID for this unit is shown in Figure 5. The Gas Utility Modules will be, with slight modification, interchangeable on the two units.

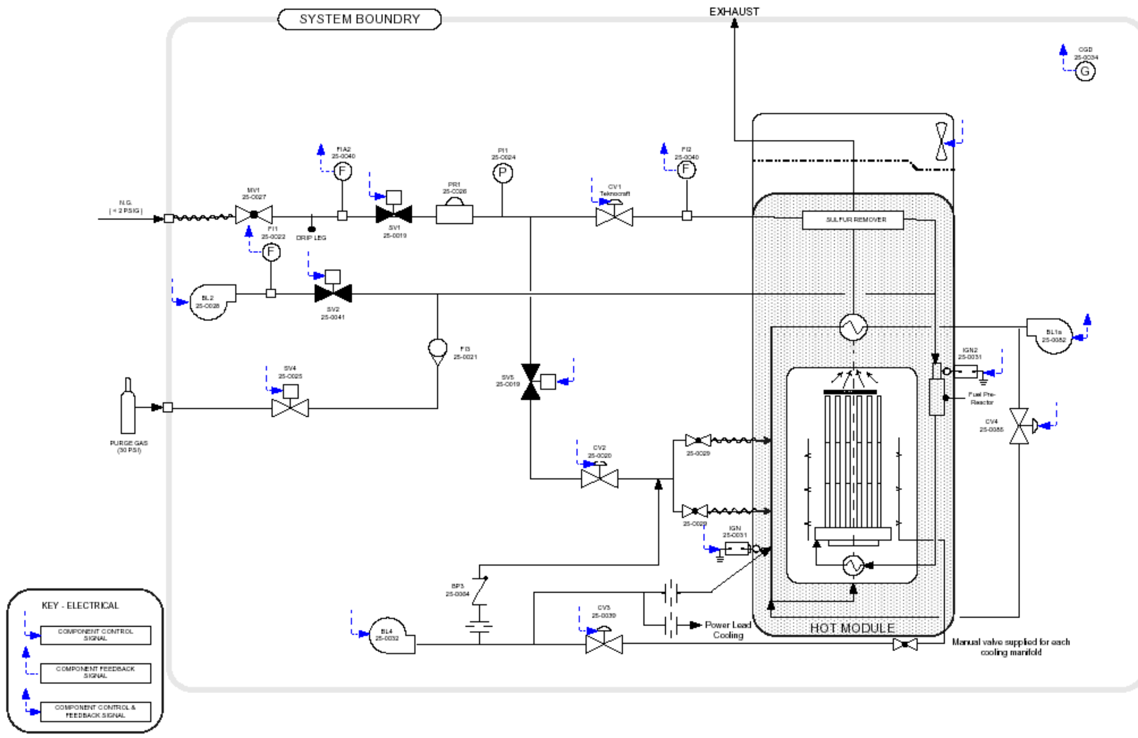


Figure 5: P&ID for SECA Generator 2 test layout – Vertical stack configuration with production orientated gas utilities

A gas utility module meeting the flow and dimensional requirements of the prototype generator was designed and assembled. The initial version of this design will be used to operate a four stack, triple chromite current collection, test generator. The Gum layout was modified to suit the lower fuel cell module profile afforded by the shorter 11 manifold stacks. Other changes include relocating the Anode air supply blower to the right side of the GUM, reducing the length of airline required. The Primary and Cooling Air Manifold (PCAM) has been modified, with a reduction in length of the manifold, and addition of two additional air ports. A manual valve has been installed on one of the air ports to supply cooling air to the power leads. A fuel flow meter has been installed on the front end of the generator to monitor total fuel consumption, and track burner performance. A photo of the assemble unit is shown in Exhibit 7.

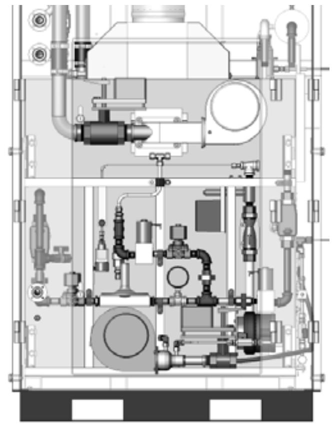


Exhibit 7: GUM illustrated in a CAD drawing used to finalize final integration of the GUM with the Hot Box and cabinet

No further problems have been experienced with the fuel cell stack thermocouples. The solution implemented involves the use of a higher quality ceramic insulator, and placement of the thermocouple so that the insulator (sheath) does not touch the current collection.

Subtask 1.7 – AC/DC Inversion

Fabrication is done and testing of the inverter control board continues. The power supply and DSP sections have been tested and communication with the DSP has been established. Incremental circuit builds and test stages will follow.

An initial inverter power board design is laid out to evaluate a novel thermal management design, testing commenced in late February.

The schematic design for a prototype power stage of a single H-bridge PWM amplifier has been completed. Each of the four switches in the amplifier is to be implemented using four paralleled MOSFETs. The amplifier will be implemented on a high power printed circuit board, the layout of which is ongoing. The preliminary board layout is shown in Figure 6.

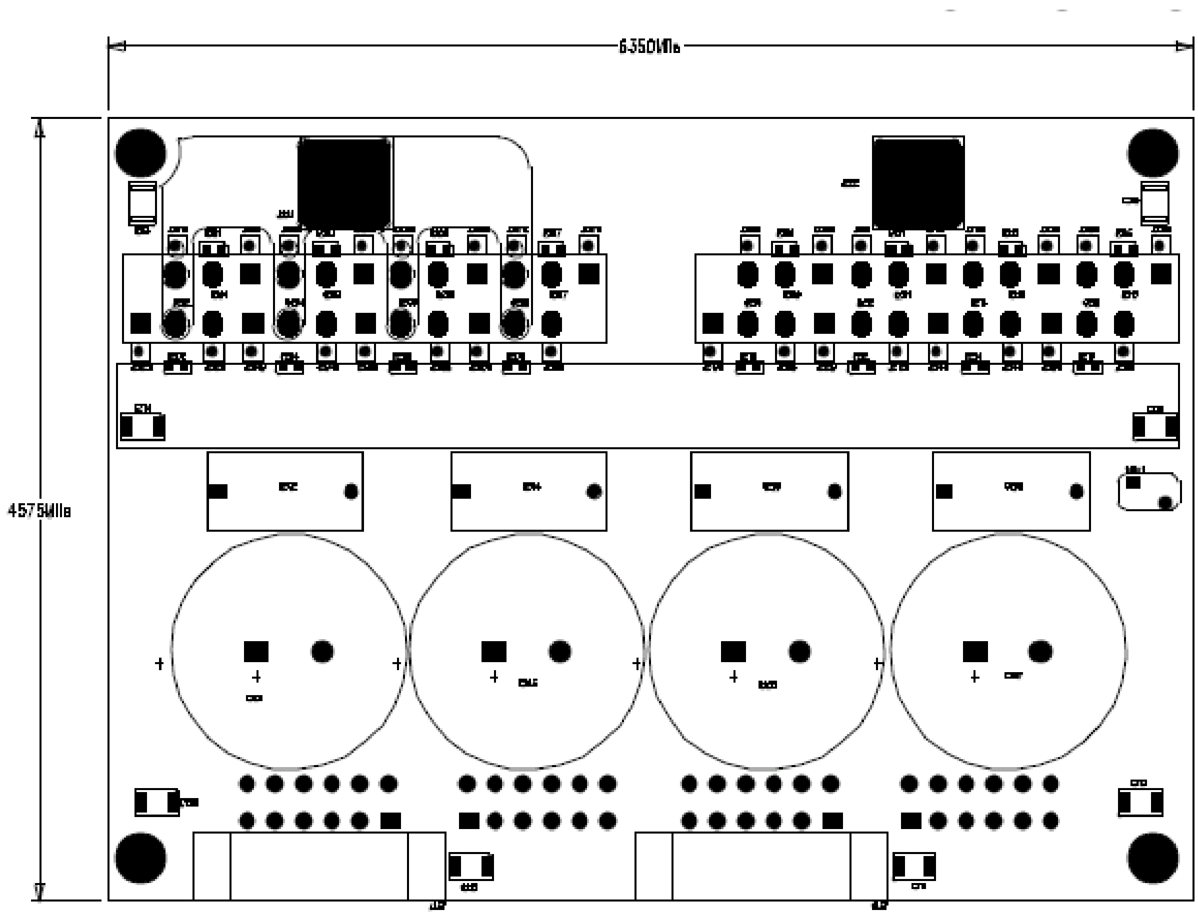


Figure 6: Fuel Cell Inverter PWM Amplifier PCB Layout

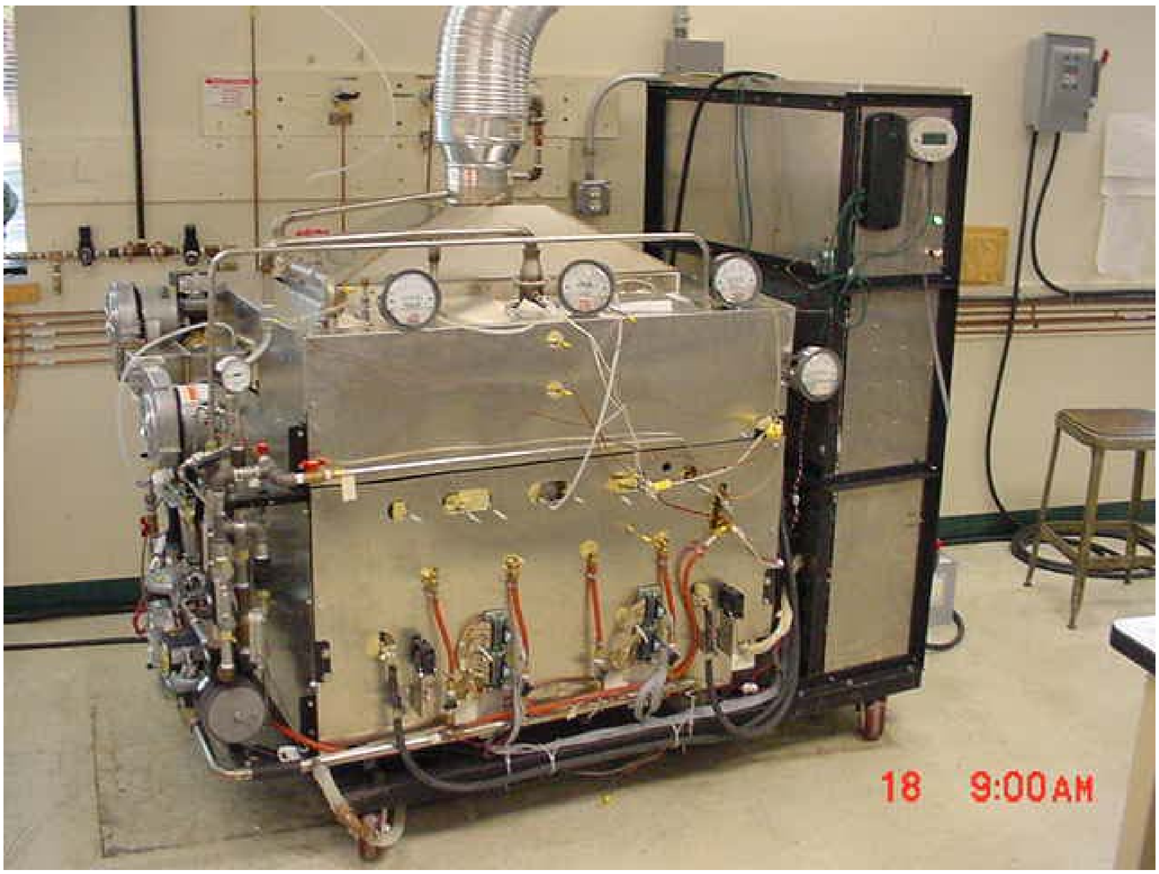
Software for the inverter control is developed and will eventually be tested with our previous “proof-of-concept” inverter hardware.

Most major functions and inputs / outputs on the inverter control board have been successfully tested. Communications to a PC based monitoring application have been established.
Control software from the inverter simulator development effort is being ported into the control board. This includes both control and calibration algorithms. These are being combined with RTOS upgrades into the TI DSP/BIOS system, as was done for the fuel cell controller.

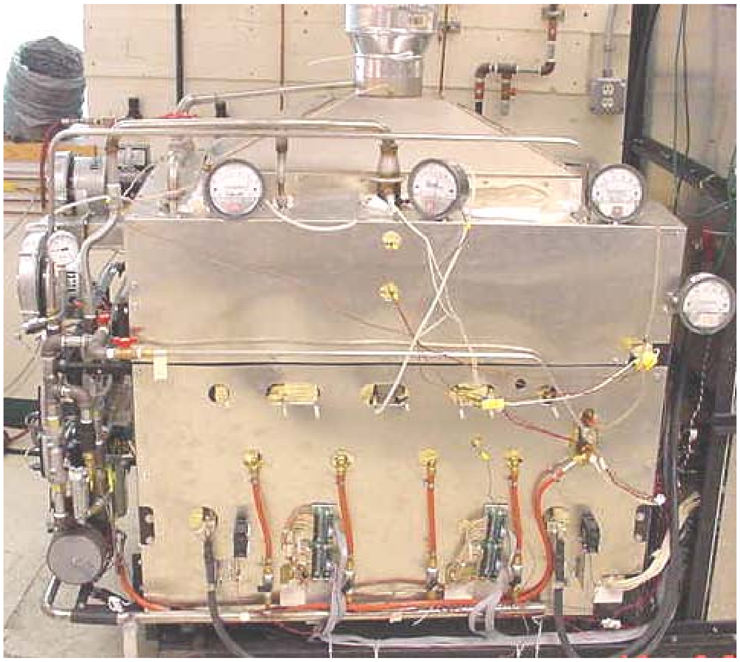
Once these efforts are completed the control board will be calibrated. It will then be interfaced to a FCIC dc/dc converter (modified to function as a dc/ac inverter) to function as a control development platform.

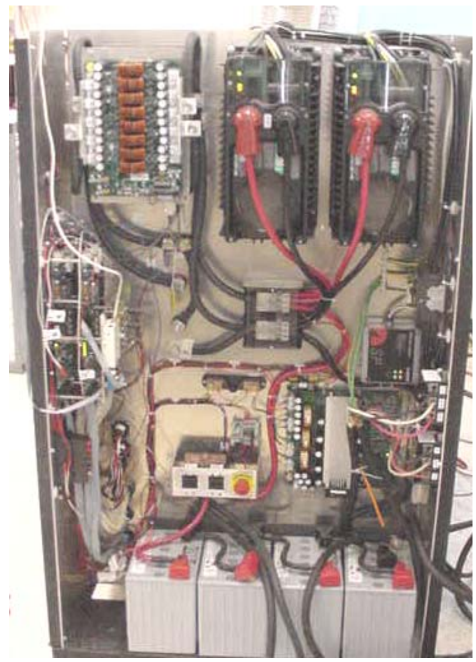
Subtask 1.8 Prototype Assembly

The assembly of the prototype stationary generator was completed and integration of the fuel cell module, gas utility module and control system was successfully carried out. The photos on the next page show the completed system in its test location.



(Photo 3)





(Photo 4) **(Photo 5)**

<u>Task 2.0 – Cell Technology Development</u>

Subtask 2.1 -- Anode Tube Composition Optimization

No work to report this period.

Subtask 2.2 – Electrolyte Composition

A number of standard production fuel cells were measured to have high cathode to anode resistances during processing, but developed low resistances during cell testing. This did not appear to affect cell performance, as would have been expected. These standard cells have silver paint overlapping the cathode and electrolyte on the braze cap side. It has therefore been hypothesized that the problem is due to pinholes in the electrolyte, which the silver migrates through to short the cell.

In the following experiment cells will be developed with improved electrolyte coatings to address this issue. To evaluate this, four processing variables, listed below, will be examined.

1. Double Dip

   It is envisaged that a second dip into electrolyte slurry should cover any pinholes left by the first dip. To achieve this, tubes will be dipped once, dried, dipped a second time, dried and sintered normally.

2. Longer Dip

   Longer dip times will be evaluated to determine if this improves the leak tight nature of the electrolyte. For this trial, the dip time will be increased to greater than 13 seconds to increase coating thickness. The tubes will then be dried and sintered normally.

3. Higher Sintering Temperature
   Higher sintering temperatures will also be evaluated for standard tubes that have been dipped and dried in a standard way.
4. Longer High Temperature Hold
   Finally, longer sintering times at standard sintering temperatures will be evaluated in an effort to create a denser electrolyte and eliminate porosity. The tubes will again be dipped and dried in a standard way.

<u>Outcome</u>

All of the tubes sintered were fired in the same furnace with the same kiln furniture setup. Exhibit 8 shows the kiln furniture setup utilized to sinter the control and experimental cells.

Exhibit 8: Kiln Furniture Setup to Sinter Control and Experimental Electrolyte Cells

After sintering, tube shrinkage and color of the anode was determined. Higher sintering temperatures and longer soak times yielded tubes that shrunk more and appeared a darker green in appearance as expected.

An inspection for defects in the electrolyte coating was also conducted after sintering. Four types of defects were found and reported.

The tubes that survived the sintering were reduced under hydrogen so that a leak rate and the anode-to-anode resistance along the length of the tube could be determined.

Tubes were then sectioned into three parts, so that microscopy could be performed to determine the electrolyte coating thickness along the length of the cell from the different electrolyte process conditions performed. Table 1 displays the electrolyte coating thickness results obtained from microscopy.

Tube	Code*	Fuel In (μm)	Middle (μm)	Fuel Out (μm)	Average (μm)	*Stand Dev*
C380108	Control	22.1	21.8	19.3	21.1	1.6
C380100	DD (4/9 sec)	49.3	45.0	42.8	45.7	3.0
C380095	LD (25 sec)	30.2	29.7	28.2	29.4	1.3
C380093	LD (17 sec)	27.5	27.1	25.3	26.6	1.7
C380084	LH (6 hr)	22.3	20.3	19.2	20.6	1.8
C380080	LH (4 hr)	22.4	21.6	20.0	21.3	1.6

* **Code:** (DD: Double Dip), (LD: Longer Dip), (LH: Longer Hold)

Table 1: Electrolyte Thickness Along the Length of the Cell Produced from Different Electrolyte Processing Parameters

The fuel in section of the tube is slightly thicker than the other sections. This is because the tubes are dipped vertically and this section is the first to be dipped and the last section out of the slurry tank.

<u>In Summary</u>

- The leak, as measured by vacuum decay, for standard tubes was between low. This rate reduced significantly for tubes that had been sintered at higher temperature and at the standard temperature for longer times.
- Tubes that underwent a double dip also showed good leak rates but these tubes have a excessive electrolyte thickness.
- Tubes which had a longer dip time but were fired at the same temperature as standard tubes, showed no improvement over standard tubes.
- Using a double dip technique but the same total dip time as a standard tube resulted in an electrolyte thickness that was roughly double the thickness of a standard cell.

Subtask 2.3 – Cathode Composition

No work to report this period

Subtask 2.4 - Cell Testing

Instrumentation software for the new methane fueled CPOX test-stand has been debugged and is currently monitoring cells under test.

A new test stand has been developed to cater for testing of bundles of cells at the substantially higher current levels of the latest cells. This stand will allow for testing at up to 600 A and/or 4 kW. The stand has been completed, and is currently testing 30 cells of the triple inter-connect design.

Modeling

Heat transfer due to conduction, convection and radiation was incorporated into the cell model. The convection heat transfer coefficient was estimated as 5 W/m^2K from correlations and a surface emissivity of 0.3 was assumed. Predictions for the triple banded La Cr cells are shown in Figure 36. Again no fitting was performed – the same exchange current densities were used, as used previously in the validation of the DB model performed in early 2004

Although agreement is fair the thermal model does over predict the performance at high current densities. A comparison of the isothermal and thermal predictions, suggests that this could be due to an over-estimate of the temperature, or the influence of temperature on the electrode over potentials.

Task 3.0 Stack Test Development

Subtask 3.1 – Cathode Current Collector Improvements

An investigation is underway to evaluate cells with lanthanum chromite ($LaCrO_3$) plasma sprayed bands as an alternative anode interconnect to the nickel braze cap currently used. Cells have already been produced and evaluated with a single central sprayed band and multiple sprayed bands of lanthanum chromite. Encouraging cell test results for both single and triple banded chromite cells have been obtained. Cells of this nature allow for the anode current to be collected from three positions along the length of the cell, thus lowering resistive losses, resulting in increased cell output.

However, a cell with three $LaCrO_3$ bands creates a challenge when trying to dip coat the cathode since it must not come into contact with the chromite interconnects. For the initial experimental three banded cells that were cathode coated, the chromite region was masked off with tape before coating, dipped, then the masking tape removed. This process is labor intensive and cumbersome. In addition, time was also spent cleaning off excess cathode from the cell where it had traveled under the tape during dipping and therefore a risk of shorting in the finished cell was also present.

The promising performance of cells with three $LaCrO_3$ bands distributed along their length has prompted the need to simplify cathode application on such cells. A new cathode dipping regime has therefore been designed and developed to allow significantly improved cathode consistency and decreased dipping times of the applied coating.

Outcome

To achieve three uncoated areas of cathode along the length of the tube using a single dip, two cathode receptacles were designed and fabricated from polycarbonate, each with a filler piece made of PVC and two polycarbonate inserts to create gaps in the cathode around the $LaCrO_3$ bands. The third gap in the cathode was obtained by adjusting the space between the two cathode tanks, which these then sit on top of a reservoir tank.

- The new dipping fixture produces cathode coatings which appear visually more uniform than the previous coating methodology.

- A significant reduction in cathode application time for dip-coating tubes with three $LaCrO_3$ bands has been achieved by redesigning the cathode tank to allow for three uncoated sections.

- The two-cathode dip tanks are adjustable in that placement of the cathode coatings may be adjusted to optimize cell design.

Subtask 3.2 - Anode/Cathode Current Collection

The single chromite band 5 manifold bundle (BT-101805) remained on test and has accumulated 1330 hours of operation under load as of 1/31/06. The bundle is on its 14th thermal cycle. During this month there were three thermal cycles taken, two resulting from mass flow controller oscillations that created air/fuel ratio faults and one resulting from overheating of a power capable and corresponding loss of load.

<u>Stack Tester #3</u>

Fabrication and check out of a stack tester capable of testing the longer, higher power, chromite cells was completed. Calibration of the mass flow controllers was performed and a hot shakedown test confirmed that all systems were operational prior to placing a chromite bundle into the hot box. Exhibit 9 shows the tester at the completion of assembly.

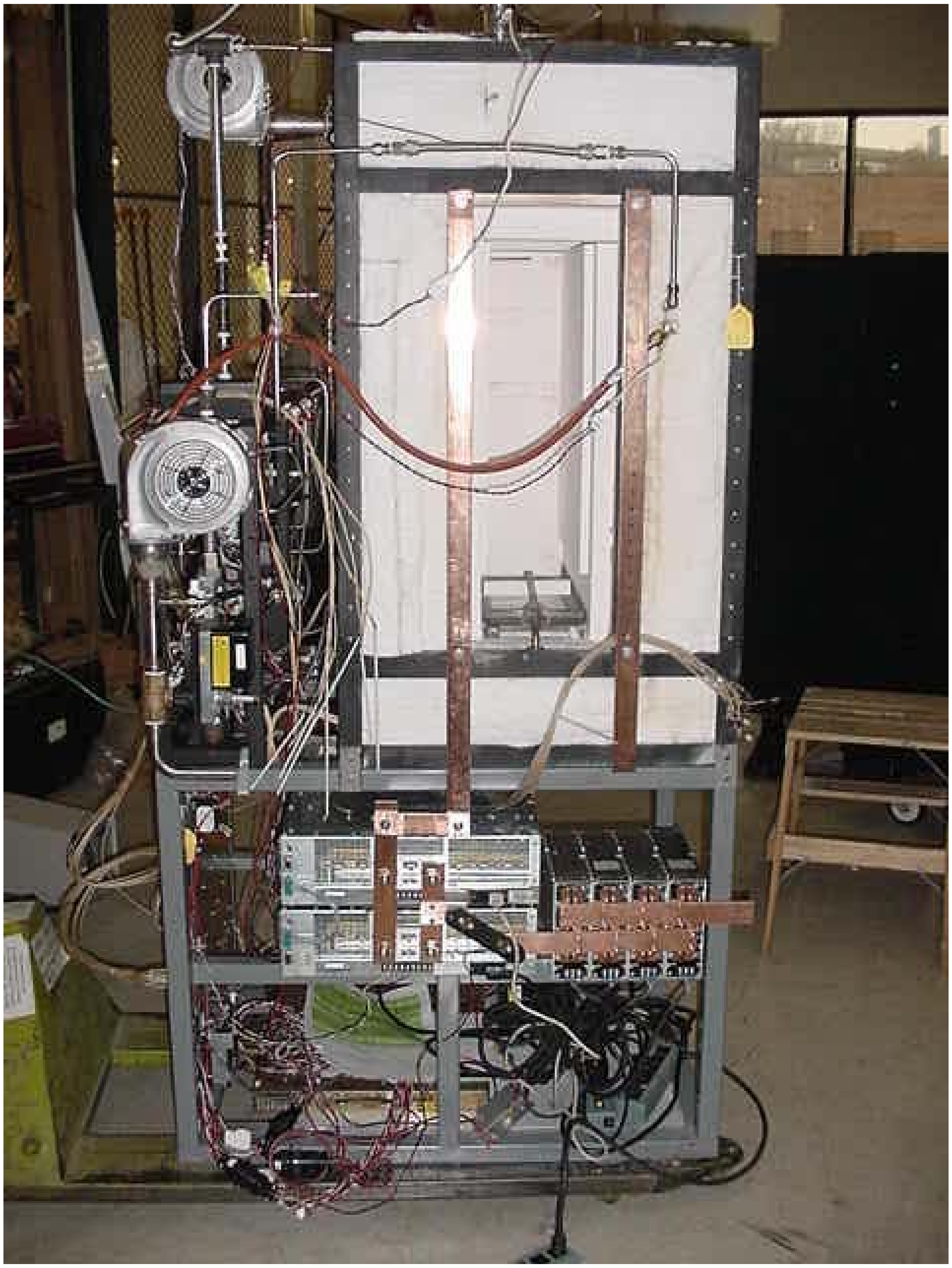


Exhibit 9: Stack Tester #3

The condition of plasma sprayed chromite interconnect layers has been variable in that a number of sprayed samples have shown a green tint under the sprayed chromite band post thermal treatment. It has been hypothesized that these sprayed bands look green in color due to oxidation of the nickel in the bond coat layer, likely the result of a chromite topcoat, which is too thin as sprayed. The purpose of this investigation is to determine if there is a difference in the plasma sprayed coating of a "good" and a "bad" (green band) chromite plasma sprayed coating.

Micrographs of the cells D010088, a "good" coating and, C520111 a "bad" coating were taken in order to determine differences in the $LaCrO_3$ bands. Both coatings went through similar preparation steps during fabrication, both heat-treated at 1400 ˚C for one hour.

In Summary

- Cells that appear to have poor coatings appear that way because their top coatings are too thin. This makes the nickel within the bond coating more vulnerable to oxidation, which in turn can give these bands a light green tint.

- Cells that appear to have poor coatings also tend to have scattered areas of oxidized anode beneath their $LaCaCrO_3$ coatings. These areas are also believed to be the result of an inadequate chromite layer.

The test stand in the carbon deposition experiment was used in the investigation of leaks in the lanthanum chromite current collection system. The experiment sought to determine gas leakage out through the LaCr due to Pousielle or pressure driven flow, and the ingress of O2 into the tube, through the electrolyte or LaCr via diffusion or electrochemical means. By sealing the cell on the outside with O-rings the coatings are isolated for leak testing. By fixing the gas flow with an MFC and comparing the exhaust flow as the cell is pressurized, leaks can be measured.

Triple Cromite Interconnect Bundle (BT-122105)

The four manifold, triple chromite bundle test was terminated on June 7th after 3200 hours of accumulated operation and 12 thermal cycles. Lifegraphs for the overall test and for the month of June are presented below. As seen in the monthly graph, there were no significant changes in operation during this seven-day period. There was a slight drop in cell voltage during the last few days of operation, which coincided with an increase in fuel pre-reactor outlet pressure suggesting that there may be some carbon fouling in the fuel lines. The reason for the shutdown was the need to move the stack tester to make way for the prototype generator test. The bundle will be tested again as part of a diesel reformer test campaign. Modifications to the test stand will be made to permit diesel reformate to be tied into the anode fuel stream. Prior to restart the pre-reactor and fuel lines will be inspected.

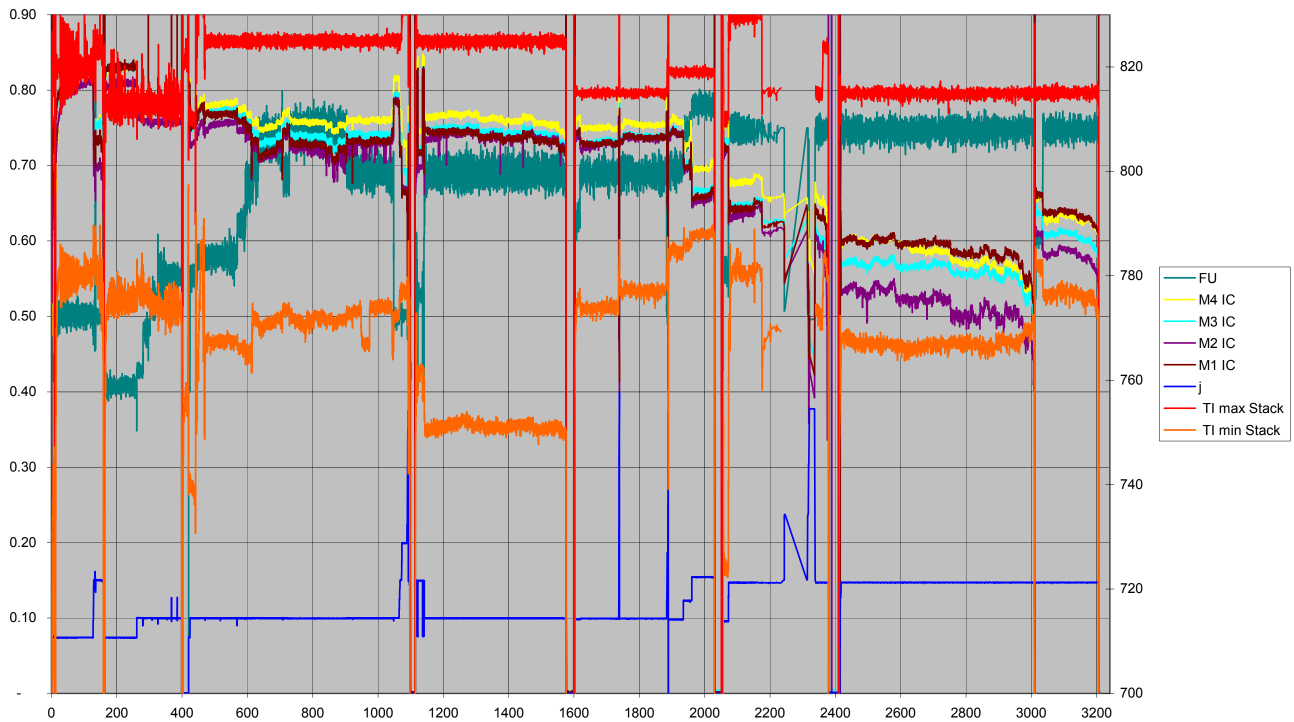


Figure 7: BT-121205 Lifegraph

Subtask 3.3 – Generator Design

Horizontal Cell Support

Based on the experimental and FEA model results performed on the cantilevered cell, a design was developed for a method to support the end of the cells and carry this load down to the base frame. The arrangement consists of a hoop of Inconel® 600 tubing connected to the cooling/spacer manifold. The hoops which support the cell ends are then connected to each other and supported down to the base of the generator with a vertical tube.

Vertical Stack Geometry

An alternative, vertical stack configuration has been developed in the event that the cantilevered, horizontal cell stack geometry proves problematic. To ensure good cathode air distribution to cells a manifold geometry was developed which will allow cathode air to pass up through the fuel manifold between the cells. Although this arrangement could be implemented on common, dual chamber plenum configurations, the initial proof of this configuration will be made on a single chamber, stacked manifold geometry. A manifold was designed that consisted of two rows of cells, in-line by ten long. Between the cells were air pass-throughs to allow a flow of cathode air along the length of the cells. The cells can either be pressed or screwed into position. Casting was determined to be the best manufacturing method.

A two manifold bundle test of the configuration is planned to validate the design. The test will be performed with an existing stack tester with a suitable plenum transition fabricated to support the manifolds and direct the cathode air to the manifold air pass through tubes. Drawings have been prepared and part fabrication is underway.

.

Stack Current Interconnect and Power Leads

The three-chromite cells have three current take-offs corresponding to the chromite bands. This means that at the base of each stack, there are three groups of silver braids that must be either connected to power leads or the adjacent stack. A design was developed to allow the braids to be gathered and fully contained to prevent electrical short-circuits while channeling the braids towards the next stack.

Also demonstrated was a method to interconnect the stacks utilizing the braids coming off the cells. At the tops of the stacks the corresponding anode and cathode braids of the stacks to be joined in series were fused together similar to the method used in joining cell manifolds in series.

Modeling

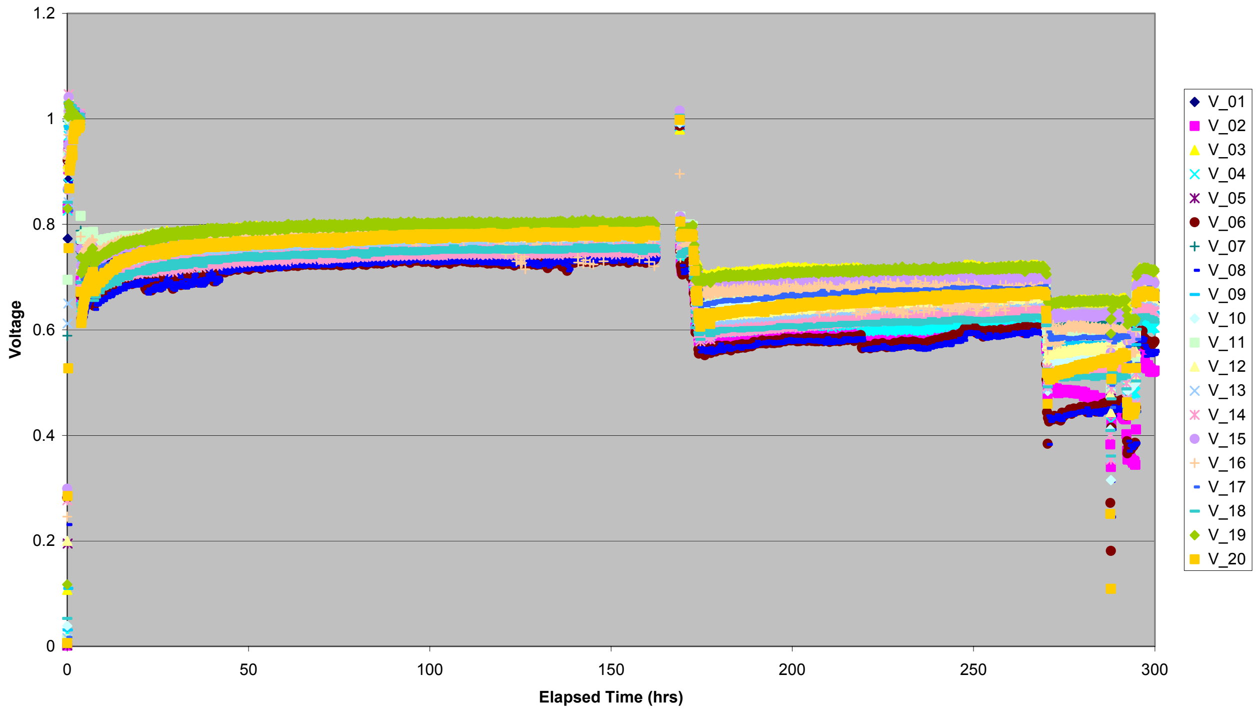
Due to the inherent nature of the vertical SOFC design, any individual cell can no longer be assumed to operate isothermally, especially at high current density. The prediction of cell performance has been approached in the framework of FEM modeling. A method for more rigorously incorporating the heat transfer to and from the cell due to convection and radiation was developed with the expectation that a more realistic description of the temperature gradient in the cell would be generated.

Vertical Cell Configuration Bundle Test (BT 042406)

The 40 cell, vertical bundle previously described was placed on test and accumulated approximately 300 hours of operation as of May 31. A life graph of the months of operation is presented below. The testing was performed using one of Acumentrics standard horizontal configuration stack testers. Additional insulation was placed between the module walls and stack tester cathode air cavity to prevent bypassing of air around the bundle.

For the first half of the test period the load was held at 75 mamps/cm^2 and 50% fuel utilization. This was followed by periods of operation at 150, 200 and 225 mamps/cm^2. Additional testing will be performed during the next reporting period to evaluate the effect on cathode airflow on the axial temperature distribution.

Figure 8-BT 042606 Lifegraph



Cell Voltages

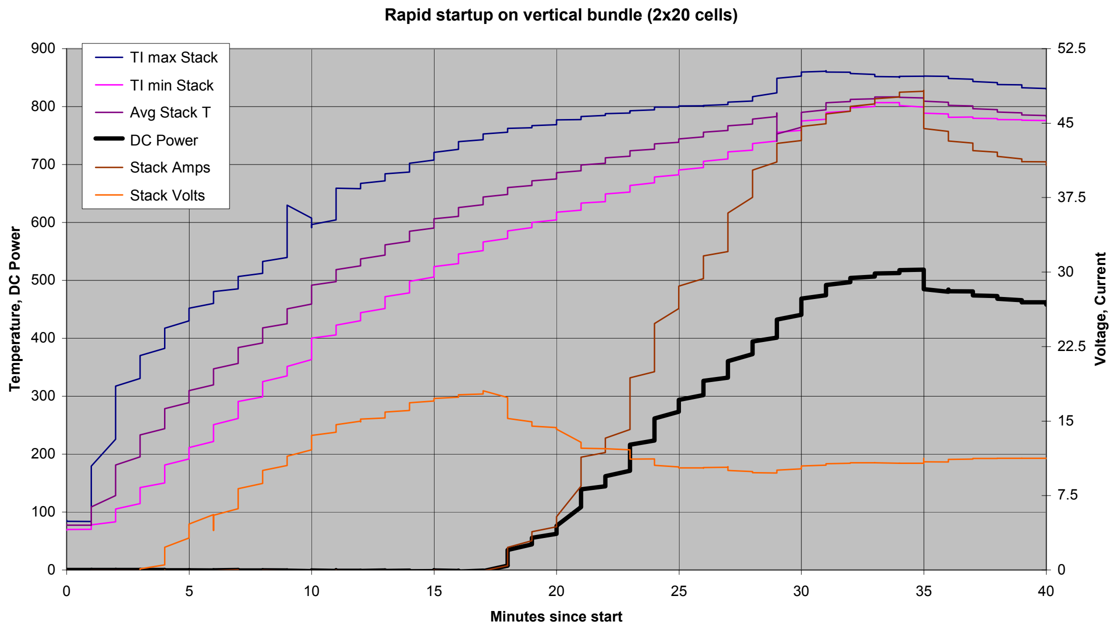


Figure 9: BT 042606 Rapid Startup Operation

Subtask 3.4 – Manifold and Cap Development

The main focus was to fully develop a brazing process to electrically isolate the anode of the SOFC from the nickel braze cup (while maintaining the current leak rate standard). Previous testing methodology incorporated the use of a single washer to create an isolated barrier. Pre-burning the washer eliminates the build up of carbon during brazing which was believed to be causing inconsistencies with electrical isolation.

Cleanliness of the surfaces is a major consideration in the bonding of unlike materials. To clean the mating surfaces better solution was used on the parts just before brazing. Leak rates did improved slightly, but cells remained out of specification. As an additional enhancement to the activation of the bonding surface, H_2 additions were made to the cover gas, bringing the concentration up. All four cells tested were both electrically isolated and passed production leak rate criteria.

The construction of a system with proper safety considerations will be the priority before brazing any level of production cells. Such a system should also provide for greater consistency in the braze joint. Following that setup, trials will be needed to determine methods for brazing multiple cells simultaneously; current experiments have been performed with one cell per braze run. Finally, some cup modification is warranted to eliminate possible shorting effects.

A large horseshoe braze coil was purchased for trials of single side-loaded 22mm cells. This type of coil would allow the construction of an automated production system that could load and unload cells into the coil in a horizontal direction, eliminating the need to manipulate the cell into a fixture through a closed loop coil.

Press-fit Braze Caps

A method of press-fitting MIM braze caps was necessary in order to populate the latest 2-chamber vertical-cell manifold (injectors in-place). Since the cells were packed in rows of two along a manifold, it was not possible to maneuver the wrench enough to screw the cell home. Thus it was decided to press the cells into place.

A cell with MIM braze cap already brazed on was placed into a lathe and the ¼" NPT thread was machined off to a diameter of 7/16". The cell holes in a manifold were drilled and reamed to accept the machined MIM braze cap with an approximately 0.0005" interference fit. The cells were then pressed from the end cap into the manifold, producing a manifold with six cells in it.

The cutting saw was updated to allow for smoother operation during the final cutting process for the finishing of the cell. This update allows for a more uniform cut, reducing chipping and therefore polishing processing in the brazing stage, lowering the labor and material cost of the cell.

If a glaze material could be procured with a higher glass transition temperature, compatible thermal expansion coefficient and minimal reaction with the AS tube, a successful joint could be developed. To this end, Pacific Northwest National Laboratories will be contacted and some samples of their SOFC glass seals with the appropriate material properties will be procured and tested in a similar manner.

Experiments were performed to produce several isolated braze joints. The results show that there was little sensitivity to the exact location of the braze coil relative to the cell position (within general limits), and that higher H_2 content in the cover gas appears to enhance the brazing process in general.

Task 4.0

Subtask 4.1 – Tube Drying

No work to report this period.

Subtask 4.2 – High Volume Tube Firing

The bisque-firing furnace at Acumentrics has undergone some modifications to the furnace lining to try to improve the turn around time and firing uniformity.

Outcome

Figure 10 shows a firing schedule from the old and modified furnace linings.

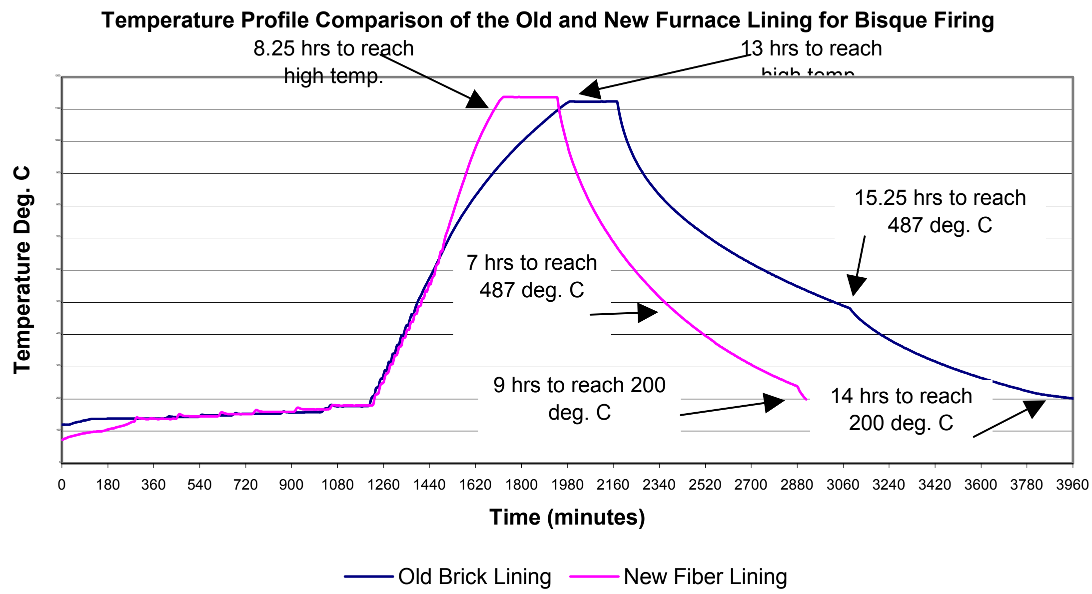


Figure 10: Firing Schedule

A substantial amount of time, 4.75 hours, can be saved during ramp up, which in turn lowers the energy cost to run the furnace and prolongs the life of the furnace elements.

As expected, the furnace cools much faster with the fiber modules than with firebrick. With the new fiber module furnace, no assisted cooling (ie: cracking the door) was used to cool the furnace to 200°C. The time saved in cooling alone is 13.25 hours with the fiber-lined furnace.

Conclusions

- Approximately 18 hours in total have been saved from the bisque firing by replacing firebrick with fiber modules
- 4.75 hours have been saved in ramp up
- Energy required to operate the furnace is reduced saving money on energy cost

Subtask 4.3 – Volume Tube Firing

No work to report this period.

Task 5.0 Fuel Processing Technology Development

Subtask 5.1 - Reformer Technology – Light Hydrocarbons

Fuel pre-reactors have been operating, as part of the bundle tests described in Section 3.2 and reactor performance has been steady with good conversion efficiencies.

Carbon accumulation in the tubing between the pre-reactor outlet and stack inlet has been observed and led to the temporary shutdown (for cleaning) of two long-term bundle tests. It appears that carbon is preferentially forming. It is unclear if this is a result of the material composition or a result of a stagnation zone. A test apparatus is being designed which will allow further characterization of this situation. Temperature, residence time and materials will be closely controlled and varied along with gas composition.

Reactor design

Isothermal reactor for 1” monolith was designed and built. Flow rates can only be tested to about 5slpm fuel currently. To allow for more significant testing, new MFCs for high flow rates are being sourced. These will be used in testing once received.

An adiabatic reactor for 3” monolith was designed and built. Testing will proceed.

Carbon Deposition Experiments

The carbon deposition experiment proceeds, with the first trial completed. Initial testing at 600^{o}C and an O/C of 1.4 did not result in any observable carbon at the flanges or tubes. Despite an initial setbacks due to the unexpected presence of CH_4 in the purge gas, renewed testing with the conditions of 600^{o}C and O/C=1.15 resulted in the development of a severe pressure drop.

An autopsy of the tubing could not discern the nucleation site for deposition although the majority of the carbon was in the tube/flange. No carbon was observed at the inlet and outlet flanges/ tubing at room temperature suggesting that deposition does require thermal activation

The experiment will be repeated (T=600C, O/C=1.15) using an assembly which is the current one for Acumentrics generators. Pending results higher O/C ratios (>1.3) will then be tested in an effort to mitigate the deposition.

Reactor design

Isothermal reactor for 1" monolith was tested in the carbon deposition furnace flow rates are generally low due to the MFC limitations. However, new MFCs for high flow rates have been ordered from Porter Instruments. The new setup will allow rapid screening of monoliths and packed bed reactors, but also will allow the testing of a new isothermal design for the SOFC generator
Adiabatic reactor for 3" monolith was attached to the vertical Bundle test limiting the performance testing to relatively low space velocities. Although a MFC was installed and calibrated, grounding issues on the stack tester resulted in poor control at flow rates higher than 5 SLPM. The monoliths are fairly large and should suffice for a 10 kW SOFC so the set-up was not an ideal test for the reactor especially with regard to conversion measurements. The pressure drop scales linearly with flow rate in the laminar flow region. Conversions are low at low space velocities due to the heat loss from the adiabatic reactor, resulting in low temperatures and relatively slow kinetics.

Subtask 5.2 – Liquid Fuel Reforming for Diesel and JP-8

InnovaTek is developing a compact fuel processor for Acumentrics that can catalytically convert multiple liquid hydrocarbon fuels, including ultra low sulfur (ULS) diesel, biodiesel, and zero sulfur JP-8 to hydrogen rich reformate gas suitable for consumption by an Acumentrics solid oxide fuel cell (SOFC) to generate electricity. This test will allow Acumentrics to gain required data on liquid fuel reforming prior to developing a liquid fueled unit. The fuel processor is built on InnovaTek's proprietary microchannel platform that can offer benefits unique to SOFC applications: sized and configured to utilize radiant sources of heat available with a SOFC (or a furnace, as provided under this contract for testing), designed for unparalleled dynamic response to power demand, yet remaining a compact manifold structure that eliminates traditional piping and fittings found in conventional systems. A manufacturing approach using diffusion bonding of inconel laminates offers a unique means to reducing production costs.

The design used is the InnovaGen® cross flow reformer with two catalyst zones tightly integrated in a process flow stream prior to the SOFC. This processing configuration will convert energy dense liquid hydrocarbon fuel to a hydrogen rich feed at a flow rate of 21 litres per minute (LPM) for a solid oxide fuel cell that produces about 1 kW electrical power.

The design utilizes InnovaTek's low temperature catalyst which operates over a wide range of temperatures from 400 to 520°C for pre-reforming and its high temperature catalyst, which operates at about 800°C for complete fuel conversion. Thus the thermal requirements of the SOFC and the fuel processor are well matched for integration. This 2-stage approach produces a robust system with a long catalyst life-time because it prevents coking problems that cause catalyst deactivation.

A diesel reformer from Innovatek was received. The fuel for the reformer tests is S-8 (synthetic zero sulfur JP-8) and will be obtained from Wright-Patterson Air Force Base. A plan for the testing of the diesel reformer and ensuing coupling with a fuel cell bundle was written and disseminated**.** Assembly and testing will start in July.

Subtask 5.3 – Light Fuel Desulphurization

No work to report this period.

Task 6.0

Subtask 6.1 – Prototype System Test

No work to report this period.

Subtask 6.2 – Generator Test Plan

A test plan was started detailing the anticipated run of the SECA Phase I generator. It is anticipated at this point that the generator will be run at 70%FU as a steady state point, performing the require one hour peak power cycle sometime near the end of test or end of the first steady-state run of 1000hr. Peak efficiency is currently anticipated to occur immediately after the peak power run, or at a time of most convenience. It is currently anticipated that the peak power for the generator will be about 6kWDC net, and peak efficiency will be slightly above 35% on CPOX natural gas.

A series of questions were fielded to the DOE to clarify aspects of the test requirements that are unclear or not explicitly stated.

Conceptual design for venting of the SECA generator was approved.

A phone conference with ETS was held to go over questions with the Acumentrics Phase I Generator test plan. ETS appeared relatively satisfied with the plan, and provided suggestions on improvements to the plan. A series of action items including some additional P&ID drawings, an electrical power diagram, and a key instrumentation list, are to be developed by Acumentrics and submitted to ETS prior to the test.

The test plan was submitted to the DOE for approval. A reply was received on the 24th of May. Some clarification is required, but most points brought forth will simply require greater clarity in the plan. It is expected that the plan will be submitted in the early part of June and the test will start around the 22nd of June.

Two of four stacks have been tested and qualified individually for the SECA Ph I generator. When completed, the four stacks will be assembled into the generator. Currently, the plan is to shut down cell testing for the duration of the generator test due to flammable gas limitations at the site.

The expected timeline is in the table below:

Action	Date
Test plan approved	5/30/06
Fuel Cell production begins	4/1/06
Pre-testing of fuel cell stacks begins	5/10/06
BOP assembly complete	5/30/06
Electronics packaging assembly completed	5/30/06
Calibration of BOP components	6/10/06
Stack testing completed	6/10/06
Assembly of entire generator	6/15/06
Start of 1000hr NOC test	6/19/06
End of 1000hr test	7/31/06
Start of peak power, efficiency, cycling test	8/1/06
Start of 500hr NOC test	8/4/06
End of Generator Test	8/25/06
Generator Breakdown/analysis	8/28/06
Test Report to NETL	9/25/06

Table 2: Timeline

Setup

The laboratory was prepared to receive the generator: The test stands were shut down and rearranged. This is due to the limited number of flammable tanks allowed on site. The ventilation for the room was enhanced by the purchase of an additional fan, and the installation of ductwork to connect to the generator. A wire was run into the room to connect the generator to the grid to dissipate generator power, as was a load unit in case the grid failed.

The generator was prepared according to the test plan, with four stacks of 72 cells. Each of these stacks was pre-tested for 48hrs in a single stack test to ensure adequate performance. Four stacks tested met requirements, and were used in the generator. BOP equipment was calibrated and checked, and the control system was calibrated against the generator readout. A calibrated oscilloscope and voltmeter were set aside for hand-checks of the values obtained in the test.

Photo 52: Generator

<u>Start</u>

On June 27 at 4:19pm, the generator heat-up burner was fired, beginning the test. The graph on the next page shows the temperature profile from startup through the end of June, as well as the net Generator power.

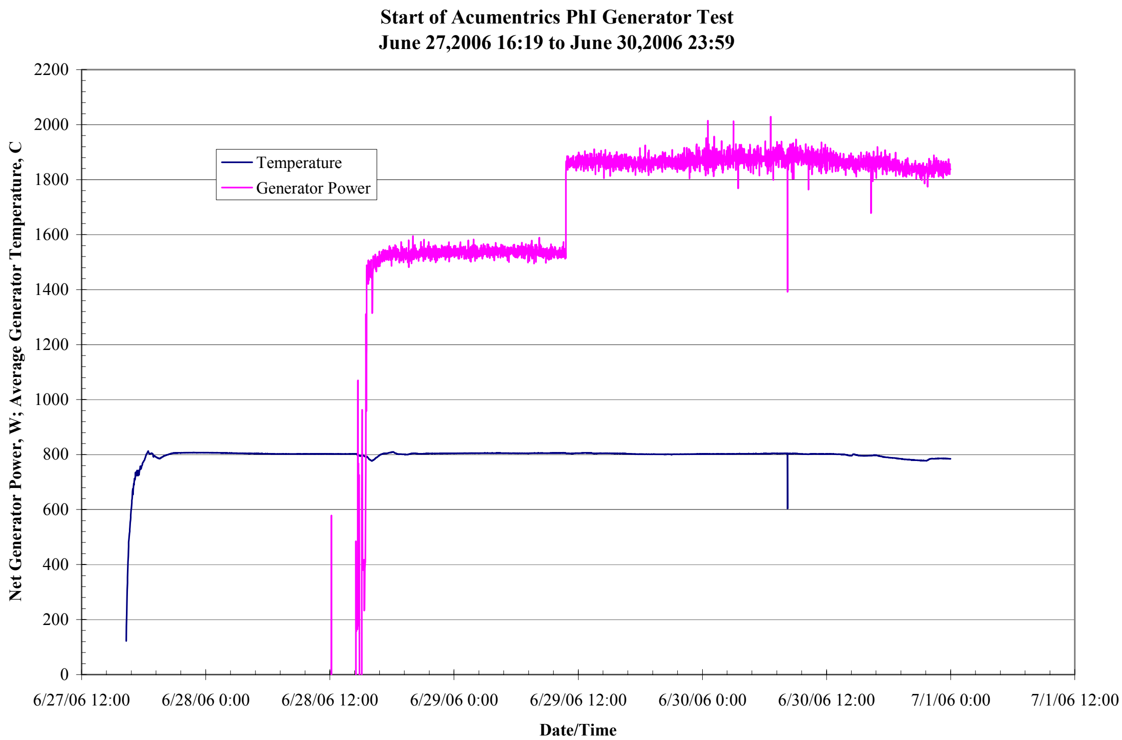


Figure 11: Start of Phase I Generator

As described in the test plan, the generator was brought up slowly over the course of multiple days. As of the end of July, there was 100% availability (79.7hrs total time), and the fuel cell stack was operating at 39.6V/49.7A/50%FU with a net generator output of 1.84kW.

The generator is being slowly ramped up to the NOC conditions, which substantially involve raising the FU to 70%. At this point, the generator is in thermal balance. As that set point is achieved, the determination will be made as to whether to determine the first efficiency and degradation points based on voltage response.

List of Acronyms and Abbreviations

AC	Alternating Current
ANSI	American National Standards Institute
ASCII	American Standard Code for Information Interchange
BOM	Bill of Material
BOP	Balance Of Plant
CAD	Computer Aided Design
CAN	Controller Area Network
CM	Common Mode
CPOX	Catalytic Partial Oxidation
DC	Direct Current
DSP	Digital Signal Processor
DTA	Differential Thermal Analysis
EEPROM	Electrically Erasable Programmable Read-Only Memory
EMC	ElectroMagnetic Compatibility
ESTOP	Emergency Stop
FCIC	Fuel Cell Interface Converter
FCS	Fuel Cell Stack
FCUPS	Fuel Cell Uninterruptible Power Supply interface
FET	Field Effect Transistor
FU	Fuel Utilization
GUM	Gas Utility Module
HMI	Human-Machine Interface
IC	Investment Casting
I/O	Input / Output
IR	InfraRed
LED	Light Emitting Diode
lpm	Liters per minute
MIM	Metal Injection Molding
mlpm	Milliliters per minute
MOR	Modulus of Rupture
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
NPT	National Pipe Thread
NYSERDA	New York State Energy Research and Development Authority
PC	Personal Computer
PCB	Printed Circuit Board
P&ID	Piping and Instrumentation Diagram
PID	Proportional Integral Differential
POX	Partial Oxidation
PLC	Programmable Logic Controller
PWM	Pulse Width Modulation
ROM	Read Only Memory
RPM	Revolutions Per Minute
RPTS	Rapid Prototype Test Station
SEM	Scanning Electron Microscope

SiC	Silicon Carbide
SOFC	Solid Oxide Fuel Cell
SPI	Serial Peripheral Interface
TEC	Thermal Expansion Coefficient
TGA	Thermal Gravimetric Analysis
UPS	Uninterruptible Power Supply
TI	Texas Instruments
w.c.	Inches water column
YSZ	Yttria Stabilized Zirconia