EERE
Final Scientific/Technical Report

Project Title: Development of a Low Cost 10kW Tubular SOFC Power System

Project Period: July 28, 2003 to March 31, 2013
Date of Report: June 6, 2013

Recipient: Acumentrics Corporation
Award Number: DE-FC36-NT41838

Working Partners: N/A
Cost-Sharing Partners: N/A

Contact: Norman Bessette, PhD, 781-461-8251, nbessette@acumentrics.com
Tom Cote, PMP 781-461-8251, tcote@acumentrics.com

DOE Managers: Reginald W. Tyler, DOE Field Project Officer
Thomas G Benjamin, Argonne National Laboratory
Dimitrios Papageorgopoulos, DOE HQ Technology Manager

Executive Summary

The DOE program funded from 2003 through early 2013 has brought the Acumentrics SOFC program from an early stage R&D program to an entry level commercial product offering. The development work started as one of the main core teams under the DOE Solid State Energy Conversion Alliance (SECA) program administered by the National Energy Technology Laboratory (NETL) of the DOE. During the first phase of the program, lasting approximately 3-4 years, a 5kW machine was designed, manufactured and tested against the specification developed by NETL. This unit was also shipped to NETL for independent verification testing which validated all of the results achieved while in the laboratory at Acumentrics. The Acumentrics unit passed all criteria established from operational stability, efficiency, and cost projections.

Passing of the SECA Phase I test allowed the program to move into Phase II of the program. During this phase, the overall objective was to further refine the unit meeting a higher level of performance stability as well as further cost reductions. During the first year of this new phase, the NETL SECA program was refocused towards larger size units and operation on coal gasification due to the severe rise in natural gas prices and refocus on the US supply of indigenous coal. At this point, the program was shifted to the U.S. DOE's Energy Efficiency and Renewable Energy (EERE) division located in Golden, Colorado. With this shift, the focus remained on smaller power units operational on gaseous fuels for a variety of applications including micro combined heat and power (mCHP). To achieve this goal, further enhancements in power, life expectancy and reductions in cost were necessary. The past 5 years have achieved these goals with machines that can now achieve over 40% electrical efficiency and field units that have now operated for close to a year and a half with minimal maintenance. The following report details not only the first phase while under the SECA program and the key achievements but also the results while under EERE's leadership and the transition to an early commercial product offering.

Phase I Goals, Objectives and Accomplishments

The Acumentrics SECA program has focused on the design and manufacture of tubular SOFC power systems approaching twice the power density achieved from state of the art anode supported tubular designs. Based upon DOE funding and a focused research effort during Phase I, the cells exceeded this goal. Commercial units are capable of entry into the telecommunication, remote residential and military markets. Operation on fuels including natural gas and propane have been developed for the telecommunication and remote residential markets. Operation on liquid fuels, including diesel and JP-8, are being developed for the military markets.

Working with Acumentrics to define market segments and market requirements were a number of key investors that are strategic players in their respective markets. They included:

- General Dynamics for liquid fuels as well as military operations.
- Northeast Utilities and NiSource for electricity infrastructure integration as well as at the multi-10+kW scale.

- Sumitomo Corporation of Japan for introduction and product definition into the Japanese market.
- MTS Corporation for introduction into the Combined Heat and Power market of Europe.

During the first three years of Phase I, a number of major accomplishments were made in advancing this technology from that of a laboratory experiment to the verge of an entry level commercial product. The following is a list of those accomplishments made throughout the Phase I program:

Fuel Cell Power Increased by 33% (June, 2003): Through the development of an advanced power take-off concept, the Acumentrics Tubular SOFC resulted in a power increase of 33% over the earlier cell design. This had been achieved by a proprietary contact technique allowing power take-off from both ends of the cell tube. This breakthrough results in an overall cost/kW of the system to drop by approximately 25%.

Brazed Electrical Connection Meets SECA Cost Target (July, 2003): The electrical take-off from the anode of Acumentrics' tubular SOFC had been accomplished prior to the SECA program utilizing a braze material adding over $1,300/kW to the product cost. Under a SECA task, a number of braze materials and mixtures had been tested with one achieving the necessary performance requirements while only resulting in $1/kW to the overall system cost thereby reducing the system cost by over $1,300/kW.

Cathode Current Collection Materials Decreased by 55% (August, 2003): Work on improved cathode current collection resulted in a decrease in silver usage for current collection by over 55%. This reduction of material came with no detrimental impact on fuel cell performance and results in a nearly 12% reduction in system cost.

Reduce Manufacturing Temperature by Over 50°C (Sep, 2003): The electrolyte sintering-temperature was reduced from 1500 to 1450°C with solid evidence this would drop to or below 1400°C to lower fabrication costs and potentially result in an improved performing SOFC.

Prototype DC/AC Inverter Achieves Over 96% efficiency (Nov, 2003): Acumentrics developed a DC/DC regulator capable of achieving over 98% efficiency and also prototyped a DC/AC inverter stage over 98% efficient. The full system was verified to achieve over 96% efficiency (excluding transformer) which was above the DOE sponsored energy challenge requirements.

Increase Stack Power Density by 20% (Dec, 2003): Demonstrated that six cells rather than five cells can be placed within the same manifold volume resulting in an increase in 20% power per unit stack volume over previous designs and a decrease in manifold count by 17% for the same number of cells.

Stable Cell Performance Exceeds 6000hr Operation (Jan, 2004): Demonstrated stable cells performance over 6000 hours with average degradation rates below 0.25%/500 hours, nearly achieving the 2010 Phase III SECA goal of 0.1%/500 hours.

Improved Anode Conductivity Increasing Power by 10% (Feb, 2004): Cells which had an additional high nickel contact layer added to the inner diameter of the fuel cell tube showed an improvement of 10% in power over standard cells with current collected at one end of the tube.

Regenerative Blower Capable of Improving Efficiency by 2-3% (March, 2004): A fuel recirculation blower was designed and preliminarily tested to avoid the need for steam generation and condensation systems in the SOFC generator. This device decreases the amount of energy transported and thereby can increase the overall efficiency of the machine by 2-3% points.

Two 7mm Diameter Cells Completed over 10,000 hours of Operation (May, 2004): Cells were tested under electrical load for over 10,000 hours of operation with stable performance. These cells have also experienced over 15 thermal cycles to room temperature over the course of testing.

Reduce Manufacturing Temperature by an Additional 50°C (Aug, 2004): The electrolyte sintering-temperature was demonstrated to be gas tight by reducing another 50°C from 1450 to 1400°C, which can lower fabrication costs and potentially result in an improved performing SOFC.

Demonstrated a 400% Cost Reduction of a Ceramic Recuperator (Oct, 2004): A ceramic recuperator was tested for comparison to the typically available metallic designs. These recuperators have a greater than 400% cost reduction over their metallic counterparts while avoiding long term scaling which degrades metallic recuperators. These units still had not achieved effectiveness of their metallic counterparts.

Reduce Tube Firing Time by a Factor of 400% (Nov, 2004): The typical tube firing sequence which took nearly 48 hours was demonstrated to reduce to less than 12 hours with the use of a microwave de-binding and belt furnace firing process.

Demonstrate the Integrity of Stamped Braze Caps (Dec, 2004): Demonstrated that braze caps, made by a stamping operation similar to the process for computer electrical connectors, can physically attach to the fuel cell tube and withstand the operating environment. These caps are five times lower cost than the existing machining process.

Demonstration of a 22mm Diameter Anode Supported Cell (Jan, 2005): A number of experimental cells were built at a diameter of 22mm versus the standard 15mm showing a power enhancement of 60%. By moving to larger diameter cells, the overall generator cost decreased due to the lower number of tubes.

Achieved a Mechanically Stable Ceramic Interconnection for Power Take-off (Jan, 2005): A process was developed to apply a ceramic power take-off connection along the length of the fuel cell tube which is stable in both oxidizing and reducing atmospheres. This connection allows for multiple axial power take-off points which can significantly reduce the length penalties of anode cells and potentially increase power per cell by a factor of three.

Successful Completion of an Independent Audit of SECA Phase I Cost and Performance Goals (March, 2005): In keeping with the Government Performance and Results Act (GPRA), an independent audit of the Acumentrics program was completed by Spencer Management Associates and Argonne National Laboratory to determine the technical risk of meeting the SECA phase I cost and performance targets. The program requires achieving <$800/kW and stable operation over 1500 hours to pass the first gate of the program. It was determined that Acumentrics should exceed the cost targets and the probability of achieving performance goals was high.

Demonstrated Cell Power Density Increases from 150 to 297mW/cm^2 (April, 2005): Different geometry cells were manufactured and tested showing the viability of doubling the power per tube. This was accomplished by adjusting the anode tube chemistry while also changing the number of current collection points on the tube. This accomplishment has the ability to cut the required number of tubes per kilowatt in half and also dramatically reduce the size of the fuel cell generator.

Implemented Advanced Generator Manifolds Reducing Cost by over $1000/kW (April, 2005): One of the first advanced manufacturing techniques pursued to decrease overall cost of the SOFC generator was validated for operation in an SOFC environment with substantial cost reduction. A Metal Injection Molding (MIM) process was developed to net shape cast high temperature metal parts which was previously only capable of making low temperature aluminum parts. This process allows for the saving of many labor hours of machining and overall cost reduction of the SOFC generator.

Demonstrated Generator Operation on Diesel and Synthetic Diesel Fuel (May, 2005): A 5kW SOFC generator was tested and proven to operate successfully on liquid diesel fuel. This unit also operated on synthetic diesel fuel made by renewable domestic sources. The unit was baseline tested on natural gas and found to have nearly identical performance on liquid fuels as on natural gas.

Demonstrated a Tubular SOFC achieving >40W/tube (July, 2005): The latest advancements in larger diameter tube technology and multiple take-off connections

were integrated into a single cell design. This cell was electrically tested and achieved over 40W from a single cell. This power level is more than twice the power achieved by a single anode supported fuel cell. It was believed with some further advancement this same cell will achieve between 50-60W.

Cell Testing Exceeds 11,000 hours of Operation (Aug, 2005): Three cells achieved more than 55 thermal cycles and 11,000 hours of testing at 75%FU. Degradation rates were less than 3/4th required of the SECA Phase I goal.

Successful Fabrication and Testing of a Closed End Isopressed Anode Tube (Sept, 2005): Anode tubes, presently fabricated by extrusion, were manufactured through isostatic pressing containing an integral closed end. Successful completion of this development allows the reduction in the number of steps required to make an anode tube from four to one, significantly decreasing cost. This process also decreases the total manufacturing operation by removing the need for a metallic braze cap presently used to form a closed end.

Demonstrate a Tubular SOFC achieving >60W/tube (Oct, 2005): Further advancements in larger diameter tube technology and multiple take-off connections were integrated into a single cell design. These advancements take the single cell power from 5W/tube at the start of the SECA program to >60W at the end of Phase I.

Cell Testing Exceeds 13,000 hours of Operation (Nov, 2005): Cells that had been on test for 12,253 (and 59 Thermal Cycles) and 13,429 (70 Thermal Cycles) were taken off test for analysis. These cells operated at or above 75% fuel utilization for the entirety of the test achieving high efficiency. The results of the post test analysis were used to enhance further generations of anode supported SOFCs.

Ceramic Interconnection Stack Test Exceeds 1400 hours of Operation (Jan, 2006): The first small stack test incorporating ceramic interconnections exceeded 1400 hours of operation and completed thirteen thermal cycles. There was no noticeable degradation.

Ceramic Interconnection Stack Test Exceeds 2400 hours of Operation (March, 2006): The first small stack test incorporating ceramic interconnections continued to operate and exceeded 2400 hours of operation and completed fourteen thermal cycles. There was no noticeable degradation.

Prototype Assembly (June, 2006): A prototype system was fabricated to complete SECA Phase I testing. This system incorporated the latest cell technology advancements as well as generator and BOP enhancements.

Commencement of the SECA Phase I Machine Prototype Testing (June, 2006): 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. Data was taken on temperatures and power conditions and the first stage of the 1000 hour run began.

Achievement of >35% Net Efficiency on SECA Phase I Machine (July, 2006): The SECA phase I machine was operated at >35% net DC efficiency on July 6, 2006 for a period of over 1 hour. This represents the first milestone of efficiency in the test.

Achievement of 700 hours operation and nearly 50% of SECA Phase I Testing (July, 2006): The SECA Phase I machine exceeded 700 hours of operation, nearing the 50% mark of total run time required for the machine. Degradation on the cell stack was undetectable and availability was well over 90%.

Phase I Cell Technology

The Acumentrics SOFC state-of-the-art technology was based on an anode-supported tubular design that was developed under the SECA Phase I umbrella. This cell was 88 cm total length, with a diameter of 2.2 cm, supplying over 125 W per tube. The design of the fuel cell was central to the success experienced. The tubular structure exhibits inherent strength in form, resulting in higher processing yields, flexibility in handling, and improved response to transient events in generator systems. In addition, the anode supported design allows the discrete handling of both the cathode and anode gases within any system, easing requirements for recycle and CO_2 capture, as well as allowing flexibility in plant integration. Research has shown the ability to scale the system as required, as well as the flexibility to handle highly variable fuel gases.

Cell Manufacturing

Acumentrics cell manufacturing methodology was comprised of nine major processing steps detailed in Figure 1. Materials used in the process are detailed in Table 1.

Many of the processing functions have been exclusively developed and established at Acumentrics, and as such these processes are tailored from the ground up to be simple low cost easily automatable fabrication techniques. For those processing techniques developed externally, such as isostatic pressing and plasma spraying, robotic fixturing to allow full automation of these processes was either already in place or in the process of being designed and implemented.

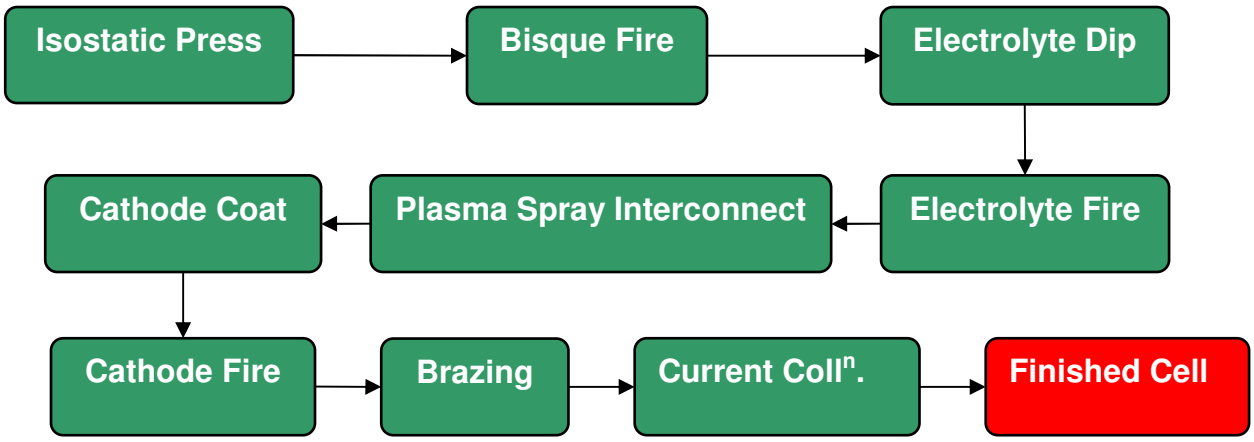


Figure 1 Cell Fabrication Process Flow Route

Since submitting the successful Phase I Factory Cost Estimate (FCE) to DOE, which came in at $726 /kW (significantly under the $800 /kW target), a number of cell manufacturing process enhancements have taken place. Acumentrics has replaced four processes (mixing, extrusion, drying and cutting) with a single process: isostatic pressing. This simplification resulted in significant labor cost reduction since pressing is fully automatable. Electrolyte drying has been eliminated due to the implementation of a new enhanced electrolyte dipping system which relies upon a newly developed kiln furniture arrangement allowing firing in a vertical orientation.

Isostatic pressing is the first step towards fabrication of Acumentrics current cell and relies upon the automatic feeding of a blended anode powder from a hopper into a mold where it is automatically tamped down, followed by introduction into the pressure vessel. The tube is then pressed and removed from the vessel by a robot. Tubes are then loaded by hand into Acumentrics designed flat plate with orifice kiln furniture, followed by bisque firing. The flat plate with holes kiln furniture concept not only allows vertical firing of the tubes but also provides a common platform for handling multiple tubes through the fabrication process.

Following bisque firing, the tube is vacuum infiltrated with electrolyte while remaining upon the same kiln furniture. As mentioned previously, the electrolyte drying step was no longer required due to an enhanced dipping apparatus and methodology. The dipped tubes are transferred into the electrolyte furnace while still remaining upon the same common furniture. This is an extremely significant step forward in terms of automation in that fixturing and movement of the tubes has been unitized on this furniture from pressing all the way through to plasma spraying.

After the electrolyte firing, banded segments of the sintered electrolyte are removed by grit blasting to facilitate placement of the lanthanum chromite interconnect (IC) by plasma spraying. Removal of the electrolyte is made possible by an in-house designed grit blasting machine, the automated version was fabricated and went online at the end of Q4 2007. Automation of the plasma spray process was successfully achieved at

Acumentrics with implementation of a robotic fixture which allowed batch spraying of up to eight cells at any one time. Future development of this machine will include an upgrade to allow full automation for continuous operation.

Table 1 Materials Summary

Component	Composition
Anode Support Tube	NiO/YSZ 50/50 vol. %
Electrolyte	15 μm YSZ
Cathode Interlayer	YSZ/$La_{0.84}Sr_{0.16}MnO_3$ 50/50 vol. %
Cathode	$La_{0.84}Sr_{0.16}MnO_3$
Interconnection	$La_{0.85}Ca_{0.15}CrO_3$
Current Collector	Silver wire

Application of the cathode is the next step in the process. This is achieved by using Acumentrics in-house designed slurry dipping apparatus which is a simple to use cost-effective dipping fixture achieving near 100% slurry utilization. Moving forward, this fixture will be enhanced to allow full automation of cathode dipping and will encompass the cathode drying step into the dipping function, thus minimizing part touch count and therefore further reducing cost. Initial evaluation trials have already been successfully completed with a PLC controlled tank to effect this change. A fully automatable cathode application fixture was ready for use in Q4 of 2007, which eliminated the individual cathode drying step. Cathode firing is a batch process but was easily automatable into a continuous process with applicable furnace and furniture.

The brazing process is a batch process which involves inductively heating the applied braze cap and braze material to allow the tube to drop into the cup, creating a seal upon cooling. The brazing process and cost has been simplified somewhat since one of the two brazes has been eliminated due to the isostatically pressed closed end tube.

Current collection is then applied to the cell in the form of a wire wrapped over a backbone or bus, both of which travel the length of the cell for maximum performance. The current collection system is applied to the cell using a standard wire wrapping piece of equipment which utilizes a spool and rotation of the cell.

Acumentrics manufacturing capacity was >400 finished cells per week for the type of cell identified in the SECA Phase I FCE. This run rate has been achieved on a regular basis for extended periods of time and was factored for yield.

Acumentrics manufacturing effort next was focused towards the fabrication of >100 W cells which were 88 cm in length with a 2.2 cm OD and have seven IC positions, see Figure 2.

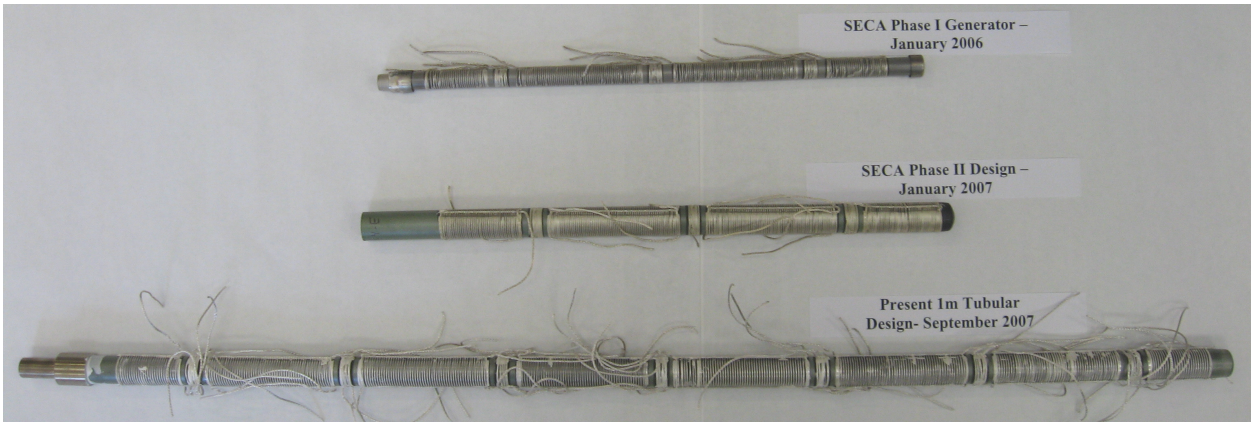


Figure 2 Progression Of Cell Design To Current 125W Cell

Production of the baseline unit cell commenced with the first few cells through the fabrication process and in cell testing. Scale-up of fabrication equipment for this larger cell size was also underway and for a number of processes already complete. The largest gating factor with respect to increasing throughput of the larger baseline unit cell was implementation of a flat plate with orifice kiln furniture design. In conjunction with other fixture modifications, implementation of this furniture was instrumental in increasing capacity to >200 finished cells per week, easily satisfying the Phase I cell requirement.

Cell Performance and Degradation Progress

Since program inception in 2001, and with the guidance and acceleration provided by the SECA program, the performance of fuel cells and generator systems has improved dramatically. As the cell diameter has increased from 0.7 cm OD to 2.2 cm OD, and length has increased from 33 cm to 88 cm, performance has improved in *both* power per cell, starting with 1 W in 2002 to Acumentrics' current 125+ W (Figure 3), as well as area specific peak power density, which has increased in single cell testing from 95 mW cm^{-2} to 470 mW cm^{-2}. The gain in cell power density at a 0.7 V operating condition is illustrated in Figure 4. In addition, the degradation rate of cells in cell testing was significantly reduced from over 1000 % per 1000 hours to under 1 % per 1000 hours during the same time period (Figure 5).

These significant achievements culminated in 2006 in a 5 kW-rated generator that was run to complete the SECA Phase I goals, demonstrating >35 % efficiency (LHV to net DC), 6.2 kW net DC, >95 % availability, and over 5800 h of operation with negligible cell degradation.

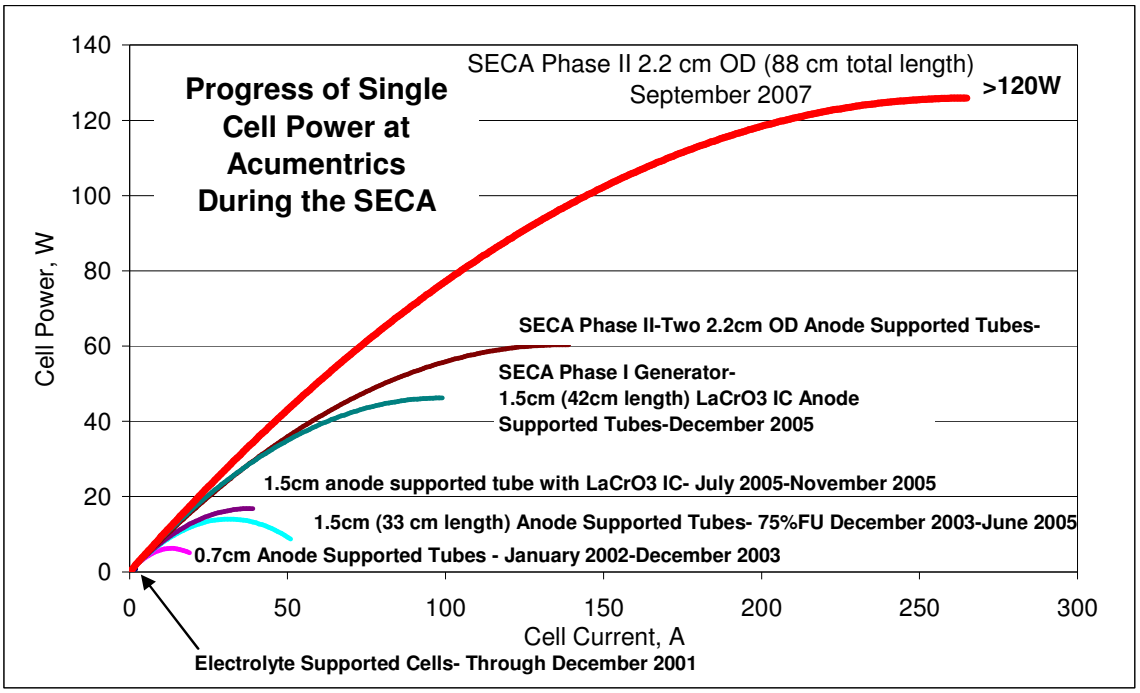


Figure 3 Single Cell Power Improvements during SECA Program

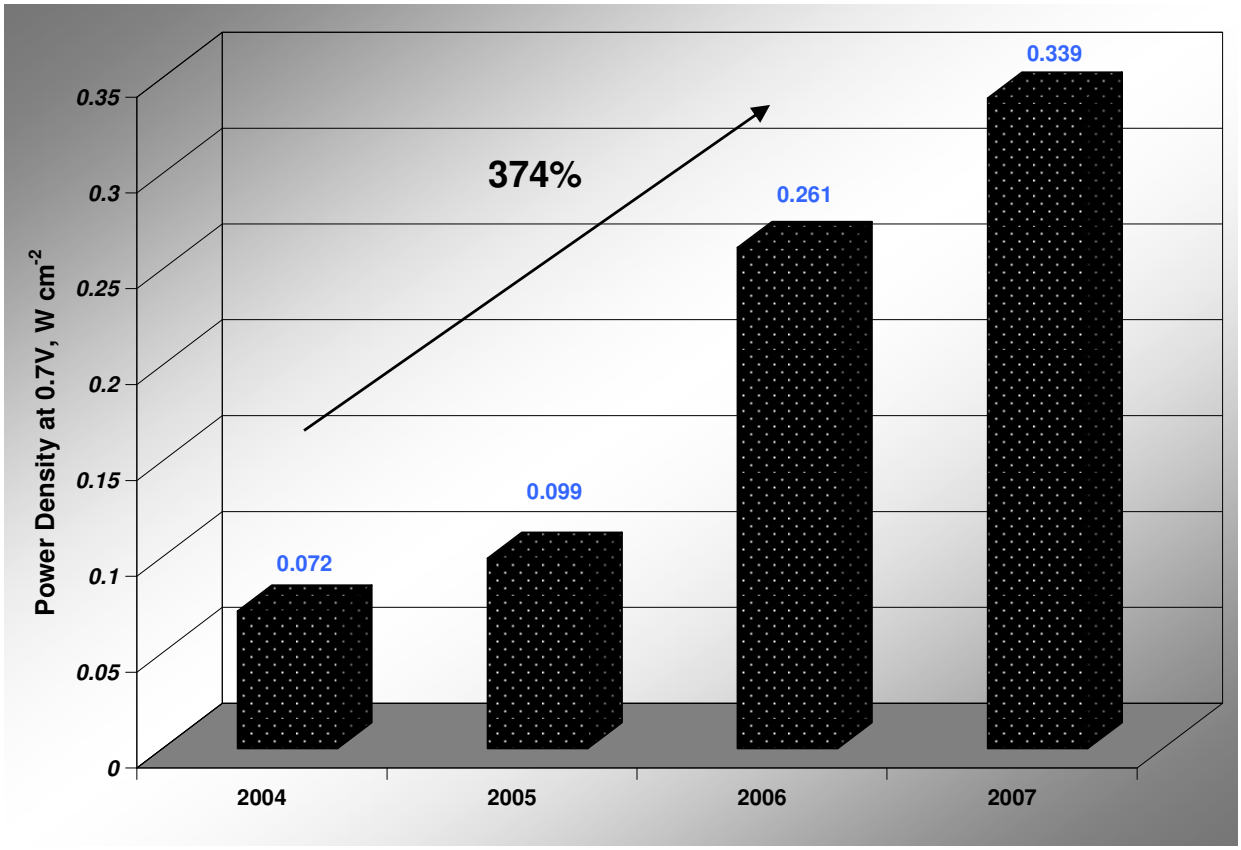


Figure 4 Increase in Cell Power Density at 0.7 V

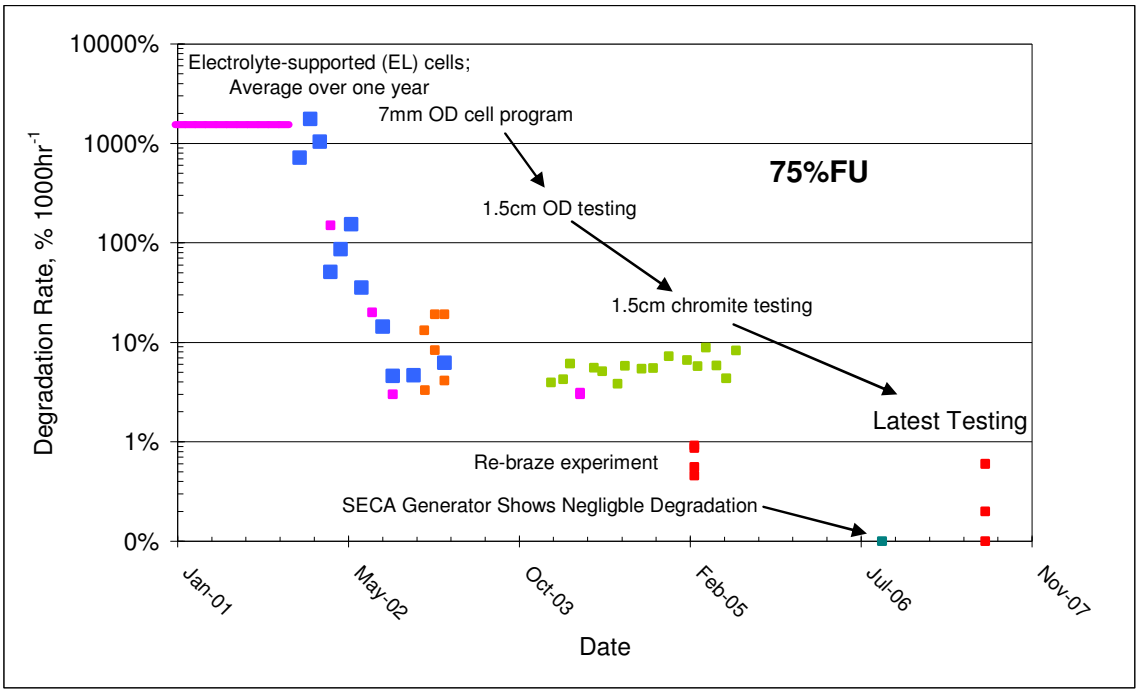


Figure 5 Reduction in Cell Degradation Rate

Two experiments in particular identified current collection through the braze cap as a significant source of degradation. The first was a 13,000 h test of 3 cells with over 60 thermal cycles on each. The degradation of each of these three cells was below 2% per 1000 hours. Each of these three cells utilized a Ni-foam insert at the anode. Due to the porosity (>95%) of this insert, current-carrying capacity was not significant. However, post-mortem pictures indicated that the foam was in contact with both the anode and braze cup in close proximity. In addition, examination showed that there existed a gap between the anode and the braze cup (retarding conductivity).

In the second experiment, five cells (tested for over 5000h) were taken from testing, the braze joints cut off, new joints applied, and the cells retested. These experiments clearly showed that the source of degradation was not the cells, but the braze joint which was required to be both gas tight in a dual atmosphere, and an excellent conductor, passing the current to the anode of the fuel cell. The fuel cell exhibited excellent stability once the effect was removed.

When the current takeoff was changed from the braze joint to the present chromite technology, cell degradation was observed to remain consistent with the previous testing. A cell was thermally cycled 106 times between 800°C and ≤300°C over the course of over 3000 h testing. During that time, the cell was loaded at 800°C between cycles to observe performance changes. A significant performance loss was noted at about 3000 hrs and 62 cycles. When the test was cycled down to room temperature and examined, it was discovered the connection of the wire leads to the LCC interconnection had failed. A new current collector wire was put in place, and the test

restarted. Performance after that was spectacular, with about 0.7% per 1000 hours degradation overall at 75% FU on H_2.

Experimentation on varying the cathode length for a standard anode-supported fuel cell demonstrated that shorter length cells gave higher power density. This was attributed to the length of the current path on both the anode and cathode sides. Reduction of this path could result in significant power improvements. These improvements were realized in full cell experiments through the use of the banded chromite interconnections interconnection. Where peak power densities were approximately 150 mW cm^{-2}, power densities of 300 mW cm^{-2} were consistently realized in single-cell testing.
The latest generation of Acumentrics anode-supported fuel cell is currently being manufactured and tested. That cell, 88 cm in length with a 2.2 cm OD, is capable of producing over 125 W (Figure 3). With no additional improvements to geometry, power densities are comparable to that of the 2.2 cm OD 40 cm length fuel cell generation.

These experiments demonstrate the inherent stability of the Acumentrics anode-supported fuel cell design, the integrity in the processing, and the areas of focus. In addition, it shows the ability to substantially increase both power per cell and power density while cell diameters and lengths are increased.

Phase I System Design

Acumentrics has developed innovative methods and technologies for incorporating its tubular fuel cells into high power density, low cost stacks. As part of the SECA Phase I program, Acumentrics demonstrated these methods, proving soundness of design. Vital to the successful operation and performance of the overall system is the proper packaging of the system components and subsystems to maintain correct operating temperatures, pressures and gas compositions. Through construction and field operation of over 30 generator systems, Acumentrics has acquired significant knowledge in the packaging, shipping and field installation of its fuel cell technology. Figure 6 shows a completely integrated 5 kW system.

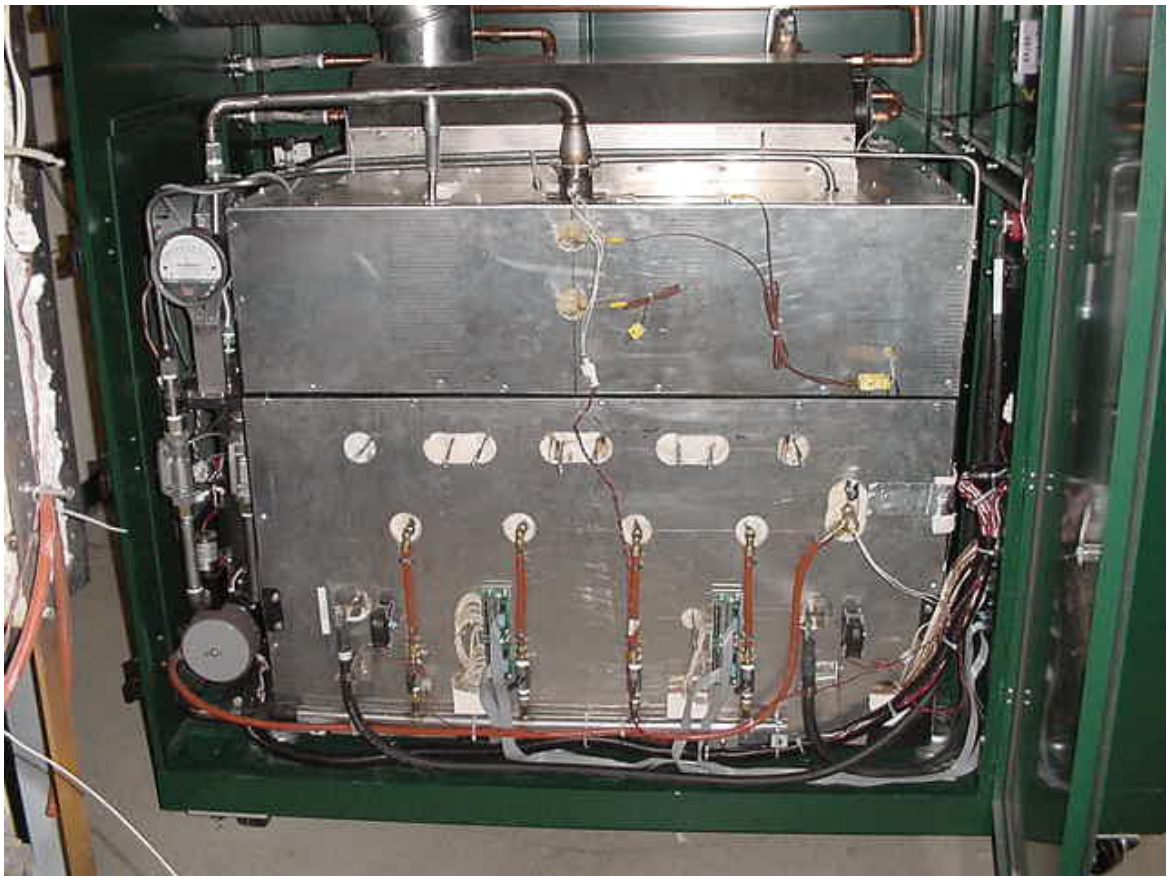


Figure 6 Integrated 5 kW SOFC Generator

Cell Bundling

Acumentrics fuel cell geometry utilizes fuel on the inside of the cell providing a unique way to deliver fuel to the cells and to collect the off gas leaving the cell. Fuel from the common fuel chamber is delivered to the end of the cell via a fuel injector. Spent fuel (offgas) leaving the cell is collected in an integral offgas chamber. Because this design provides complete control of the off gas, recirculation of the offgas is possible, as well as the ability to send this CO_2 rich stream into any CO_2 recovery/sequestration process.

A system of 'bundling' cells was devised. Anode-supported tubular cells are packaged adjacently to significantly reduce the power package. Figure 7 elucidates the significant reduction in package size of a 1 kW module. The number of tubes has been reduced from 126 to 72 to 45, resulting in a weight reduction of 75% and volume reduction of 82%.

Figure 7 Module Compression (1 kW Evolution)

With 2.2 cm OD cells, the bundling package has been further reduced to only 28 cells to achieve the same power (Figure 10).

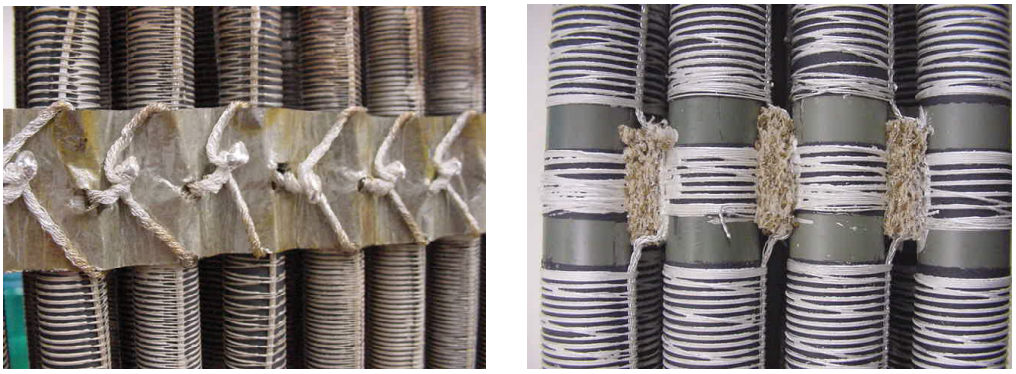
This reduction in cell count significantly reduces cost, and increases reliability due to fewer parts and connections. In addition, large gains can be made with the use of a common plenum or manifold and simple fixturing in comparison to the SECA Phase I generator.

Key to this offgas recovery was the development of an induction brazing process to braze the caps to the cells. Acumentrics has also had success with cemented joints. Various braze materials have been utilized and both conductive and non-conductive joints have been produced. Key to both these joining techniques is the ability to match thermal expansion coefficients. Figure 8 shows cells with brazed versus cemented caps.

Figure 8 Cells with Brazed Caps and Cells with Cemented Caps

The caps themselves have been produced via machining, low cost metal injection molding and metal stamping processes.

A second key aspect of the stack geometry is the method of transferring current between cells. Acumentrics chromite interconnects provide an efficient way to effect close-proximity series and parallel connections. The current collection wire on the cathode can be directly attached to the immediate interconnect of the next cell. Both “sintered” bundle and “fused” wire techniques have been utilized as shown in Figure 9. In the fused method the cathode and anode braids are melted together using a micro torch, and in the sintered method the cells are sandwiched together forcing the cathode braid in contact with the anode. Initial conditioning of the fuel cell bundle results in sintering of the silver connections, resulting in a durable, low resistance connection.



Fused Sintered

Figure 9 Fused and Sintered Current Collection Methods

Figure 10 shows an example of a sintered bundle utilizing 22 mm diameter cells. This bundle also utilizes a common manifold geometry as shown above.

Figure 10 Sintered Bundle with 22 mm Diameter Cells

Bundle Testing Data

Acumentrics engages in the practice of testing new systems first in cell tests, then small-scale tests, finally followed by full-scale system tests. The small-scale tests, referred to as bundle tests, allow the demonstration of multiple cells, with the configuration and assembly methods of a full-scale system.

When comparing the results of bundle testing to cell testing, performance is virtually identical. Bundle and cell testing can also be correlated directly to generator performance, as demonstrated in Figure 11. The graph clearly shows the direct scale up of Acumentrics fuel cell testing, showing the direct applicability of cell testing to the final product. This is a result that is unique to the Acumentrics tubular design and is not found in other geometries.

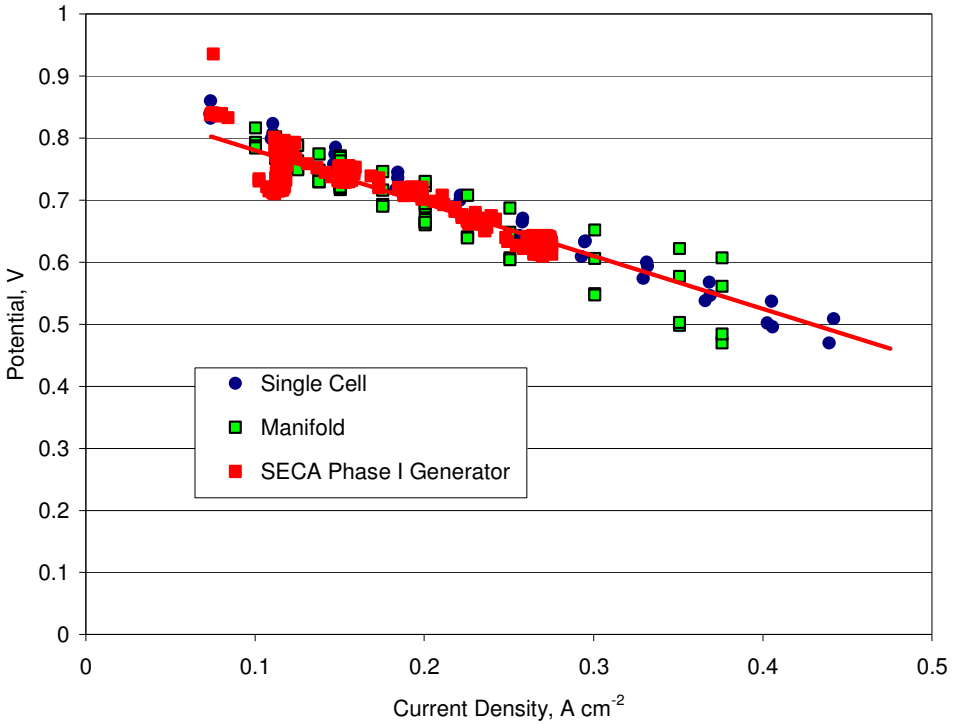


Figure 11 Comparison of Single Cell to Bundle and SECA Phase I Generator Performance

Balance of Plant

Acumentrics fuel cell technology lends itself to simple and inexpensive incorporation into generator systems. This is due in large part to the fact that the fuel is contained within the inside of the cells, resulting in a fuel containment and delivery system consisting of metallic manifolds or plenums and associated piping. The cathode air which is on the outside of the tube and makes up the larger system volume can be contained in a simple refractory structure and can be closely coupled to the heat recovery system. Even in pressurized systems this configuration allows for a straight forward pressure vessel without the need for a high temperature liner.

Acumentrics, working in conjunction with key vendors, has developed components for efficient cathode air preheat, fuel processing and gas handling, and has proven this technology in over 5800 h of 5 kW generator testing.

Heat Recovery

A key component in the 5kW SOFC generator is the cathode air heat exchanger or recuperator. The function of the recuperator is to ensure that the cathode air, and thereby the cells, are at sufficient temperature to permit ion mobility, and to improve overall SOFC system efficiency by reducing stack losses. A brazed, shell and tube, fin-core recuperator has been developed which can exceed 85%

effectiveness. Close integration of the recuperator with the fuel cell module eliminates costly, high temperature ducting.

Work continued to further optimize this technology by incorporating ceramic components to avoid the use of high alloy steels. A schematic of this hybrid recuperator technology is illustrated in Figure 12.

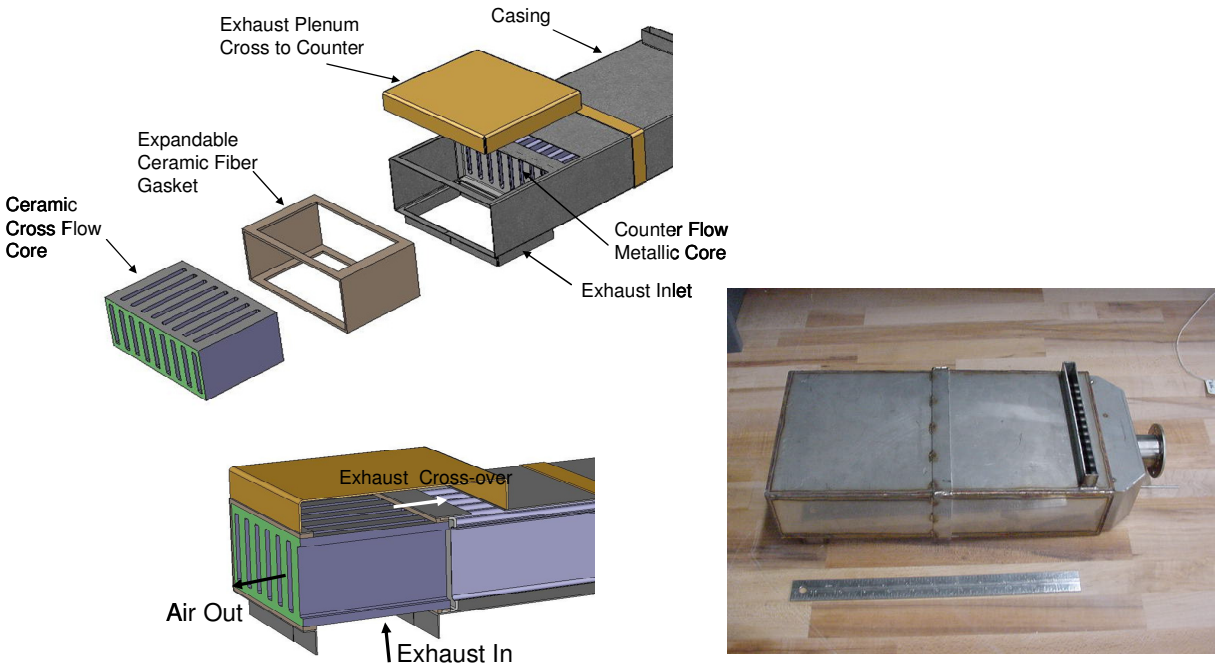


Figure 12: Hybrid Recuperator Development

Fuel Processing

Acumentrics fuel cells have been successfully operated on hydrogen, natural gas, propane and reformed diesel. Both partial oxidation and steam reformation of gaseous fuels has been demonstrated. Steam reformation has been via direct steam injection and offgas recirculation utilizing a high temperature recirculation blower. In addition, individual cells and bundle tests have been operated on a large range of compositions, mimicking well the expected composition ranges in syngas produced from coal gasification processing. The ranges are summarized in Table 2.

Table 2 Gas Composition Based Fuel Cell Testing (mole fractions)

Species / *Test*	*H_2*	*H_2O*	*CO*	*CO_2*	*N_2*	*CH_4*	*other*	*Hours testing*	
Reforming test 1	0.227	0.341		0.284		0.15		3000	Two cells
Reforming test 2	0.281	0.314	0.061	0.237		0.11		600	two cells
Diesel test 1	0.35-0.30	0.57-0.48	0.10-0.05	0.07-0.06				1330	bundle test

JP8 test 1	0.295	0.113	0.14	0.064	0.39	Trace C1/C2/C3	24	bundle test
Normal cell test	0.97	0.03					>100,000 numerous tests	
Normal CPOX test	0.36	0.03	0.18	0.01	0.42		>100,000 numerous tests	

This range of experience gives confidence that the Acumentrics tubular system can be efficient and stable on virtually any syngas available.

Power Conversion

Having been founded to create custom power conversion solutions for difficult applications, Acumentrics has relied on in-house expertise to regulate the electrical output of their fuel cells. During the SECA program this was first demonstrated with the implementation of the Fuel Cell Interface Converter (FCIC), providing a DC to DC conversion efficiency of 98%. Control of the FCIC is implemented over a CAN bus, with the specification of a maximum input current (fuel cell), minimum input voltage, and maximum output voltage. This leads to multiple fold-back behaviors, each of which occurs on millisecond timescales. Supervisory control can then determine the operating mode of the FCIC and attached systems (fuel cell and load) by careful specification of these limits.

During Phase I, Acumentrics also developed a high current, low voltage inverter by modifying two FCIC power stages and implementing a new power control system (Figure 13). This 5 kW inverter exceeded 94% efficiency, the highest of any produced in the SECA program.

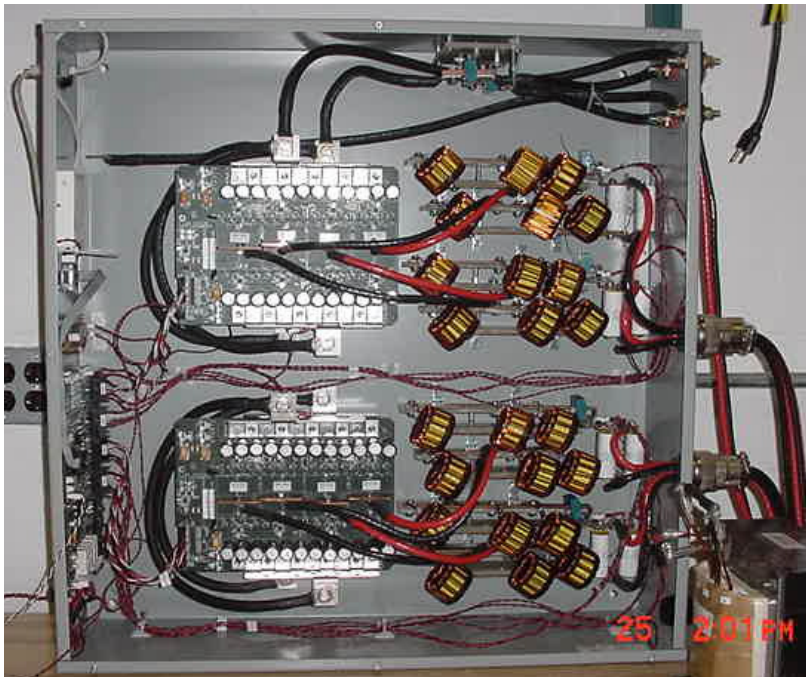


Figure 13 Program Leading SECA Phase I Inverter Prototype

Control Systems

Acumentrics' fuel cell control systems development has been undertaken with a highly granular, iterative approach. Multiple test machines have been developed, with a steady stream of controls improvements made at each new deployment. As the system design has converged, the nature of control improvements tends toward the ephemeral, dealing in algorithmic and firmware improvements. However, as system design changes accumulate, occasional changes to the control system hardware design are warranted.

Prior to joining the SECA program, Acumentrics had already undertaken the significant development of a custom control solution to replace a commercial PLC system. The useful life of this system, for development purposes, was extended by adding a CAN (Controller Area Network) bus, allowing additional instances of the PCB to be used for I/O expansion. Late in Phase I of the SECA program, a new board was developed providing expanded I/O and an updated DSP/MCU. This board was integrated into the Phase I test article and has been used in multiple field-trials.

Algorithmic aspects of the currently developed control system design capture the interplay of various fuel cell operating parameters necessary for elementary automated operation and incorporate the following features:

- Multi-layered state-machine, with supervisor and subordinate machines.
- Classical control elements (e.g. PI/PID control, high/low/band-pass filter, delay)
- State-dependant gain scheduling and slew rate controls.
- Supervisory fault handling with programmable machine-dependent state responses.
- Input filtering and/or over sampling.
- Operator over-rides for manual intervention.

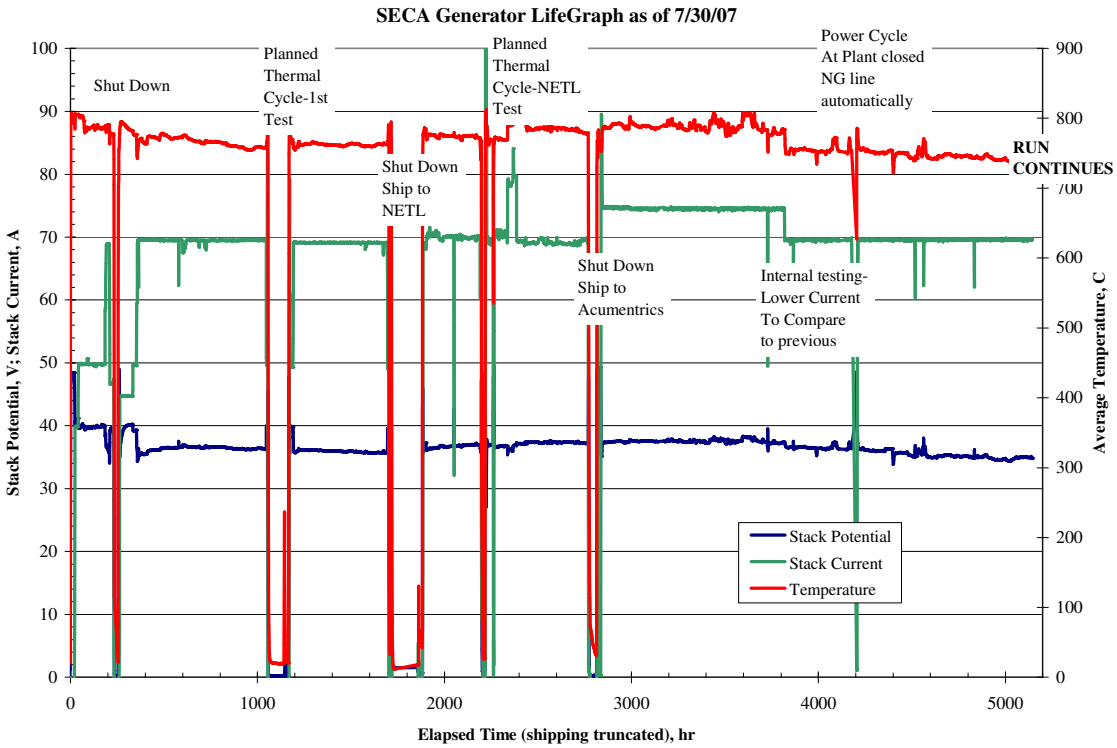
Phase I Goals Met or Exceeded

A 5kW rated stand-alone SOFC unit was utilized in the SECA Phase I generator testing. That generator was run under a stringent test criteria set by the DOE, and audited externally. The generator achieved the required 1500 h of operation in initial testing, was shipped, and performed over 800 h additional testing at the DOE site. It then was shipped back to Acumentrics where it accumulated over 5800 total hours of operation. As part of that test, over 20 power cycles were performed demonstrating the quick response of the anode-supported system, the peak power of 6.2 kW net DC as recorded by the DOE, and the >35% net DC efficiency that was achieved throughout the test. The requirements and results of testing are shown in Table 3.

In addition, the generator validated the single cell and bundle testing performed prior to operation. A performance curve was generated from the generator around 1000 h operation, and compared to performance curves generated in the bundle test at 120 h and 1000 h. The comparison of these curves shows the bundle testing (and by default of previously discussed data, single cell testing) to correlate extremely well. In addition, the performance observed in the generator system validates the robust nature and quality processing of the fuel cell design.

Table 3 Phase I SECA Test Results

	Goal set by DOE	Acumentrics Phase I Generator	DOE-NETL On-Site Testing
Peak Power DC	3-10kW	6.1kW (Intended 5 kW)	6.2kWDC (NETL) 6.5kWDC (Acumentrics)
Degradation Rate %/500hr	≤2%/500 hrs	0%/500 hrs	-1.5%/500hr (Output increased)
Peak Efficiency %	35%-55%	36.9%	Avg 36% (four tests)
Availability %	>80%	97.5% (10 thermal cycles)	96% (including startup, testing, 3 thermal cycles, & grid failures)
Short-Term Power Degradation After Thermal Cycle %	<1%	0.75%	Not measurable
Cost $/kW*	<$800/kW	$729/kW	$717/kW



Phase II Project Objective

The overall objective of this project was the development of a low cost, high efficiency, 3 - 10 kW, Solid Oxide Fuel Cell generator system for use in stationary, transportation and military applications. Research and development in Phase II focused on refining the design and manufacture of a tubular SOFC power system capable of achieving greater than twice the power density of anode supported tubular designs available at the start of Phase I of the program. These units are capable of entry into the telecommunication, remote residential, and CHP markets. Operation on fuels including natural gas and propane have been developed for all markets.

Goals of the Phase II program include:

1. Adapting the generator design for integration of the next generation higher power multiple connection Chromite cells.

2. Development of an anode supported tubular cell capable of further doubling the power density presently achieved.

3. Integration of a Steam Reformed Recirculator to achieve the SECA Phase II efficiency goal of >40%.

4. Prototype testing of a natural gas unit meeting and exceeding SECA Phase II goals.

Phase II Go/No-Go Decision Point

Acumentrics was required to achieve two separate goals by Q4 2009: The first was the testing of a stack for 1500hrs with <1%/500hrs degradation and the second was the thermal cycling of cells demonstrating at least 50 thermal cycles with <0.5% loss in voltages. The exact wording from the SOW is as follows:

"In an attempt to assure that the research and development proposed was making adequate progress, a key performance metric related to SOFC stack performance was utilized as a decision trigger to continue funding. Under section 3.3 milestones there was a goal of completing stack performance tests. By the end of Q4 2009, Acumentrics would demonstrate an SOFC stack meeting the phase II performance milestone of 1500 hours operation with <1% degradation/ 500 hours operation at constant stack voltage. Acumentrics would also demonstrate 50 thermal cycles with less than 0.5% loss in voltage on cells tested in single cell test stands. "

The successful completion of these two goals, ahead of schedule, is shown in the sections below.

Thermal Cycles

Thermal cycle degradation is a key component of system degradation due to the natural system cycles found in any smaller CHP (combined heat and power) system. For example, when hot water is not required, and only trickle power is needed, system capacitance can ensure adequate load enabling the fuel cell to shut down, potentially increasing the lifetime of the system. The system might also shut down if in a peak-shaving mode in conjunction with the local grid. If, however, there are significant losses on cycling due to thermal expansion or component mismatches, this important aspect of CHP operation can turn into a liability.

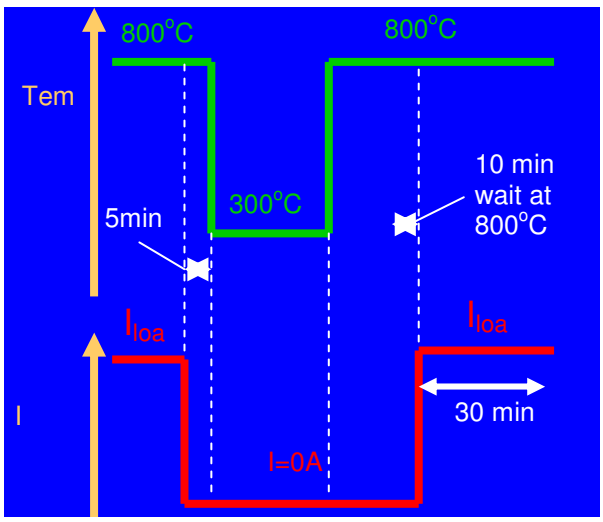


Figure 14: Schematic of the operation of a single thermal cycle.

To this end, Acumentrics tested a number of different single-cell configurations to determine the robustness of the cell as well as the mechanics of the surrounding electrical support system. These

thermal cycles were performed by first operating the cell under standard conditions (800°C, 75%FU, H_2/H_2O). Shown schematically in Figure 14, the cell was unloaded to open circuit, and then cooled to 300°C. This cooling operation required most of the time for a thermal cycle as the furnace system was not designed to be actively cooled, and thus was convectively limited, similar to a generator. At 300°C, the furnace was restarted, the cell brought back to temperature and reloaded. The data points shown are actual operational points only, as this is the critical parameter in such a test.

The best results were found with an electroplating process (shown in Figure 15 in comparison to standard cell configurations), which demonstrated 116 thermal cycles with 0.41%/50 thermal cycles degradation and an additional 339 thermal cycles were performed to demonstrate stability. This data represents the average of multiple cells tested, further increasing confidence in the result.

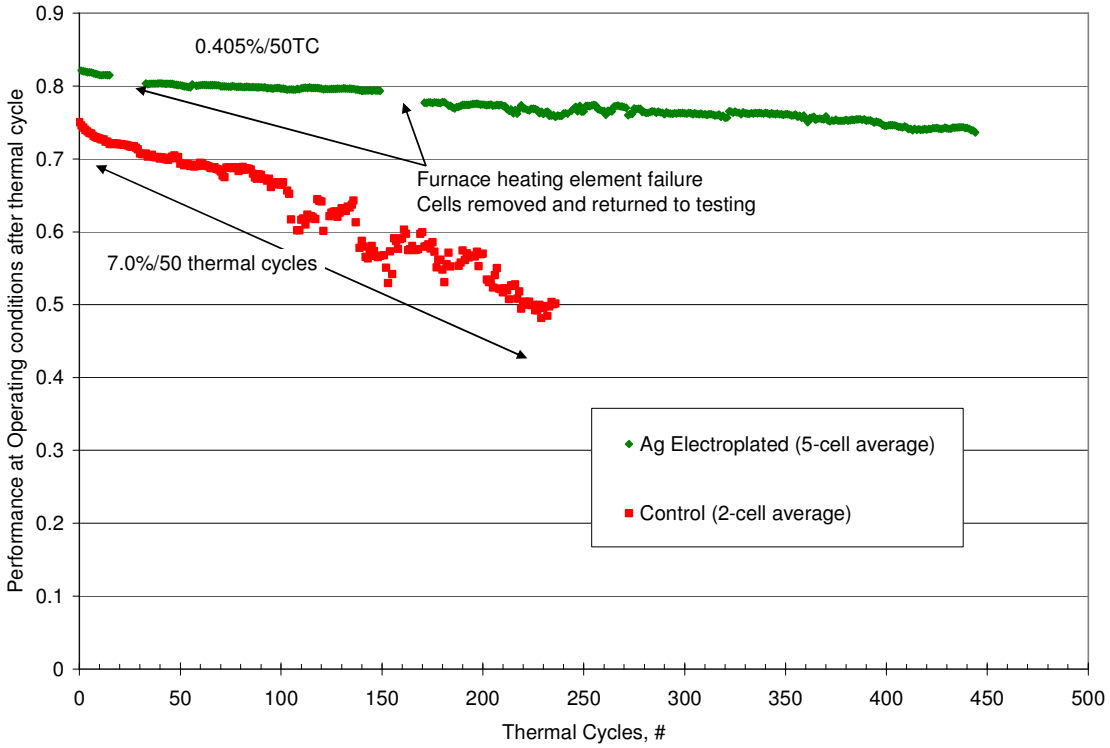


Figure 15: Graph showing five cells with over 400 thermal cycles, demonstrating <0.5%/50 thermal cycles degradation rates.

In short, while un-modified cells showed significant degradation of 7%/50 thermal cycles and could only achieve 250 thermal cycles, modified cells showed significant longevity over 400+ thermal cycles with degradation rates <0.5%/50 thermal cycles. This rate was proven using multiple cells, demonstrating the robustness of the Acumentrics fuel cell design and the significant progress at Acumentrics in achieving design goals through EERE support.

Stack Testing

Acumentrics tested a 36-cell standard stack configuration for 473 hours in a dedicated stack tester, and then put that stack into a generator (independent operation using a natural gas POX system at an O/C=1.4 and FU of about 65%) shown in Figure 16. The generator was run for the requested 1500hrs and the data recorded.

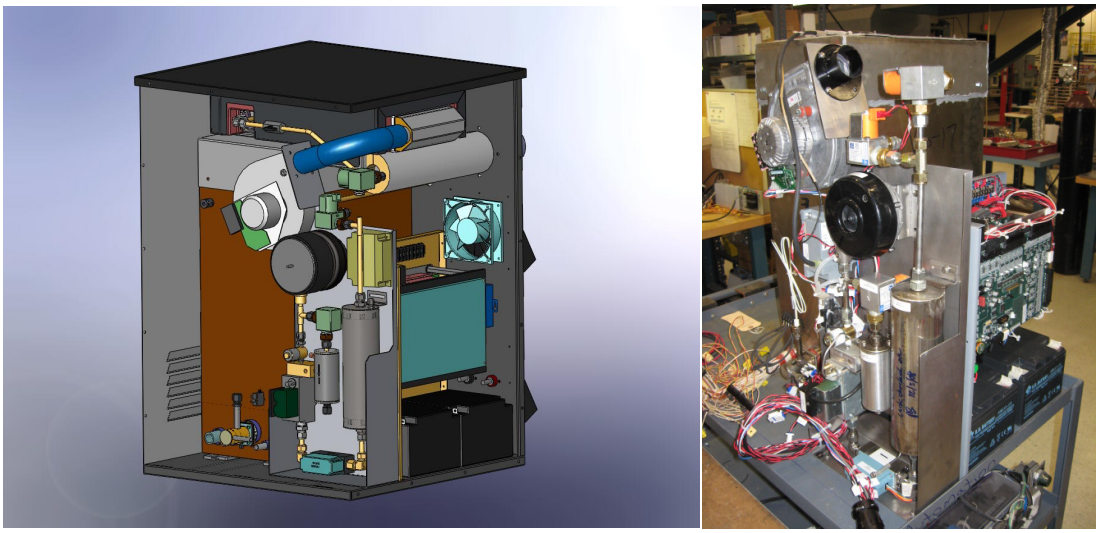


Figure 16: Unit into which the stack was placed; cartoon showing placement and actual system.

The run, shown in Figure 17, occurred at constant current density and a slightly increasing FU at an average stack temperature of about 800°C. The starting average cell potential for the stack, at 23 hours on the graph, was 0.824V and the potential at 1565hrs (1542hrs operation in the generator configuration) was 0.813V. Using these numbers, a degradation rate of 0.43%/500hr is calculated. However, it needs to be remembered that the stack was previously run; if that 473hr run is taken into account, the total degradation of the stack is 0.34%/1000hr.

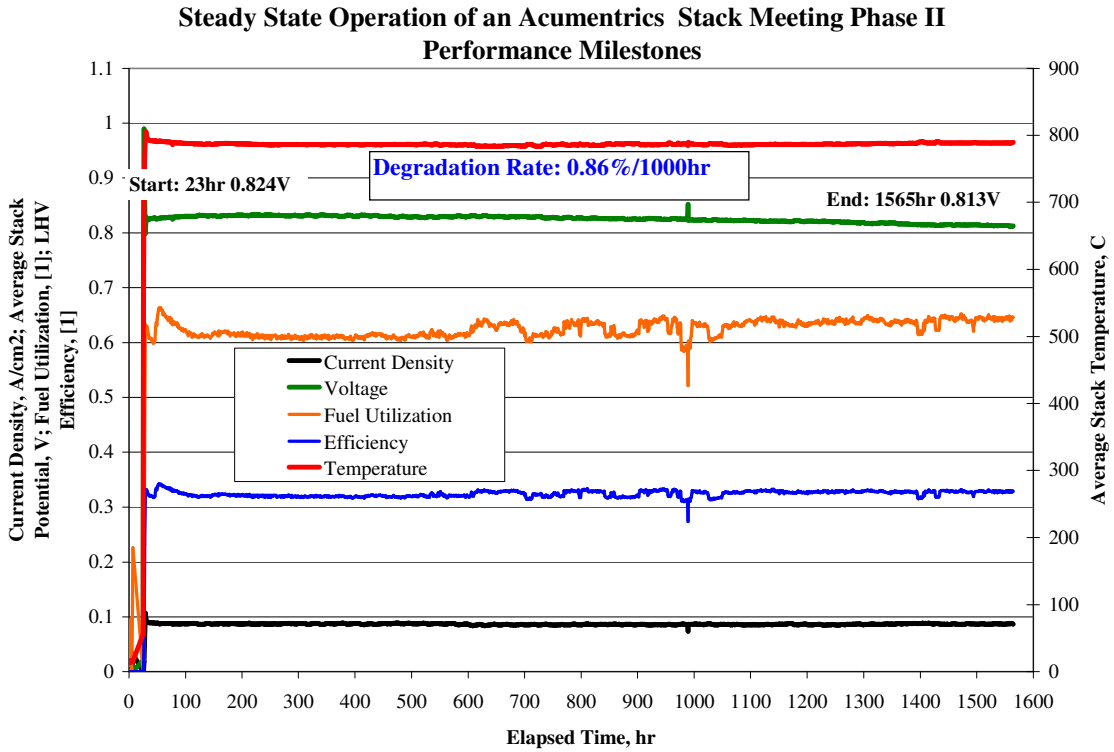


Figure 17: Figure showing the steady-state performance of Acumentrics' state-of-the-art stack over the initial 1500 hours of operation in a complete system on natural gas. The stack was previously tested for an additional 473hrs prior to the start of this test.

Clearly, the stack exceeded the required performance by a factor of two, indicating the robustness of the Acumentrics fuel cell and generator design, bringing the commercialization of fuel cell systems one step further. Degradation rates such as these take Acumentrics' stack from the realm of scientific test to engineering reality.

Acumentrics Corporation demonstrated an SOFC stack meeting the phase II performance milestone of 1500 hours operation with <1% degradation/ 500 hours operation at constant stack voltage. Acumentrics Corporation also demonstrated 50 thermal cycles with less than 0.5% loss in voltage on cells tested in single cell test stands. Upon verification, the DOE approved the results and allowed Acumentrics to move forward with the project.

Phase II Goals and Accomplishments

1.0 System Development and Integration

1.1 - System Development and Integration

In Phase II, system design efforts were directed towards development of a systems capable of entry into the telecommunication, remote residential, and CHP markets. A key factor in meeting this objective is the design of a system that maximizes overall system efficiency capable of high reliability utilizing affordable system components. Techniques for accomplishing steam reforming of the fuel to improve the overall system electrical efficiency were evaluated including offgas water recovery and reinjection, offgas recirculation and advanced partial oxidation/internal steam reformed systems. Fuel reforming evaluations are discussed in Section 1.4 and 5.1 while this section reports on the overall system configuration utilizing these technologies.

Figure 18 presents the overall configuration of the integrated micro-CHP system. Acumentrics considers the micro-CHP system to be divided into four main components: The Hot Box, which incorporates the fuel cells, fuel plenums, cell current collection and insulation; the Process Instrumentation which includes the pumps, blowers, meters, and valves for control of the system, the Hot Water Group which includes the hot water heat exchanger and peak burner; and the Electronics, which include the power and control electronics, the hardware associated for those devices, and the control software.

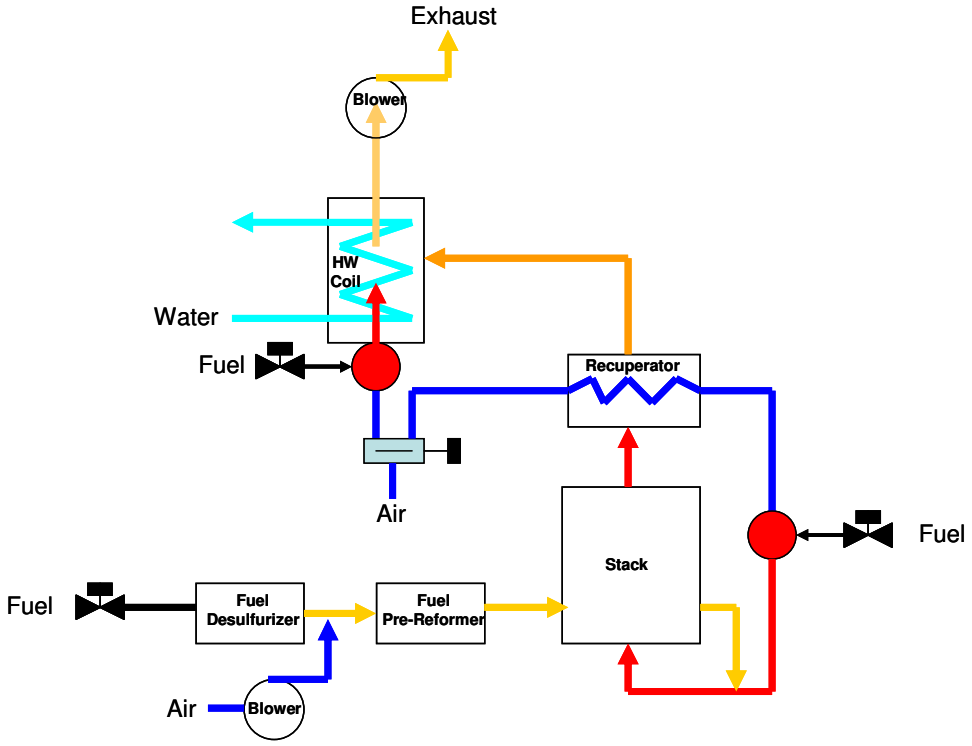


Figure 18 System Configuration

Gas control to the cells consists of a low-pressure blower (air), valve (natural gas) and venturi system that provides the correct air to fuel mixture to the cells through a catalytic partial oxidation reaction (CPOX). An air to air, high

effectiveness recuperator is integrated directly with the stack hot box providing the necessary preheat to the incoming cathode air. A startup burner is located between the outlet of the recuperator and the stack to bring the system up to temperature. Unspent anode fuel is directed into the incoming cathode air thereby oxidizing the remaining fuel and further preheating the cathode air.

Spent cathode air leaving the recuperator is directed to the system hot water coil for further heat recovery. This coil also obtains thermal input from a convention pre-mixed burner assembly which is fired as necessary to maintain the hydronic system supply temperature at the prescribed set point. Motive force for both the fuel cell and hot water coil burner is by means of a single induced draft fan which maintains suction on the system and discharges to the exhaust. Hot water burner combustion air and fuel cell cathode air are regulated by a multi-port rotary control device.

The entire system is controlled though Acumentrics proprietary software, which will appropriately adjust fuel/air/current set points to allow operation of the generator in the desired regime, with the desired electrical and/or heat output.

The hot water group consists of a heat exchanger that can receive thermal input from the spent cathode air exhausting from the fuel cell stack as well as from a dedicated burner. The heat exchanger is made up of three zones as shown in Figure 19: the burner zone, cathode air zone and a mixed, condensing zone. Air for both the fuel cell and peak burner is supplied by an induced draft fan which draws air through the systems. The peak burner utilizes a conventional gas valve/venturi combination to achieve proper air/fuel ratio over the operating range of the burner. The burner zone of the heat exchanger is fitted with a spark igniter and flame rod for ignition and flame verification.

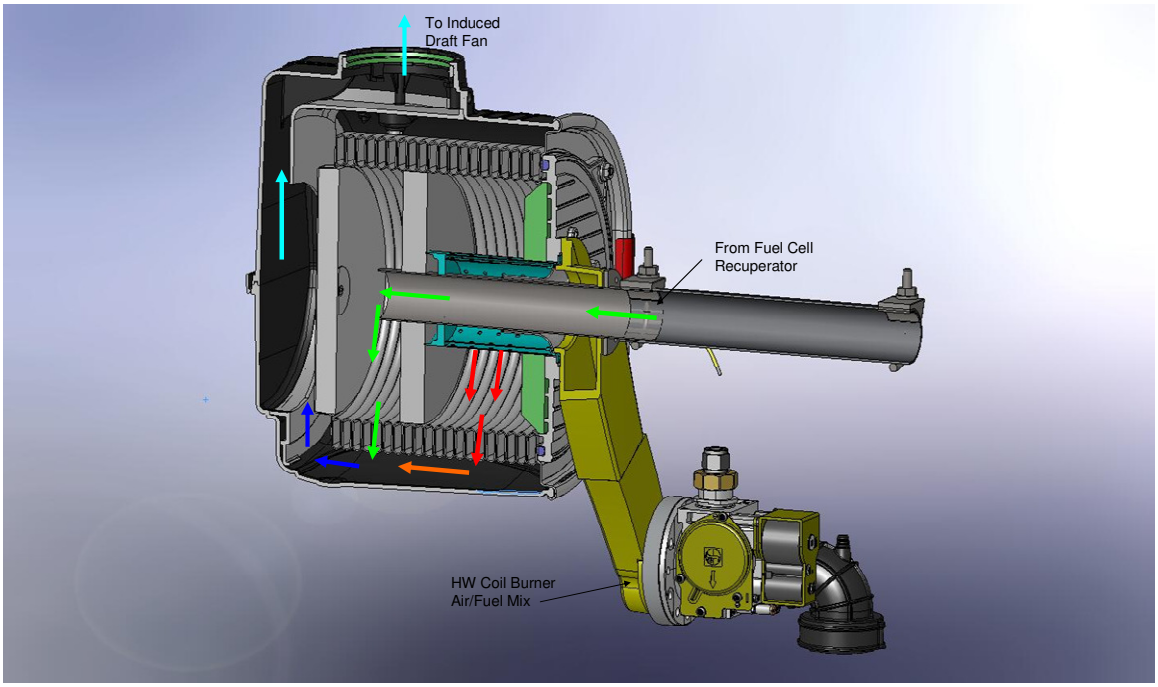


Figure 19 Hot Water Coil with Burner

Various valves, sensors, blowers and associated devices are utilized to control the flow of gases to the system. The Process and Instrumentation Diagram (Figure 20) depicts the overall configuration of the system as well as the devices utilized.

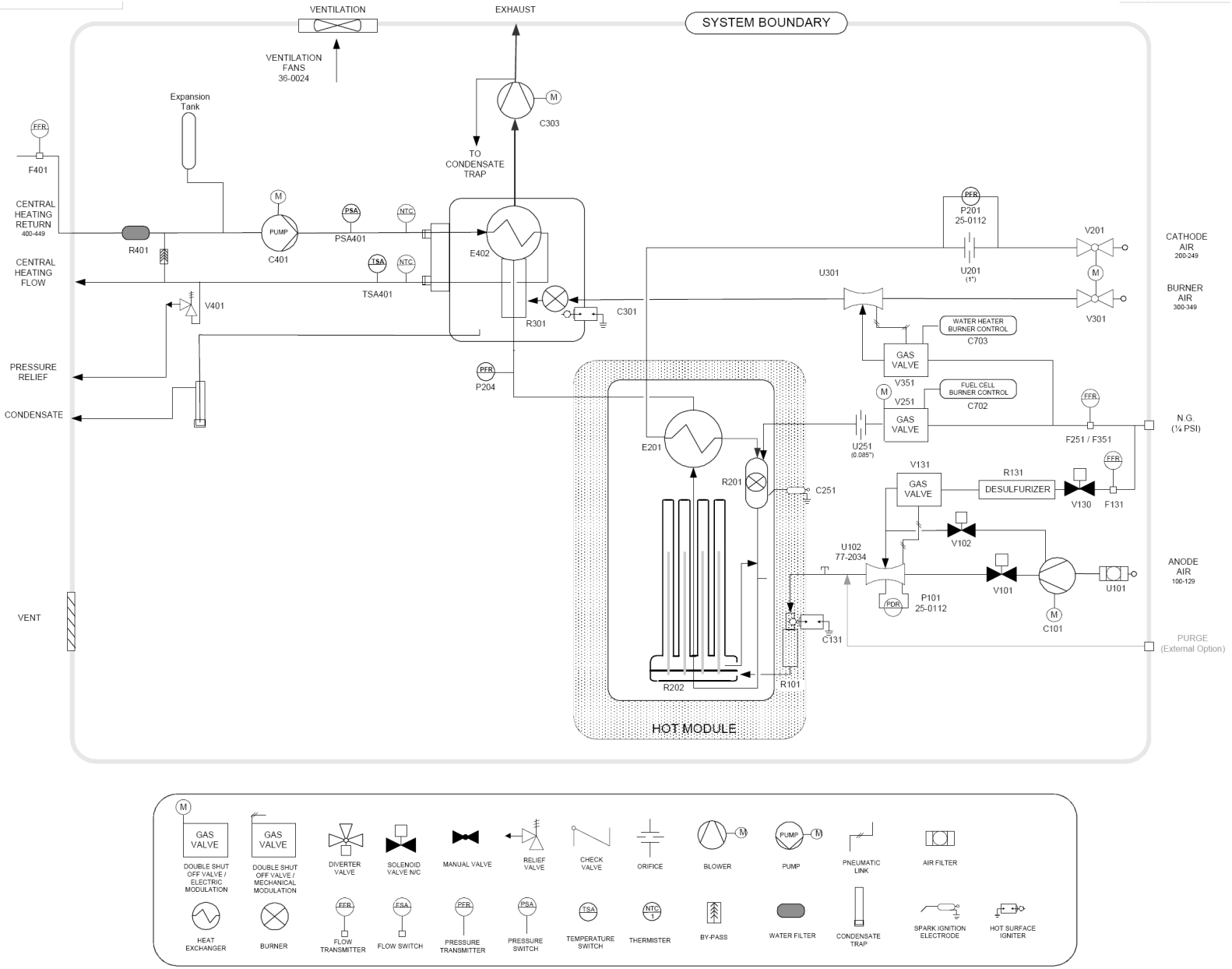


Figure 20 Process and Instrumentation Diagram

A schematic of the micro-CHP electrical layout is given in Figure 21 below. The system includes a DC/DC converter which regulates the current flow from the fuel cell stack and provide a regulated 48 VDC outlet for charging the batteries and supplying the DC to AC inverter. The inverter has a 48 VDC input from the DC buss and output 110 VAC 60 Hz power to the local grid. A transformer is utilized to supply AC power to 230 Volt components.

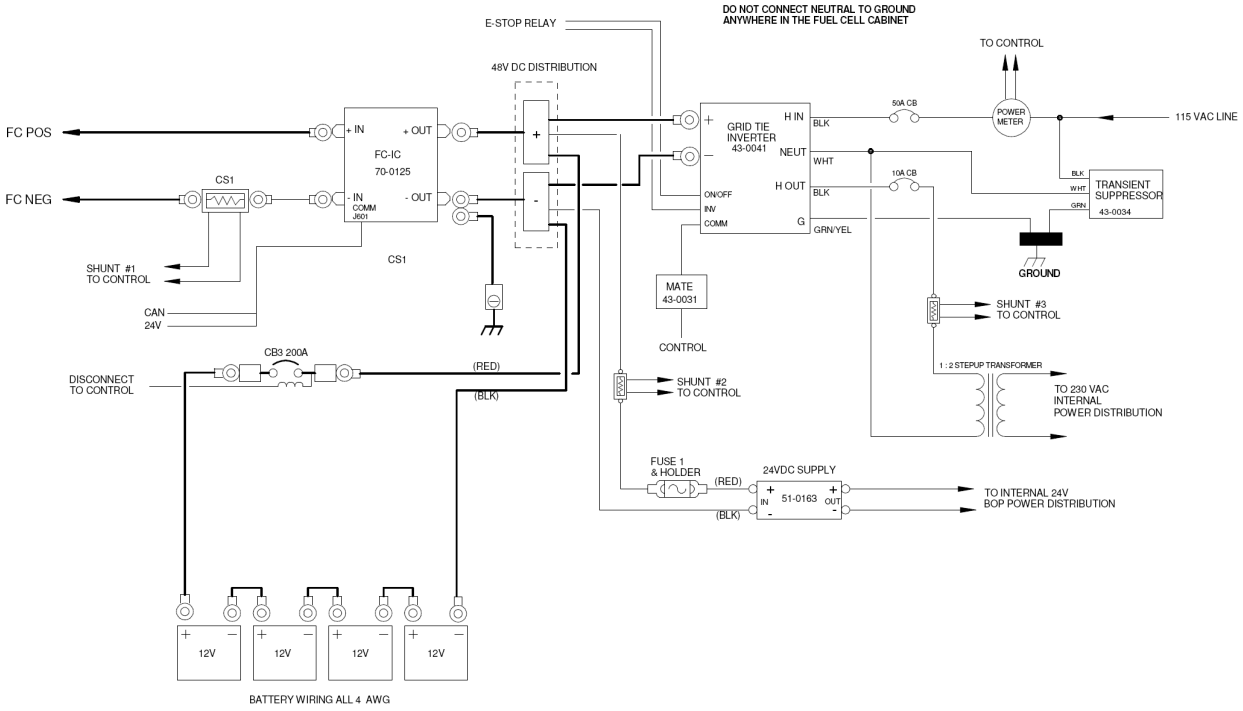


Figure 21 *Electrical Schematic*

The general layout of the micro-CHP system is illustrated in the CAD model in Figure 22. The system is packaged into a floor mounted enclosure which provides easy access to system components and allows for quick replacement if necessary. The basic functionality of the fuel cell generator and hot water boiler system is similar to the ones in wall hung versions.

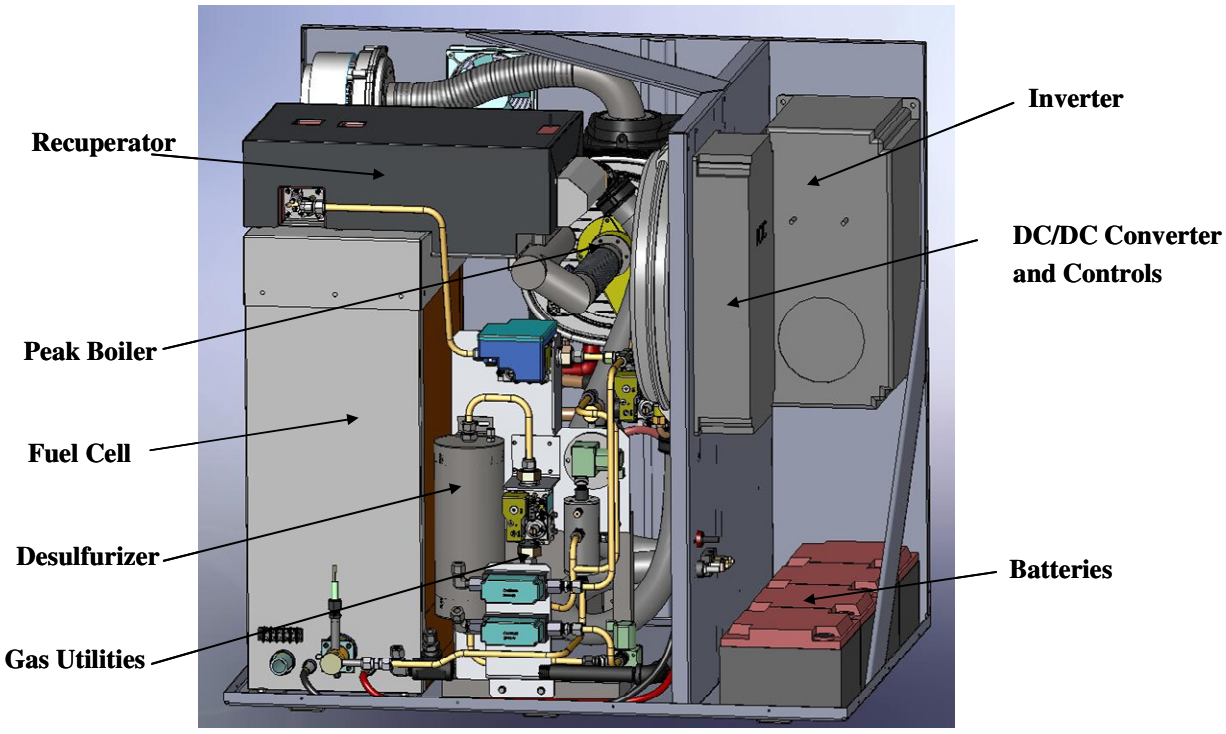


Figure 22 Micro-CHP Layout

A variant of the above system utilizing fuel steam reformation was also designed, built and tested. As illustrated in the equations below, the steam reformed reaction provides more useable fuel to the fuel cells than the partial oxidation reaction. In addition, the endothermic reaction assists in controlling cell temperatures in Acumentrics axial flow tubular geometry.

Partial Oxidation: $CH_4 + 1/2O_2 \Rightarrow CO + 2H_2$

Steam Reformation: $CH_4 + H_2O \Rightarrow CO + 3H_2$

Figure 23 gives a Process and Instrumentation diagram (P&ID) for the system. Water utilized in the anode stream is city water processed through a residential grade, 5 stage reverse osmosis purification system. Figure 24 is a photograph showing the system configuration.

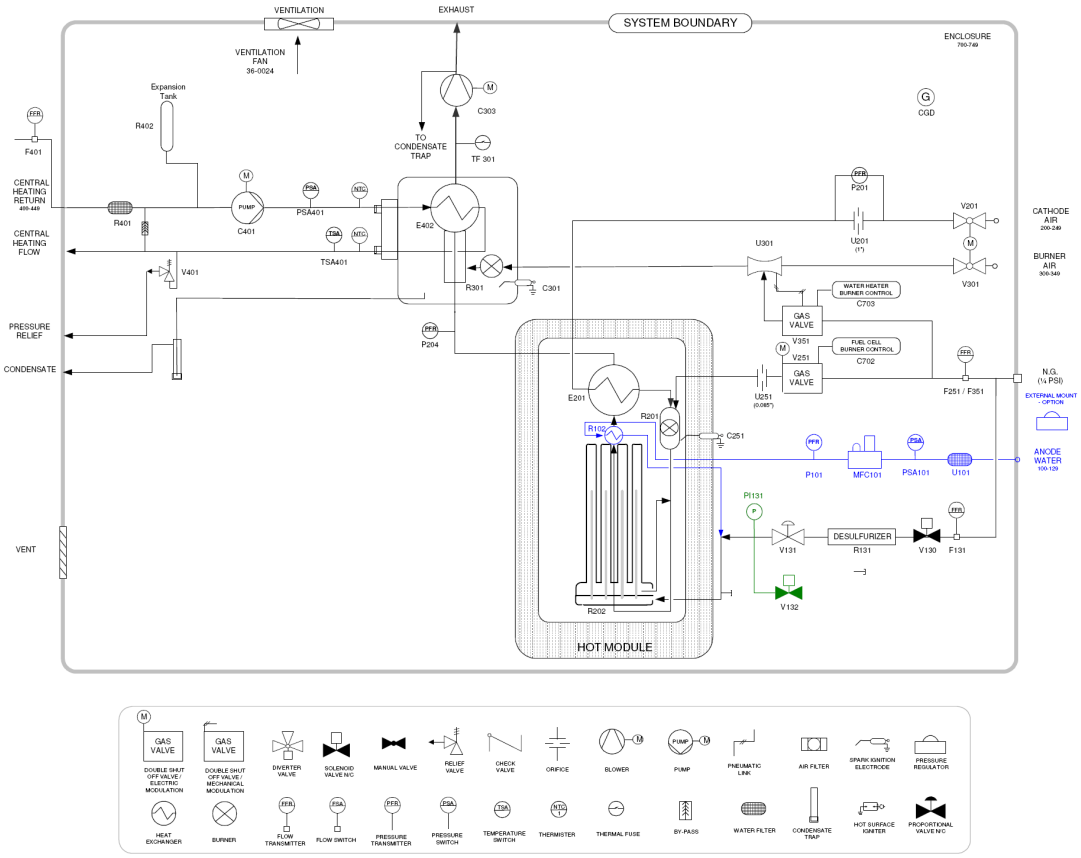


Figure 23 HEA-103 Process and Instrumentation Diagram

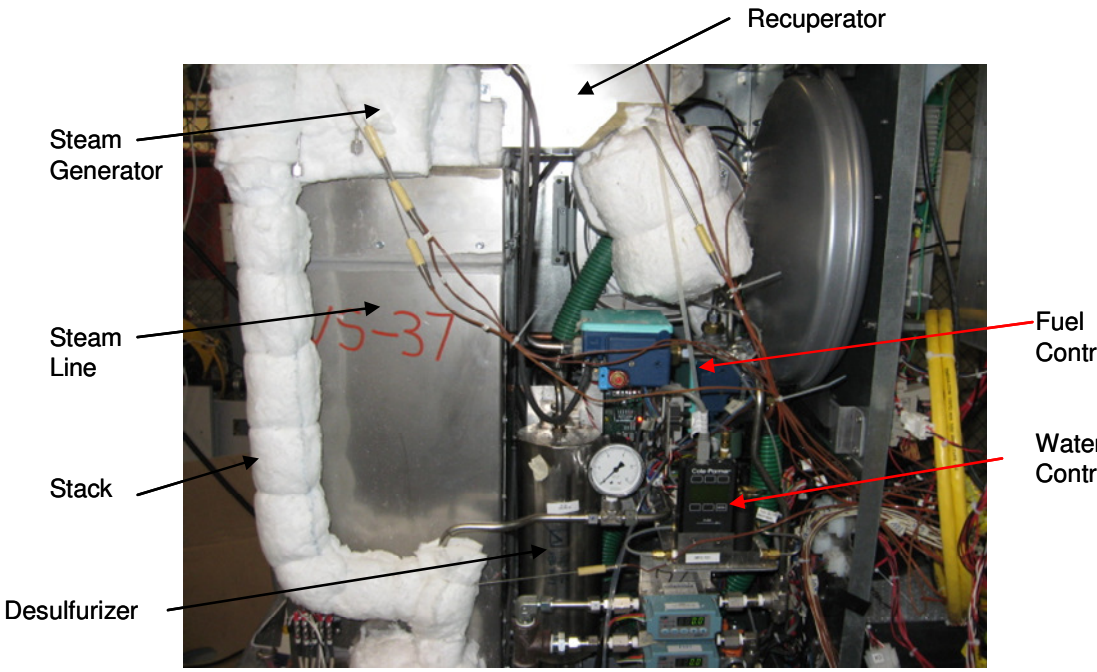


Figure 24 HEA-103 Configuration

As shown on the P&ID, the steam generator is located between the stack outlet and recuperator inlet. For this initial unit the steam line is routed external to the fuel cell module but can be routed internally in production systems.

For remote power applications where heat recovery is not required, such as telecommunications and oil and gas industry, sensing instrumentation and pipeline catalytic protection, a system was designed without the heat recovery feature described above. Also since steam reformation via water recovery or potable water purification is not practical for these small remote power (RP) generators which must be low cost, highly reliable and operate under extreme ambient temperature conditions, the Remote Power Unit was designed as a CPOX system capable of standard POX operation or the high efficiency, advance POX system developed later in the program (See Section 1.4). Several generations of this RP unit were built and tested incorporating the latest advances is stack designs. Figure 25 shows the overall system configuration. The system has been designed as a grid independent system, capable of supplying regulated DC voltage from 5-52 Volts. The output can be selected to be constant current or constant voltage. The process and instrumentation diagram for this system is given in Figure 26.

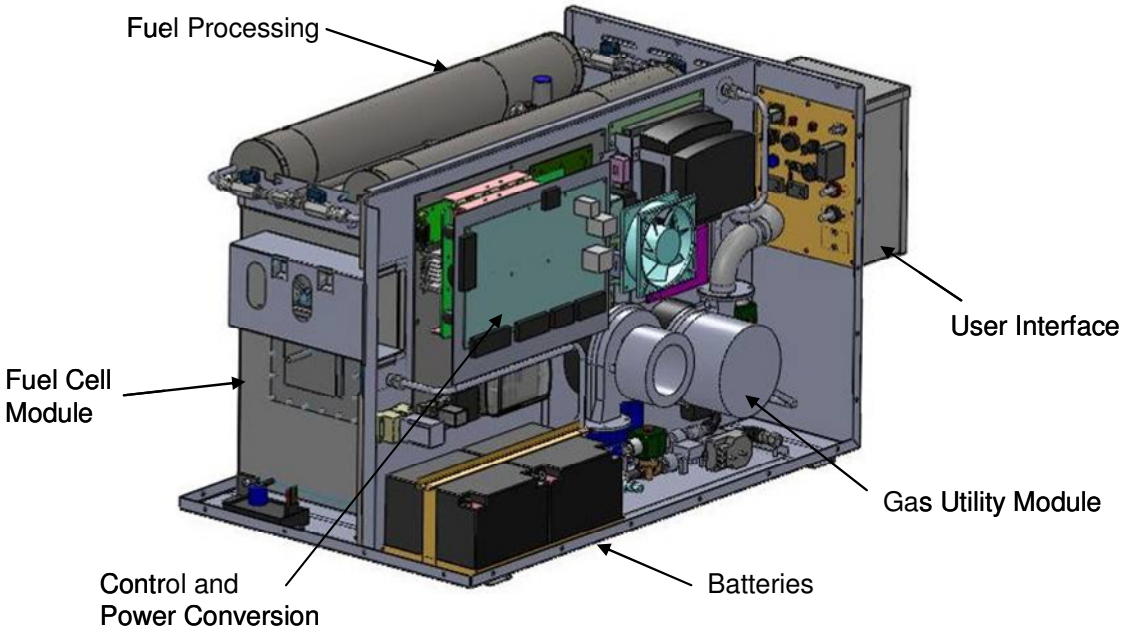


Figure 25 Remote Power Generator Configuration

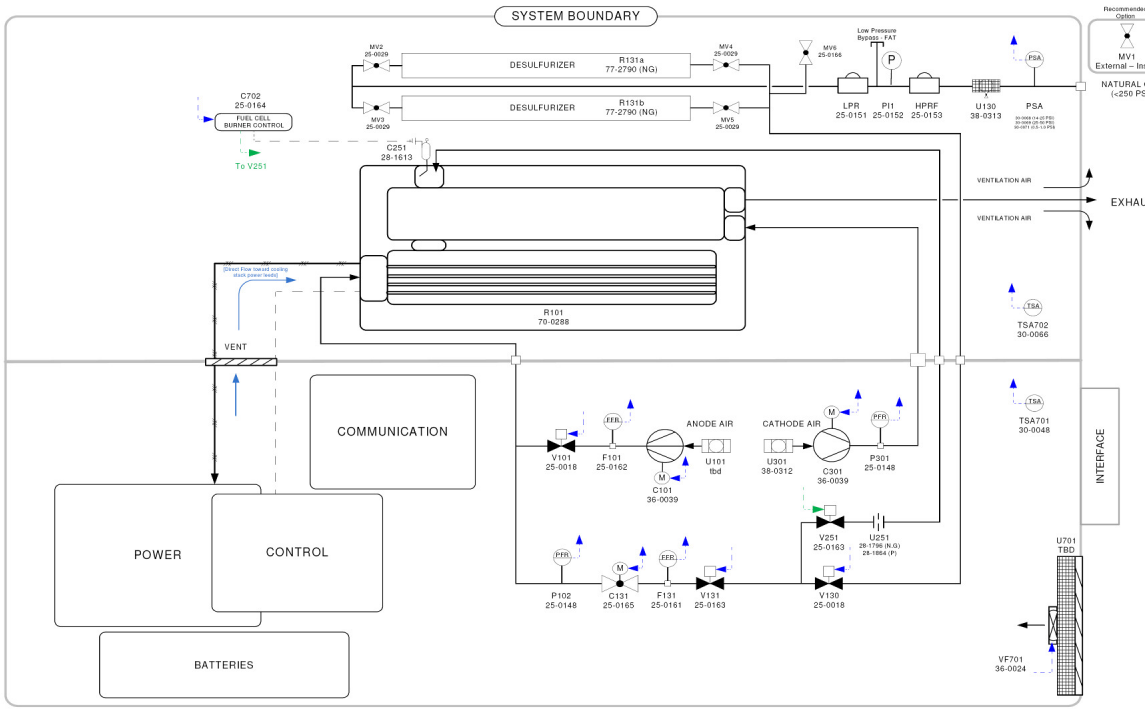


Figure 26 Remote Power Unit P&ID

Over the course of Phase II approximately 50 of these remote power generators were built and tested. Along with several laboratory units, generators were placed in the field under a variety of applications and test conditions. Among these are: pipeline and well head catalytic protection, chemical injection pumps, cell towers, wind assessment units (LIDARS), outdoor lighting and a National Park Service visitor center. Table 4 provides a summary of the field unit operations at the end of the this program. The units highlighted in green are propane fueled whereas the remainder are natural gas fueled.

Table 4 RP Fleet Summary

Unit	Bundle	Stack Current	Stack Volts	Stack Power	FU	Iout	Vout	Pout	Run Hrs	Total Hrs	Availability
RP20-7	RB20-14	6.2	11.2	70	19%	0	0	0	8575	9251	93%
RP20-18	RB20-54	3.3	19.6	63.4	11%	-0.1	48.6	-4.2	2382	2384	100%
RP20-20	RB20-45	5.1	19.2	96.7	16%	0.8	52.9	41.5	2377	2377	100%
RP20-11	RB20-59	24.9	16.3	406.3	69%	6.2	53.2	327.3	3418	5579	61%
RP20-43	RB20-	23.1	16.7	384.6	75%	5.9	53.2	312.2	2449	2459	100%
RP20-44	RB20-	24.9	14.6	364	60%	5.4	52.9	283.3	2454	2508	98%
RP20-59	RB20-	26.2	15.9	415.9	70%	6.4	53.3	343.7	733	733	100%
RP20-16	RB20-32	30.1	15.5	464.9	65%	14.6	26.2	382.1	3835	5873	65%
RP20-23	RB20-42	25.9	16	413.6	61%	29.8	11.5	343.1	4569	4570	100%
RP20-24	RB20-40	23.9	15.9	378.8	65%	24.0	12.1	378.8	4276	4572	94%
RP20-25	RB20-41	46.1	15.2	699.4	65%	30	20.1	602.3	4074	4074	100
RP20-26	RB20-43	18.5	16.3	301.9	0%	24	9	217.1	4544	4545	100%
RP20-28	RB20-49	29.6	15.4	454.8	50%	24	15.6	374.2	3253	3253	100%
RP20-29	RB20-48	4.3	18.6	80.5	14%	0	1.1	0	3023	3250	93%
RP20-30	RB20-47	12.8	17.2	220.5	36%	16.1	7.6	121.6	3179	3232	98%
RP20-31	RB20-44	49.9	14.6	727.8	75%	39.4	15.7	620.9	3228	3229	100%
RP20-35	RB20-55	6.8	18.4	124.6	22%	8	5.5	43.6	3062	3181	96%
RP20-36	RB20-56	15.2	16.9	257.2	41%	16	10.9	174.8	3204	3204	100%
RP20-37	RB20-58	6.3	18.6	118.1	21%	8	4.9	39.6	1101	1170	94%
RP20-38	RB20-57	49.9	14.9	743.9	65%	22.2	28	622.2	3178	3178	100%
RP20-4	RB20-19	22	15.6	343.6	53%	16	15.4	246.2	9232	9232	100%
RP20-5	RB20-13	11.5	15.4	177.8	28%	8	7.5	60	9253	9253	100%
RP20-6	RB20-12	18.6	15.7	292.4	49%	20.3	8.5	172.8	9147	9277	99%
RP20-52	RB20-73	48.5	15.2	737.7	65%	40	15.3	610.5	1356	1359	100%
RP20-53	RB20-65	7.6	18	136.7	25%	8	7.5	59.9	982	1333	74%
RP20-54	RB20-66	11.9	17.7	211.3	39%	15.9	8.3	132.1	1332	1336	100%
RP20-55	RB20-74	44.3	15.1	667.2	64%	21	26.8	561.2	1352	1355	100%
RP20-61	RB20-79	45.1	13	586.6	65%	20.6	23.1	474.5	350	351	100%
RP20-62	RB20-86	11.8	17.9	210.9	38%	16	8.5	136.2	375	375	100%
RP20-63	RB20-69	55	13.2	723.8	65%	30.2	20.5	618.5	17	17	100%
RP20-64	RB20-84	29.3	16.5	482.8	61%	32.2	12.4	399	305	305	100%
RP20-65	RB20-?	35	14.3	499.4	64%	22.4	19.3	431	662	663	100%
RP20-27	RB20-46	9.9	16.3	156.3	29%	6.7	13.6	91.2	3737	3899	96%
RP20-41	RB20-64	14.3	17.5	250.3	40%	16	11	176.8	2363	2363	100%
RP20-19	RB20-33	5.9	18.9	111.9	19%	1.4	27	39.2	5887	6522	90%
RP20-32	RB20-51	6.8	18.6	126.2	22%	1.7	26.9	45.7	2989	3396	88%
RP20-51	RB20-?	6.1	19.2	116.4	20%	1.7	26.2	45.1	593	593	100%
RP20-56	RB20-?	6.6	17.9	117.8	21%	1.6	27	43.9	206	964	21%
RP20-57	RB20-?	7.9	17.5	137.3	26%	2.5	26.9	66.6	922	922	100%
RP20-58	RB20-?	7.4	16.2	119.5	24%	1.7	27.2	46.1	207	207	100%
RP20-12	RB20-23	33.4	15.5	519.2	61%	21.7	21	456.1	8069	8102	100%
RP20-13	RB20-27	30.8	14.3	441.8	45%	16.8	20.9	350.4	7903	8101	98%
RP20-14	RB20-24c	40.1	14.6	583.1	70%	14	37	516.4	7140	7572	94%
RP20-15	RB20-28	38.5	14.5	558.1	70%	11.9	37	441.5	7094	7571	94%
RP20-2	RB20-4	34.9	11.2	391	50%	10	27.7	276.7	11484	12611	91%
RP20-8	RB20-37	24.3	15.9	386.5	53%	13	22	285.6	4529	5675	80%

1.2 – Control Strategy Development

During Phase II control algorithms were refined to improve the overall operations of the CHP and RP systems including push button start capability. Additional control logic was developed to accommodate steam reforming and high efficiency CPOX operations. Several control board respins were implemented to further reduce the cost of the control board taking advantages of reduction in I/O requirements. I/O reductions were accomplished by developing a more thorough understanding of system operation, improving flow and thermal uniformities and reduction of cell count.

To simplify the wiring and improve the functionality of several miscellaneous electrical components, an extended distribution board was designed and manufactured which contains auxiliary control system functions such as low

voltage dc sources, fuses, isolation circuits, etc. Figure 27 contains photographs showing the progression. The photo on the left shows the interconnect wiring being carried out through terminal blocks and discrete components where as the photo on the right shows the distribution board (upper) mounted adjacent to the control board. Wiring (not shown) between the two is direct with either ribbon cables or wire harnesses with connectors.

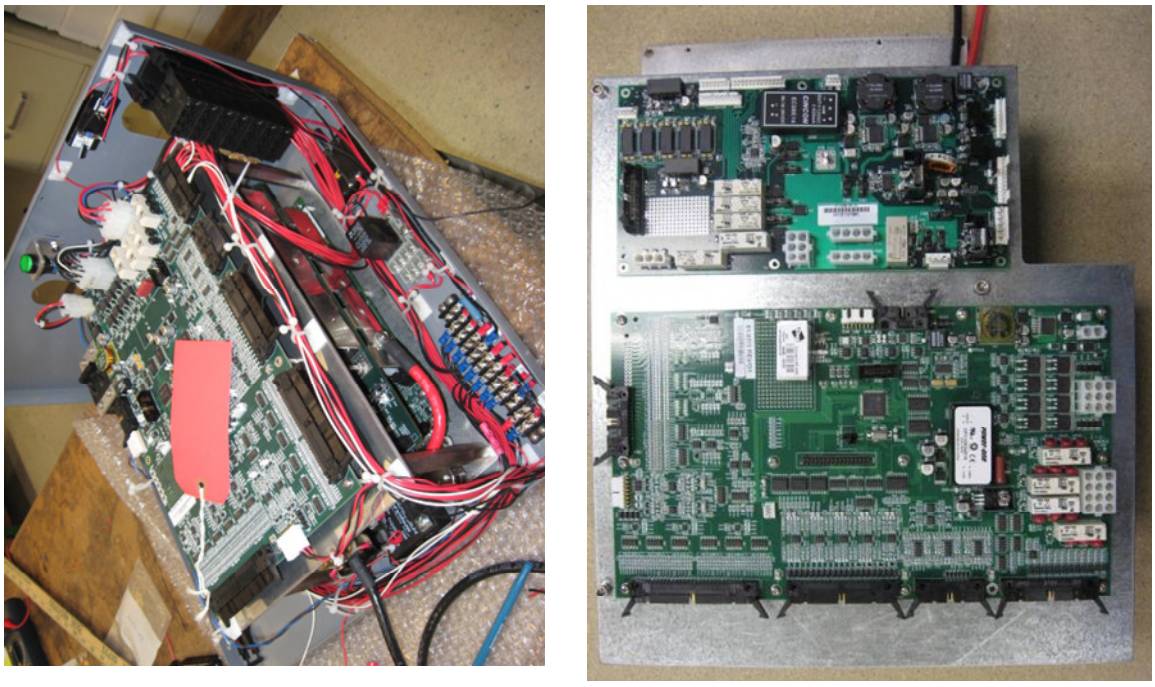


Figure 27 Distribution Board Development

Once the distribution board was adequately tested and demonstrated, a further simplification was made by combining the control and distribution boards into one. Figure 28 shows the combined board.

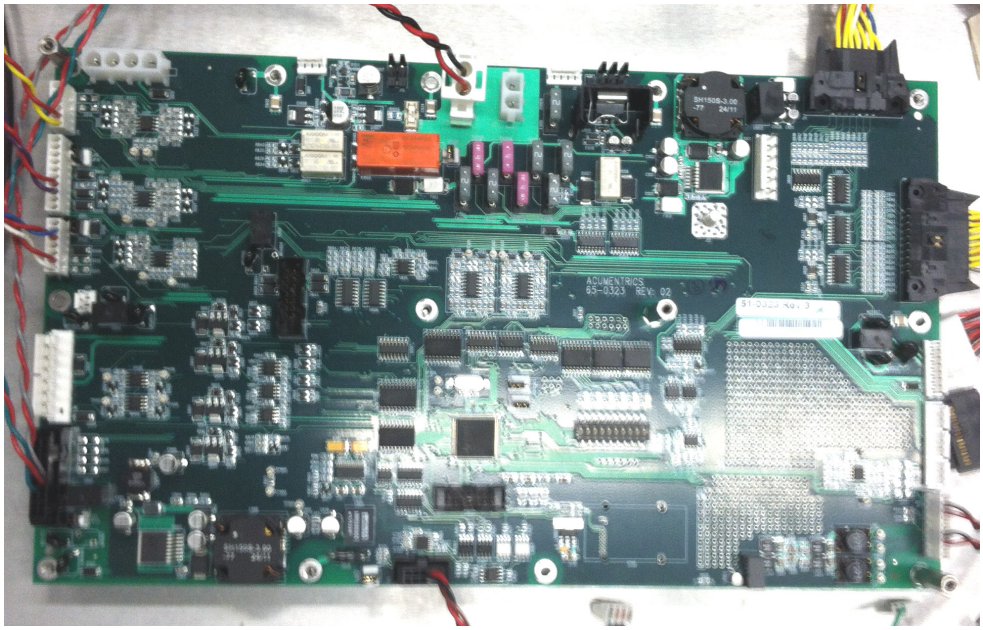


Figure 28 Combined Control and Distribution Board

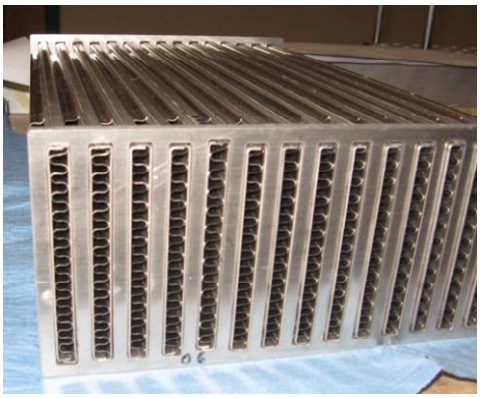
Several improvements were also made to the DC/DC converter used in the generators to reduce costs and optimize the performance for the intended markets. Galvanic isolation of the control/power package was adjusted and fit the grounding requirements of both the cathodic protection and telecom applications.

Steady improvements were made in the ability to remotely monitor and control field units and to streamline data gathering and analysis. The ability to communicate remotely via satellite and cell based systems was implemented. Software was developed to automatically download data daily, implement data reduction and create graphical summaries of system performance. A spreadsheet based dashboard system was developed to provide “at a glance” comparison of operating units and out of bounds “warning flags”.

1.3 – Heat Recovery

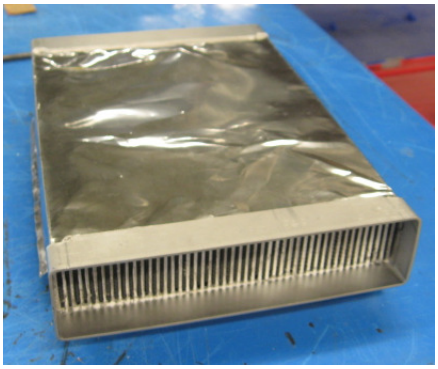
Cathode Air Recuperator

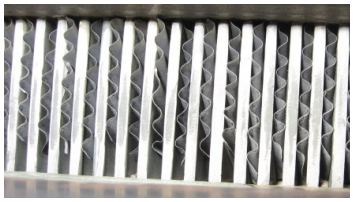
In Phase II, Acumentrics continued the assessment of fin core and folded sheet designs with particular attention placed on researching cost reduction methods for fabrication. Since a large portion of the recuperator cost arises from the heat exchanger heads and tube to tube-sheet joining, investigations into alternate assembly techniques were evaluated. In addition, integration of the recuperator with the fuel cell stack box was accomplished reducing duct and transition complexity and insulation requirements. Figure 29 shows the recuperator styles evaluated.



Radiator Style

Shell and Tube





Accordian Foil Style

Figure 29 Recuperator Styles Evaluated

While the above recuperators rely on multiple air/gas passages with corresponding need to ensure adequate sealing between adjacent chambers, a single panel recuperator was developed minimizing the complexity and therefore cost of the side to side sealing. This recuperator relies on a greater percentage of secondary finned heat transfer surface but greatly simplifies the header and tube sheet geometries. Essentially air to exhaust side sealing is across a single flat sheet as opposed to multiple rectangular or circular passages. The flat geometry also allows for close integration with the stack hot box and fuel cell bundle eliminating the need for additional ductwork, headers and supports. Figure 30 shows the geometry. Critical to the recuperator performance is the contact between the flat panel and the fin assembly. A detailed assembly procedure was developed to allow vendors and/or braze shops to manufacture the units. The procedure provides detailed steps for cleaning, assembling, fixturing, and brazing the unit to ensure good primary to secondary heat transfer contact and good overall performance.

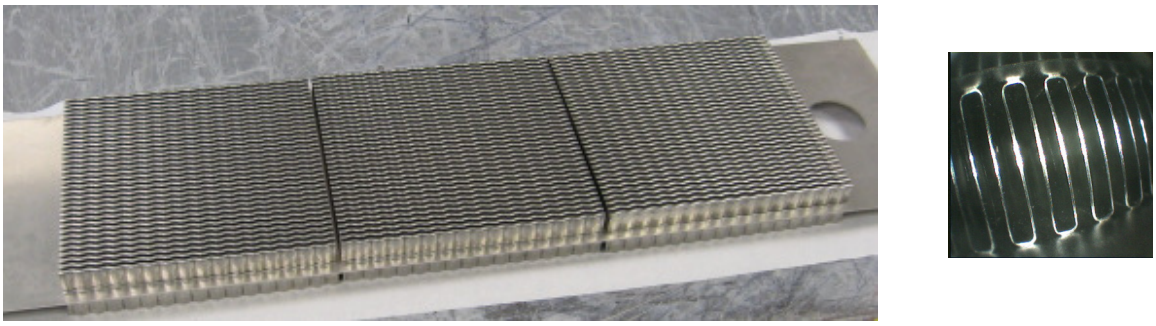


Figure 30 Wavy Fin Single Panel Recuperator

Fuel Recirculator

During Phase II, Acumentrics continued to canvas industry for a blower or fan that could be used to recirculate the fuel cell offgas as a means to provide steam for fuel reforming reactions. A cost effective hot gas (800 C) recirculator could not be found. A low temperature alternative was considered. Here to, although lower in cost than the hot option, the additional cost associated with cooling and reheating the offgas and obtaining a low to moderate temperature recirculator that could safely operate with the anode offgas which is high in carbon monoxide was deemed prohibitively expensive for the intended markets.

High Efficiency POX

A novel method of reforming the natural gas fuel stream was developed which allows systems operating under Partial Oxidation (POX) reforming conditions to successfully operate at low oxygen to carbon (o/c) ratios. In previous POX configurations, an o/c ratio of greater than 1.2 was required to ensure that soot formation within the fuel piping and cells was avoided. With this new technology POX systems can be run at o/c ratios as low as 0.5 without dropping carbon. This reduction in o/c ratio results in a significant improvement in the stack operating efficiency as illustrated in Figure 31 **Fuel Cell Efficiency versus Oxygen to Carbon Ratio**As shown in the graph, at low o/c ratios the stack efficiency approaches that of a steam reformed configuration.

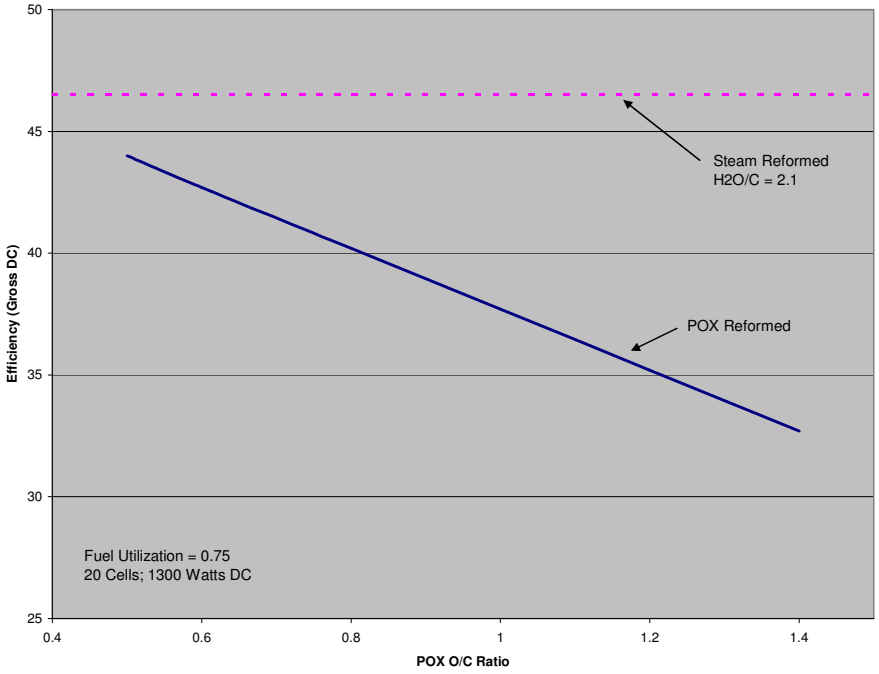


Figure 31 Fuel Cell Efficiency versus Oxygen to Carbon Ratio

In addition, this new fuel processing technique allows for the use of a cold fuel plenum arrangement and provides an additional heat sink within the stack which allows for enhanced thermal management. Several thousand hours of single cell testing was conducted to verify the operation of the cells under these operating conditions and full scale prototypes have been designed and tested. The benefits of cold fuel plenum are discussed further in Section 3.3.

1.4 – Gas Utilities

In Phase I, a totally integrated gas delivery system, capable of meeting the flow, stability and reliability requirements of the prototype generator, was designed, built and operated. In Phase II, work focused on reducing component count and implementing the use of commercially available high volume components presently utilized in the automobile and home heating system markets.

Although most combustion based HVAC systems require good air/fuel ratio control to achieve low emissions and high overall efficiency, generally in these systems the quantity of fuel flow is important only in maintaining sufficient thermal input to match the thermal load imposed on the system. For fuel cells, accurate knowledge of the fuel flow is highly important to ensure that the desired fuel quantity is delivered to the cells to avoid oxidation of the cells. The air/fuel ratio also needs to be more accurately controlled to ensure proper fuel processing catalyst performance.

Two approaches were used to achieve fuel flow control and air/fuel ratio control: a venturi based system and independent air and fuel flow measurement. The venturi based system was utilized primarily on CHP systems. For these systems, fuel composition is generally known and controlled within regulatory specifications making the venturi based approach viable. The P&ID for the CHP system given in Section 1.1 illustrates this approach. An anode air venturi is utilized in conjunction with a fuel zero pressure regulator to deliver the correct proportion of air and fuel. A fuel flow meter measures the fuel flow to ensure the correct fuel utilization is obtained. Figure 32 shows the venturi/gas regulator assembly.

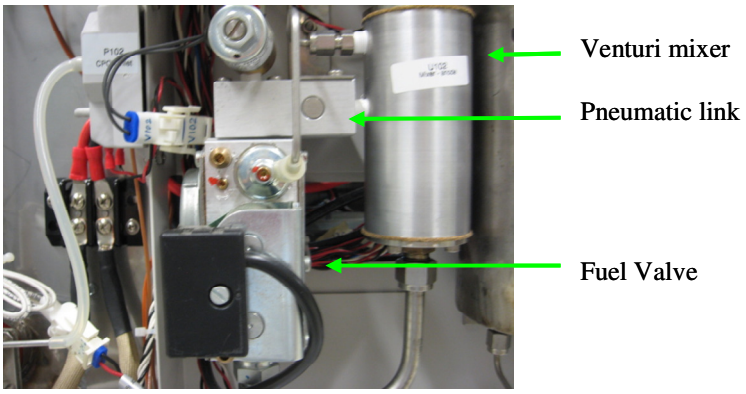


Figure 32 Venturi Based Air/Fuel Ratio Control

For the independent flow measurement system, flow meters are utilized on both the air and fuel streams and a modulating fuel valve is used to meter the correct amount of fuel flow. In both systems, the anode blower speed is modulated to vary the air flow. The main control system is utilized to calculate the air and fuel flows, control each and maintain the correct air/fuel ratio. For remote power systems, especially well head and pipeline applications, where fuel composition can vary substantially, this system has advantages in that flow measurement and ratio control can be adjusted electronically rather than mechanically.

Figure 33 shows a photograph of a typical flow meter based Gas Utility Module. The gas utility module has been designed as a subassembly that can be assembled and tested prior to installation into the generator. A semi-automated test station was developed to perform quality control testing of the subsystem. The QC test procedure ensures that all components are functional and that anode air /fuel ratio and flow values are within specification.

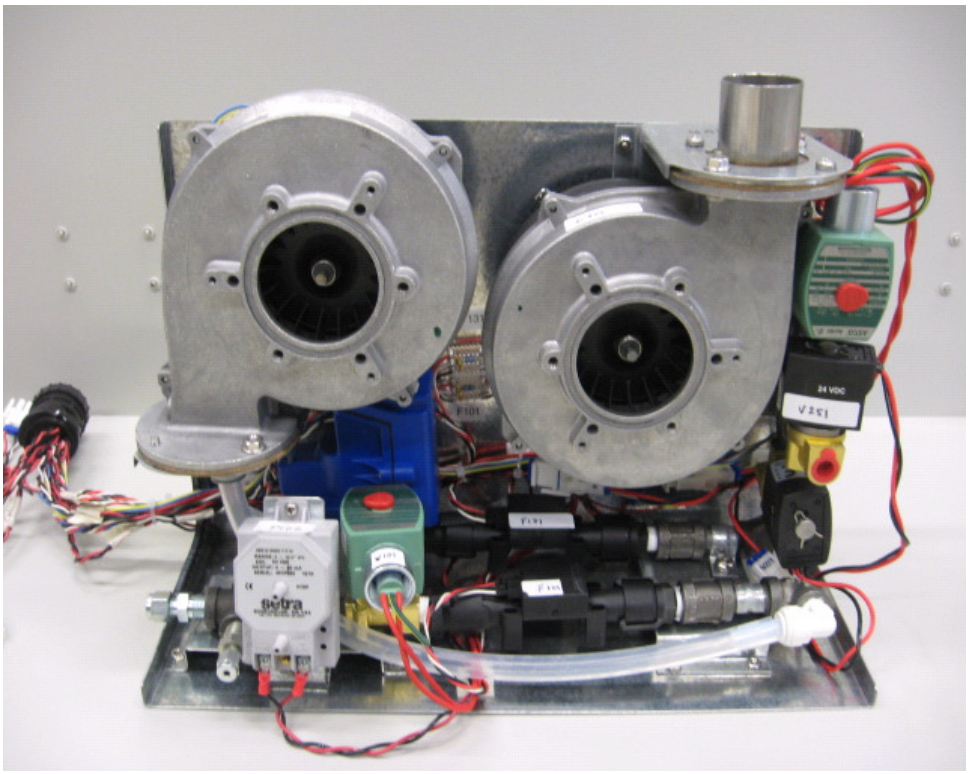


Figure 33 Flowmeter Based Gas Utility Module

1.5 – Prototype Assembly

As discussed in Section 1.1, Acumentrics has manufactured several prototype systems as part of the Phase II effort. Figure 34 is a photograph of the combined heat and power unit and Figure 35 shows the Remote Power Unit.

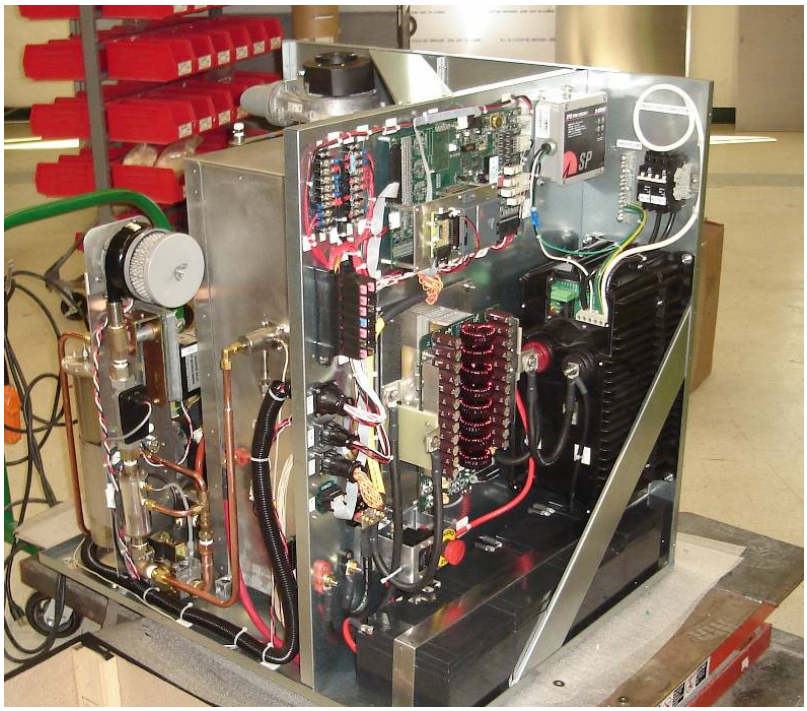


Figure 34 Combined Heat and Power Unit

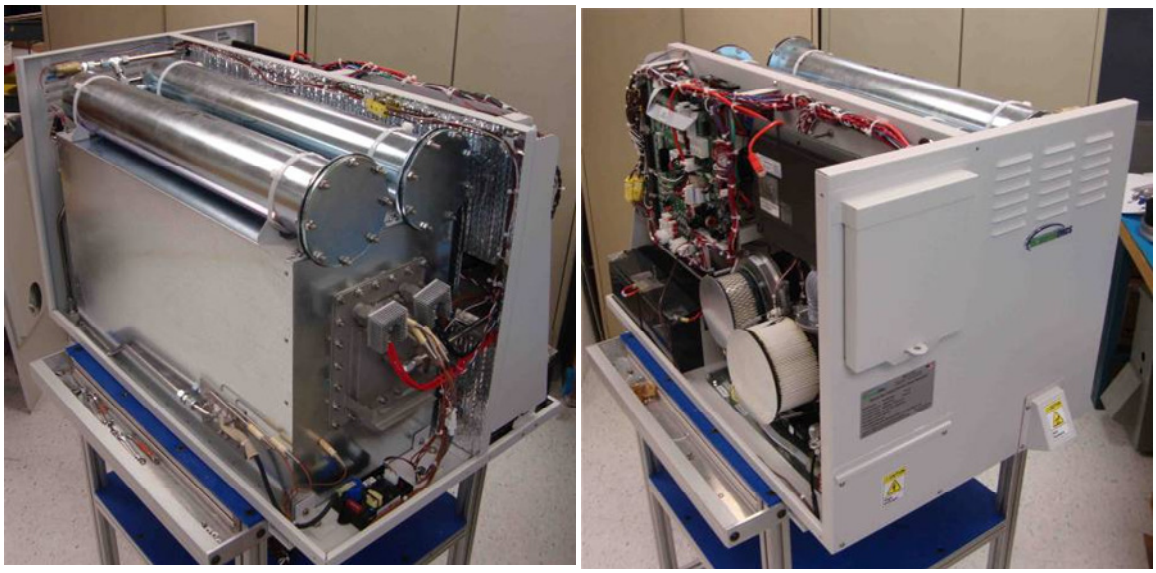


Figure 35 Remote Power Unit

For the Remote Power Unit a transition has been made from prototype assembly of units to a production based assembly. Complete documentation of the system (BOM's, detailed drawings, assembly drawing and standard operating procedures) is complete. A vendor base has been established for the outside manufacture and procurement of sheet metal parts, enclosures, printed circuit boards, wire harnesses, etc.

2.0 – Cell Technology Development

2.1 – Anode Tube Composition Tube Optimization

Acumentrics' anode tube structure consists of three phases: Ni, YSZ, and porosity that provide percolation paths for electrons, oxide ions, and gaseous hydrogen and water respectively. To increase electronic and ionic conduction pathways, and as a result the triple phase boundary, the surface area of Ni and YSZ must be maximized while maintaining the highest possible porosity. While enhancement of Ni/YSZ surface area along with maximizing porosity is extremely important for cell output maximization, underlying this performance optimization is the requirement to minimize any resultant degradation at the elevated temperatures utilized in the recipient's generators.

During Phase I, a number of anode formulations containing varying Ni/YSZ ratios were evaluated for stability and performance. Results showed that increasing the Ni ratio to a high level resulted in delamination of the electrolyte as expected. Reducing the Ni content on the other hand resulted in reduced cell performance. Analysis of different anode tubes at temperature showed that all evaluated formulations experienced an initial reduction in conductivity and increase in permeability, which was most prominent during the first 200 hours of testing. This was thought to be due to coarsening of the Ni in the tube.

Phase II built upon the anode investigations undertaken during the course of Phase I with the goal of enhancing anode performance, particularly with respect to stability and therefore minimization of degradation.

During Phase II, focus was directed to evaluation of slightly larger nickel particles in the anode formulation which are theorized, based upon Phase I conclusions, to provide a less reactive structure with time resulting in lower cell degradation. To complement this work, variations in the YSZ particle size and distribution were evaluated to determine if such changes can minimize Ni sintering at temperature and again result in reduced cell degradation. A number of Ni content variations were also evaluated to supplement the work carried out in Phase I.

A further area of investigation was the gradation of the anode support substrate thus allowing the possibility of enhanced conduction in the Ni tube bus while still retaining the recipient's optimal triple phase boundary composition at the electrolyte interface. This was achieved through isostatic pressing investigations. In addition isostatic pressing was leveraged to investigate larger cell dimensions to enable higher power cells to be fabricated.

One further area of research has been made possible by the addition of chromite interconnects developed by Acumentrics in Phase I, allowing a significant reduction in current path length to be realized on the cell. As a result of this development, it is considered that anode tube thickness could be reduced and

therefore costs and mass transfer issues on the anode side minimized. Anode support tubes were fabricated with varying wall thickness and evaluated for performance through single cell testing.

In accordance with the statement of work, tube fabrication was switched from extrusion to isostatic pressing during Q4 of 2008. This move facilitated a number of tube and process improvements, the most significant of which are detailed below.

- Thinner tube wall was made possible and implemented, leading to a 35% reduction in the material required per tube and therefore a commensurate per tube powder cost reduction.
- Isostatic pressing allowed an Integral closed end to be implemented on the tube. This eliminated the materials and labor associated with the previously required braze joint, thus reducing tube cost.
- Significant through process yield improvements have been realized by switching to isostatic pressing. This has been achieved since contamination has been minimized in the green tube due to the elimination of high shear mixing which is required for extrusion. In addition, owing to the nature of the pressed tube geometry, hang firing could be easily implemented and replaced horizontal tube firing where contamination of the product, which was laid on the furniture, was always a problem. A further yield benefit of pressed tubes was realized at the electrolyte application stage where, because of the integral closed tube end, sealing was no longer required. Historically, for extruded tubes, this temporary sealing step had resulted in a number of cracked tubes. Finally, it is easier to fabricate straight tubes through pressing due to the nature of the process.
- Isostatic pressing is a simpler tube production route than extrusion in that pressing replaces mixing, extrusion, and drying, saving labor from the fabrication process.
- Larger tube and therefore cell sizes were fabricated and evaluated for increased performance, leading to the successful introduction of Acumentrics current standard with optimized performance.

One of the challenges of implementing an isopressed closed end tube however was the fact that the tube surface must be smooth to allow application of electrolyte and electrode coatings. Initial tubes had the intersection between the tube body and closed end smoothed out by hand to facilitate coating application. Automation of this process was implemented in Q3 2010 through the design and fabrication of a fully automated fixture. This in turn allowed the realization of a uniform wall thickness along the tube length, a smooth tube surface and removed 90% of the labor associated with this step, thus reducing tube cost. In addition, with an automated process, all tube ends are uniform promoting ease of handling, storage and automation of subsequent cell fabrication steps.

In accordance with the statement of work, investigations were undertaken to determine the optimal anode structure through optimization of the anode cermet

composition. To this end, it was determined that addition of an active anode layer overtop the pressed anode tube substrate would be the preferable route for investigation of anode interface iterations. Initial investigations focused upon the application methodology for which a semi automated spray fixture was developed and optimized at Acumentrics to yield uniform coatings. From this point different slurry compositions were evaluated with varying combinations of NiO/YSZ ratios and material suppliers. After spraying the different trial compositions on the base anode substrates, all different iterations were tested in single cell testing rigs and the electrochemical performance of each determined and compared. After extensive testing, the optimal composition was determined from a compatibility and performance viewpoint, which was similar in composition to the substrate tube but a different morphology. Investigations then extended to include spraying of the electrolyte immediately after application of the active anode layer. Successful trials then ensued to develop co-sintering of the base tube, active anode and electrolyte. Optimization investigations in this area are still progressing.

In addition to the active anode layer work, significant effort has been and continues to be focused towards development of the ceramic powder material which forms the base tube itself. This work has been undertaken in an effort to try to optimize the anode powder properties and in addition to elucidate which properties have the greatest effect upon process variation and therefore quality of tube. Work has involved the evaluation of powder properties from a number of sequential powder processing trials. To evaluate the powder properties from different trials, tap and bulk density measurements along with particle size and SEM characterization of the blended NiO/YSZ powder were undertaken. Tubes formed from each of the evaluation powders were fabricated in to full cells after shrinkage data had been determined. Electrochemical testing of cells prepared using each anode powder was then undertaken and compared with each prior powder run for improvements in cell thermal cycle and lifetime performance. This in turn allowed future direction to be determined and undertaken. Results from these trials have shown that by optimization of the cermet blend, and in particular the YSZ component, the temperature required for sintering the tube and electrolyte has been successfully reduced by a significant 100°C. In addition a 40% reduction in anode cost has been realized through refining the processing route and powder supplier.

Significant progress has also been made with respect to isostatic pressing mold design and filling technology during the course of the project. The end goal of this work was to optimize tube quality, particularly wall thickness and straightness, and simplifying mold filling. With respect to the mold itself, the design and the materials that are used to make the mold have been iterated significantly with good success to yield low cost molds that produce straight tubes. In addition, the filling methodology has also been significantly optimized again with tube quality in mind. In accordance with the statement of work, both of these developments have successfully lead to the production of straight tubes

with an optimized wall thickness 35% thinner than was possible with extruded tubes.

Quality control has also improved significantly over the course of the project with the introduction of several checks. In particular tube straightness has improved with the introduction of an automated tube straightness measurement fixture which was designed and fabricated at Acumentrics. This fixture removes 80% of the labor from the straightness measurement process and as such has allowed 100% inspection and enabled data for baseline straightness.

In summary, significant improvements in cell yield have been realized through moving from an extruded to a pressed tube. This in conjunction with a 35% reduction in tube wall thickness has resulted in significant tube cost reduction. Optimization of the active anode layer and bulk tube material have successfully lead to a lowering of the sintering temperature by 100°C. In addition changes to the processing route and materials used has lead to a further 40% reduction in the anode material cost.

2.2 Electrolyte Composition

Acumentrics investigated alternative electrolyte materials to enable the replacement of the YSZ film on anode support cells, thus allowing operation at lower temperatures. During Phase I, a number of initial ranging experiments were undertaken to investigate the applicability of LSGM with the recipient's base anode supported tube. The use of LSGM as an electrolyte proved problematic in that issues with mechanical stability were noted in addition to the formation of an insulating layer through Ni migration to the LSGM, even in the presence of a ceria interlayer.

Other lower temperature oxides were identified and investigated for their applicability with the recipient's existing cell materials. Particular attention was given to evaluation of the interface region between the electrolyte and cathode and electrolyte and anode in order to maximize cell performance. Cells were fabricated using candidate materials and evaluated for leak behavior and electrical performance. Reduced temperature firing trials also took place as per subtask 4.1.

Investigations in to an alternative material to YSZ for use as a low temperature electrolyte did not progress as expected in that an alternative material that met the desired performance and cost characteristics was not forthcoming, despite significant effort in this area. In the absence of an alternative, the current YSZ material was optimized for thickness and application methodology. To this end, investigations were undertaken to reduce the electrolyte thickness on the cell to 10 microns, thus allowing lower temperature operation of cells, a goal of the work. To enable this development, it was determined that the present application methodology of dipping was not suitable and as such a more amenable spraying methodology was developed. Spraying of the electrolyte has the following advantages over the incumbent dipping technology:

- Reduced potential for electrolyte contamination since each spray uses virgin slurry. With dipping the same stock slurry is used for multiple dips.
- Reduced breakage of the base tube during electrolyte application since strong green tubes may be utilized for spraying where as weaker bisque fired tubes must be used for dipping.
- Spraying opens up the possibility to co-sinter the anode tube, active anode and electrolyte layers, saving a significant 2.5 days of processing time.

Development of a sprayed 10 micron thick electrolyte first involved the design and fabrication of a spray fixture which was fabricated at Acumentrics. Work in this area progressed through first optimization of the slurry and spray conditions to yield a uniform layer of the desired thickness with the minimum number of spray passes. In particular, trials focused upon developing the spraying conditions to allow a uniform coating on all areas of the tube, including the closed end. Firing trials then ensued to ensure electrolyte density and coating integrity. Through SEM it was established that the slurry and application developments noted above did indeed yield a nominal 10 micron thick dense electrolyte. Application of sprayed coatings was then extended to include the anode active layer which is applied before the electrolyte. As previously discussed the ability to spray both layers then opened up the possibility to co-sintering of the base tube, active anode and electrolyte.

With respect to the electrolyte, a spraying methodology has been developed which has allowed the successful application of a 10 micron sintered layer. The development of spraying the electrolyte and active anode has also opened up the possibility to co-sintering of the base tube, active anode and electrolyte.

2.3 – Cathode Composition

A large number of cathode materials were tested on single takeoff cells in Phase I. The results of these test appeared relatively inconclusive at the time. However, with the new banded tubes, a significant change has been observed in cathode performance. Measurements of the cathode activation match that of literature due to the tube enhancements, whereas before, the activation values were significantly lower than that of literature, and showed little change with variations in cathode materials. At this time, it appears that any cathode improvements that may have been tried were masked by the overall tube configuration. Therefore, it is imperative that the same materials and experiments be re-done. In addition, a literature search needs to be performed to determine if there have been any improvements since the first experiments in this area, or if SECA Core Technologies has developed a viable new material.

2.3.1 Cathode Conductivity Investigation

Acumentrics performed experiments to verify limitations in the operational performance of the currently utilized cathode material. This data provided the benchmark for alternative materials as they came to test.

In accordance with the statement of work, investigations have been undertaken to evaluate and develop the incumbent cathode materials with the goal of benchmarking this cathode. As a follow up to this work, alternative higher performance cathodes were evaluated in an attempt to achieve a performance increase for the overall cell.

Investigations in this area initially focused upon understanding sheet resistance of the cathode post firing and reduction. With respect to post firing sheet resistance, tests were set up at room and at elevated temperatures using a four point probe methodology. From these investigations the baseline sheet resistance of the incumbent cathode was determined as a function of temperature.

Investigations then progressed to determine the cathode sheet resistance after the tube has gone through the standard anode reduction step. Variation in cathode sheet resistance was observed pre and post reduction of cells. In an attempt to understand this issue, an evaluation fixture was assembled consisting of a tube furnace, a gas tight tube to allow measurement in different atmospheres and a four point probe fixture with which to measure the sheet resistance at temperature. A number of tubes with an applied cathode layer were assembled and evaluated for changes in sheet resistance at temperature while subjected to a number of different atmospheres. Collation of these results allowed determination of which atmospheres were detrimental to the cathode performance

Another area where the incumbent cathode was benchmarked was that of thickness and morphology along the applied length. Initial investigations utilized SEM to probe these parameters as a control measure for each batch of cells moving through the cell fabrication process. It soon became apparent that a rapid coating thickness measuring device was required to ensure cell quality and minimize deviation from the established baseline thickness. Trials were initiated to measure the cathode thickness post firing through the use of a laser micrometer to ensure repeatability at the cathode application stage. This work proved to be very successful and a coated layer thickness measurement device was developed initially for the cathode coating but was later extended to all coatings. The developed & implemented QC methodology to determine coating thickness has the following benefits.

- Ability to monitor cathode thickness along with other applied coatings upon a cell, all of which are critical to cell performance.
- Utilizes the same hardware as the straightness QC test already in place but uses different measurement methodology.

- Have been able to set “Go/No Go” limits at the batch level for all coatings applied to the cell.
- verified measurements of the laser micrometer through SEM

Because a rapid coating thickness measurement methodology was developed, and significant numbers of tube coating thicknesses were measured and recorded, it soon became apparent that significant variation existed in cathode thickness. This thickness variation occurred along the length of the cell and between subsequent batches. To eliminate this variation the cathode application process was evaluated and upgraded from a manual dipping process to a semi automatic spraying process. This change alone has successfully facilitated a much more uniform cathode coating. Successful implementation of a spraying process has resulted in the following significant developments;

- The applied cathode layer thickness is much more uniform batch to batch but just as significantly uniformity of the coating upon the same cell has dramatically improved
- Minimal set-up and clean down time is now required, minutes as compared to 1.5-2 hours for the dipping system
- Slurry utilization has increased from 80% to near 100% with spraying
- Greater than 99% yield through the process plus increased throughput

2.3.2 – Alternative Cathode Materials

Upon completion of the subtask 2.3.1, Acumentrics investigated alternative cathode materials with electronic conducting and mixed ionic and electronic conducting properties that can replace the LSM and YSZ as the composite cathode enabling operation at lower and wider temperatures. These materials were evaluated as to which one’s can assist in the goal of again doubling the power density of the tubular design in Phase II. Materials doped with cobalt and iron were investigated as well as a number of other rare earth combinations. Thermal expansion measurements were performed using a dilatometer to ensure that expansion characteristics match the electrolyte material up to the maximum operating temperature. Determination of susceptibility to reducing atmospheres was also ascertained to determine if the anode supported cells can be reduced after the application of the cathode to the electrolyte or if it needs to done first. This has important consequences for manufacturing time and cost.

Materials exhibiting suitable thermal expansion and re-oxidation tolerance (if reduced along with the anode) were coated on cells and under went different firing regimes and tested for electrical performance using voltage-current characterization. The electrolyte cathode interface region was also investigated thoroughly for candidate cathode materials to ensure minimization of losses from this area.

In accordance with the statement of work, investigations were undertaken to develop and evaluate alternative cathode materials with the goal of achieving a performance increase for the overall cell.

In the first instance a literature search was undertaken and a number of different candidate cathode materials were identified, the most promising of which were procured for evaluation. After screening trials it soon became apparent that an LSCF based cathode would be most appropriate due to its superior conductivity to LSM, especially at lower temperatures and its similar thermal expansion to the existing cell materials. Since LSCF cathodes are known to react with the YSZ electrolyte to produce resistive phases, a barrier layer was also developed to be laid down between the cathode and electrolyte. Application of this layer was also through spraying since the layer must be as thin as possible but be thick enough to still form a barrier.

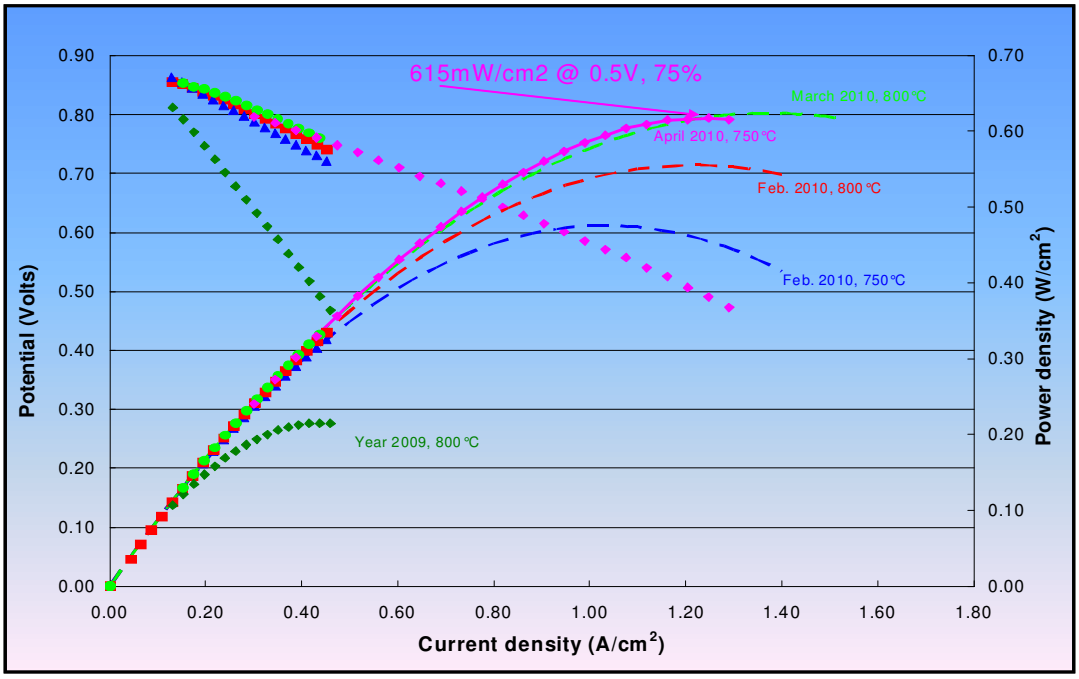
A number of issues needed to be overcome with respect to the processing of LSCF cathodes, these included optimization of slurry stability and delivery. Indeed a significant amount of work was carried out to try to minimize cell to cell variation caused by slurry instability and the methodology of application. To this end, a new slurry delivery mechanism was developed to recirculate the slurry and carefully meter it for spraying on to the cell. Work was also undertaken to improve the positioning of the cathode bands upon the cell to ensure clarity of the spray line cut off at the start and end of each sprayed band. This was investigated through varying spray head height, translation speed and slurry feed rate. Addressing these slurry delivery issues greatly assisted with coating uniformity but issues still persisted with the stability of the slurry itself.

To address this issue, investigations were undertaken into the addition of stabilizing additives to the cathode layer slurries with the end goal of improving slurry stability and as a result coating uniformity. After screening multiple additives, one candidate in particular appeared to offer great promise for its ability to produce uniform coatings. Electrochemical evaluation of cells with this additive included in the cathode were performed with good results with performance of such cells superior to standard cells. SEM of the cathode layers containing this additive were also completed and showed desirable morphology.

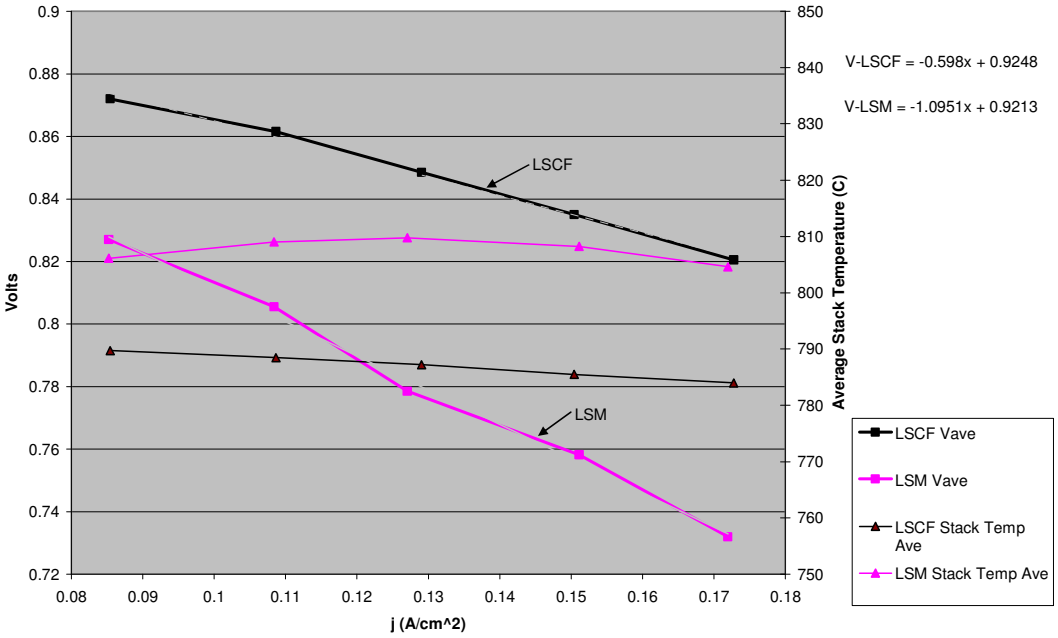
Once the general methodology of spraying had been developed for application of the cathode and barrier layer, the next step was to focus in on the most appropriate LSCF grade. Guided by literature, a number of further LSCF grades were procured with differing A and B site stoichiometries. The candidate LSCF powders were initially pressed in to bars for thermal expansion evaluation, after which slurries were made and the cathode under evaluation sprayed upon a cell, post barrier layer application for sheet resistance testing at temperature. From these results the best candidate was selected and cells were fabricated for single cell electrochemical evaluation. Initial testing showed that the candidate material performed at a much higher level than the incumbent LSM material, particularly at lower temperatures as suggested by the available literature. In addition

longevity testing showed that the new LSCF grade material showed similar degradation behavior to the incumbent LSM over thousands of hours.

The significant performance boost on moving from LSM to LSCF is detailed in the graph below at the cell level. As shown in the graph, the goal laid out at the start of the project of doubling power density has been achieved, even at lower operating temperatures which makes this achievement even more satisfying.



The performance improvement at the cell level translates to a significant performance improvement at the bundle level. This may be seen in the graph below which shows the typical performance for a bundle with LSM based cathodes and a bundle with LSCF based cathodes. From the data the superior performance of the LSCF cathodes may be clearly seen through the higher relative position and gradient of the LSCF bundle curve relative to that for LSM. In addition the temperature of the LSCF bundle is a nominal 30°C lower than the LSM bundle, further reinforcing the superior performance of LSCF as a cathode.



In summary, over the course of the award, a very successful transition has been made from LSM to an LSCF based cathode material which has resulted in a doubling of the power density for Acumentrics tubular cells, even at lower operating temperatures, a key goal for this project.

2.4 - Cell Testing

Nine cell test stands have been built to operate on H2/H2O or CPOX mixtures. Over 2400 cells have been tested during the program (see Figure 36), with all the single cell results observed in this document a result of this effort.

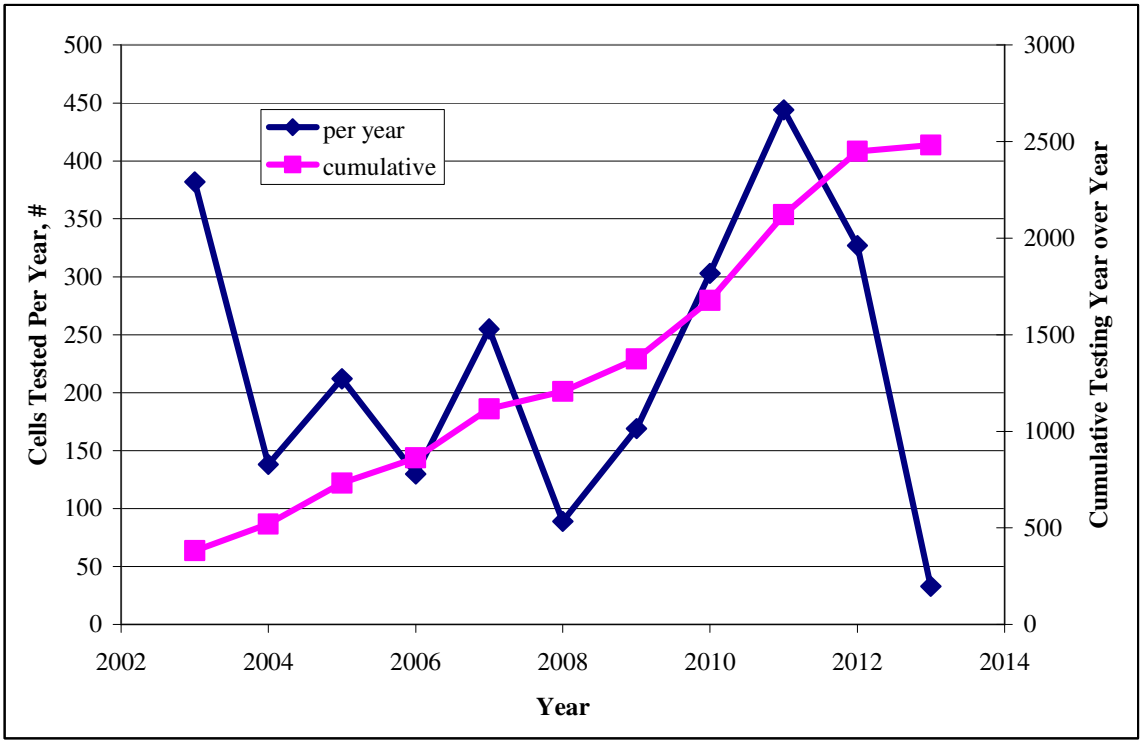


Figure 36: Cell Testing Accomplishments

Over 262,000 cell-hours of testing have been accomplished, with the stands having an overall availability of about 93% (including maintenance, and time between tests to remove cells and charge new ones to the fixtures). This is a testament to the rugged design and simplistic operations involved. Throughout all this testing, all data has been accumulated and steadily reviewed on a weekly basis. In general, the cell test stands (Figure 37) and cell testing methodologies have proven over the course of the ten years of the program to be one of the most reliable, steady, and robust machines for the evaluation of cell performance and changes.

Figure 37: Cell Test Stands

3.0 – Stack Technology Development

3.1 Cathode Current Collector Improvements

Investigations conducted during Phase I resulted in the use of chromite interconnect bands placed along the length of the anode support cell. Previously, the cathode silver current collection system had been optimized for the longer path lengths utilized in the previous cell generation. During Phase II, looked at optimizing the cathode current collection system for the new chromite cells which by implication shortens the current path and therefore potentially reduces the amount of silver required per cell. Silver is used for the cathode current collection system because of its low resistivity and resistance to corrosion in SOFC environments. For generator operating temperatures of 800°C, no other current collection material has yet been identified which is suitable. However, with a reduction in generator operating temperature realized through cell material modifications discussed in other subtasks, it may be possible to use some other material other than silver.

The current collection system on Acumentrics standard cell employs a circumferential wire wrap which holds in place a “backbone” or strip of wire braid which runs along the length of the cell. The issues associated with this type of current collection system are numerous and need to be resolved in the next generation cell:

- Expensive current collection material and inefficient use of it
- Slow, labor intensive application methodology
- Difficult to automate the current winding technique

As a result, investigations relating to current collection have been focused upon minimization of the material used in the current collection system and the development of a simplified robust methodology for its application.

To this end several different current collection iterations have been investigated for their applicability. Initial trials focused upon reducing the diameter of the wire wrap but application of thinner wire on to the cell becomes problematic with the winding methodology available. A number of novel wire winding and backbone designs have also been investigated but none were considered to be bold enough to realize the performance or cost reduction desired.

After making the decision that a radical change was needed, different current collection solutions, other than wire were sought out. Initially an electroplated metal rather than wire wound metal solution was evaluated as the application time was considered short and the amount of current collection material significantly reduced. In addition the whole of the cathode may be covered in a uniform layer through this methodology. To evaluate this technique the relevant equipment and materials were sourced and a methodology developed for application. Cells were then fabricated using this current collection system and evaluated for electrochemical performance. Initial results were very encouraging

in that the cell voltage was on a par with standard cells at standard conditions. After repeated thermal cycling however all experimental cells began to fail catastrophically through delamination of applied layers. It is considered that a combination of the way that the metal was applied and the difference in thermal expansion coefficient between the metal and the cell layers caused this delamination upon thermal cycling. A further methodology was then trialed which involved laying down a metal solution upon the cathode followed by thermal treatment. This methodology was again simple in its application and used the minimum amount of current collection material. Electrochemical performance of cells using this form of current collection again performed well until they were exposed to multiple deep thermal cycles which again caused delamination of the ceramic cell layers. Based upon these data points, it was decided to move in a different direction and trial a current collection system based upon a conductive paste.

A number of different conductive paste candidates were selected for trial and procured. The different pastes were then applied on to cells through a number of different application techniques including brushing and foam applicators. Cells fabricated in this way were then single cell tested to determine their electrochemical performance. Unfortunately cell performance was found to be variable but the catastrophic failures with multiple thermal cycles that were observed for the electroplated and metal solution current collection options were not observed with this application medium. Through rigorous testing and SEM, it was determined that the variable performance was due to the non uniform application of the current collection layer. Numerous trials then ensued to resolve how to apply the current collection paste in a repeatable fashion creating a uniform layer. This issue was resolved by taking an established application methodology and modifying it for use with Acumentrics cells and target current collection paste. The ensuing result was a fixture that could apply an even layer of current collection in a repeatable fashion and at the desired thickness. Cells were again fabricated using this new technology for application of the current collection system then tested for electrochemical performance. Cell testing has shown that at standard testing conditions, the cells with the new current collection system consistently perform at or above the level of cells with the wire current collection system. Further, longevity and deep thermal cycle testing of the cells over thousands of hours has been undertaken with no issue to date.

Testing at the bundle level is presently ongoing with thousands of hours of testing completed which has included a significant quantity of deep thermal cycles. This is the final stage of testing before release in to production.

In summary, successful implementation of the new current collection system will realize the following over the standard wire system.

- Reduce the labor required for application by >75%
- Reduce the material requirement by >75%
- Eliminate an associated process step completely

- Cleaner process
- Fully automatable process
- Greater uniformity of current collection upon the cell.

Therefore, once implemented, this new current collection system will have a very significant impact upon the cost and performance of the cell.

3.2 Anode/Cathode Current Collection

Acumentrics continued to perform research aimed toward reducing performance losses and production costs associated with anode and cathode current collectors, building on the successful implementation of the chromite interconnection during Phase I.

3.2.1 – Current Collector Braze Materials

The new triple-chromite cell does not requires the braze cup to be electrically isolated, so that individual cells can be wired as required. However, the braze cup still needs to provide a gas-tight joint for simple connection to a manifold system with control of the system fuel. With new electrically isolated requirements for the braze cup, new materials and configurations will be tested to determine the most cost-effective way in which to make a seal that isolates the cell from the cup and manifold. Possibilities include use of insulation, cement, oxides, or a change in cup materials.

During the course of this award, numerous trials were undertaken to effect sealing of the cell to the cap and manifold which at the same time provided electrical isolation between the two. Pressing a non conducting end upon the tube, thus eliminating electrical conduction from the cell through the braze cap to the manifold. In the first instance, two different YSZ formulations were spray dried with different binder loadings to evaluate this potential solution further. Pressing trials were undertaken and a methodology with which to press two materials in to one contiguous tube was successfully developed. Once formed the tubes with an isolating end were successfully sintered and then subjected to rigorous vibration and thermal cycling trials. Unfortunately it was discovered that the interface between the conductive tube material and the isolating YSZ tube end material was weak, particularly upon thermal cycling. In the light of this, it was decided to blend the YSZ material with the current cermet material to dilute the Ni content to such a level where electronic conduction is negligible. This material is then used to form the non conductive end of the tube and being similar to the tube substrate material results in better uniformity between the isolated end and the tube itself. In essence a graded tube end is formed. A number of tubes pressed with the graded end were fired successfully with the ends and interfaces between the materials remaining intact. Post reduction resistance measurements performed at the end of the tubes show them to be isolated. The fully sintered isolated end tubes were then taken and brazed into the standard end cap followed by thermal and vibration testing. As with the full

YSZ end tubes, problems arose after multiple thermal cycles which resulted in some tubes cracking around the isolated end. After numerous further iterations the cracking issue could not be fully resolved and as such a different sealing and isolation methodology was pursued.

A second sealing and isolation methodology which was investigated involved the use of non conducting oxide pastes or cements. Initial experimentation was directed towards screening different cements for their applicability. To this end, a number of different cement types were procured and evaluated. Initial investigations involved "potting" the cell in the cap with the appropriate cement followed by vibration, isolation and thermal cycling testing. Any candidate cements that were deemed to pass these initial tests were then fully fabricated in to cells to test for isolation from the cap when increasing voltages were applied between the cap and cell at temperature. This voltage breakthrough testing was set up to determine if the isolation medium is stable at the voltages which may be seen during operation. In addition, quality of seal, poisoning of the cathode by the cement and durability over time were also investigated. No single cement was found to possess all the desirable properties which were being sought. As such, it was decided to develop a sealing system in house which took the best tested ceramic oxide based cement and combine it with a glass material. Using this methodology it was considered that the best properties from each material, glass and ceramic oxide, could be utilized to achieve a gas tight isolating seal. After significant iterations a blended ceramic oxide/glass paste which was determined to be stable over thousands of hours of operation at temperature, remained isolating in nature even at elevated voltages and formed a good leak tight seal between the cell and cap was developed.

In summary, a ceramic oxide and glass blend has been successfully developed for use as a cement for connection of the cell to the cap. Use of this developed cement has resulted in attainment of a successful solution for sealing between the cap and the cell and for maintaining electrical isolation between the two.

3.2.2 Chromite Interconnections

Acumentrics performed research to reduce the performance losses associated with axial current flow along the tube length. During Phase I, a literature search was completed to determine applicability of the different available chromite materials with the recipient's base cell. Initial chromite deposition experiments were also performed which resulted in plasma spray technology being identified as the preferred methodology for application to a cell. To provide good adherence of the chromite to the electrolyte and base anode tube, a bond coat was also utilized, making the plasma spray methodology a two layer deposition process.

During Phase II, this initial chromite plasma spray work was extended to optimize the chemistry and morphology of the chromite spray powder to deliver a stable interconnect with optimized conductivity. In addition to powder modifications,

spray parameters also were investigated and optimized to produce chromite coatings which do not require a thermal treatment densification step as is currently the case. Further work is also done to negate the requirement of a bond coat and thus remove one of the two sprayed layers and hence interlayers, a potential source of losses. Cell power improvements was sought through optimization of chromite band placement and size of the band. A further development of band location which was investigated is the concept of producing a base cell which has two options for placement of interconnect bands, producing a “left” and a “right” cell. This enables easier series connection between cells when stacking.

In accordance with the statement of work, the number of interconnect bands and where they are placed upon the cell has been investigated and optimized to maximize individual cell power. The issue here is that each additional band decreases the path length, thus minimizing losses. Working in the opposite direction, each band occupies an area upon the cell that could be utilized for increased electrode area hence there is an optimal number of interconnects required for optimal cell power. Calculation backed up by empirical data has shown that 4 interconnects along the cell length is the most efficient solution.

In addition to the number of bands, trials were also conducted to determine the minimal band width which would not impede current flow and yet allow maximization of electrode area and as such cell power.

To investigate this issue, hardware modifications to the spraying fixture were undertaken allowing a number of different band sizes to be realized. Empirical trials were then conducted which showed that a significant 50% reduction in the band width could be successfully achieved without adversely effecting cell performance. Indeed, this reduction in interconnect area has lead to increased area available for the electrode, thus increasing cell power.

In order to improve the quality of the plasma sprayed interconnects, a system with which to monitor gas leakage at temperature was established. This fixture has been instrumental in improvement of the leak tight qualities of the cell through characterization of the effects of different plasma spray parameters.

In the first instance, a number of standard fully fabricated cells were evaluated for leak at temperature using the system and a baseline leak for standard cells established. Attention was then directed towards establishing the contribution that each pertinent cell component makes to the leak value in its entirety. From this work the typical leak through the interconnects was established. Changes in spray and powder characteristics were then evaluated for their effect upon leak at temperature. In particular plasma spray gun power was found to effect interconnect density significantly and this parameter, along with others, has been optimized for density of the interconnect.

In order to aid stacking of cells in to a bundle two different cell types were designed and termed an “A” and “B” type cell. Adjustments in plasma sprayed chromite band placement were then undertaken to fabricate the new cell designs. The use of two different cell designs has allowed cells to be simply and efficiently stacked in series with a metallic series connection between the cathode of one cell and the anode of the adjacent cell. Since there are four interconnects on each cell, there are four series connections connecting each adjacent cell

Significant effort was expended trying to eliminate the requirement to spray a bond coat on to the cell prior to the top coat of chromite material. The bond coat acts as a key to which the top coat adheres to. Several different methodologies were pursued which included roughening the spray area by grit blasting or by adding course YSZ during the electrolyte coating stage. Both these techniques resulted in delamination of the applied layer. Another technique that was evaluated was partially sintering the tube before spraying the interconnect. This allows for a rougher spray surface and allows simultaneous shrinkage of the tube, electrolyte and interconnect during firing. Unfortunately the tube, in this state, was not strong enough to survive plasma spraying. After multiple iterations, it was decided that elimination of the bond coat was too problematic to achieve and efforts were focused elsewhere.

Work was also undertaken to optimize the chromite top coat in terms of expanding the processing window to allow a more robust process to be implemented. As part of this development, investigations have been completed to determine the ideal alignment of powder injectors with respect to orientation of the gun. In addition, trials have been completed to determine the optimum powder injector angle. As these different trials were completed, the leak rate was determined at room temperature for each applied band, followed by single cell testing to verify that any changes were valid.

In addition to machine changes, work also focused upon optimization of the sprayable interconnect powder. To this end trials to develop a powder with improved spray properties and therefore the quality of the interconnect while at the same time reducing cost were undertaken. In the first instance a candidate powder was developed and procured. Spray trials then ensued where the spray properties of the evaluation powder were investigated and evaluation cells fabricated. These cells underwent rigorous leak and electrochemical performance testing, including longevity testing, after which this new powder was implemented in to production. Successful introduction of the new chromite powder has realized a 40% reduction in powder cost with no discernable spraying issues.

During the course of the project, a number of significant updates to the plasma spray fixturing were initiated and successfully completed. These include

- Moved from 1 tube per spray to 4 in Q2 2007, then 8 in Q1 2010

- Updated fixturing in Q1 2010 to drive tubes at both ends and allow spraying of 8 tubes per run
- Reduced load/unload time per tube by 80% - replaced chuck with push & locate
- Sprayed band uniformity significantly improved by fixturing both ends of the tube

In summary, the position and size of the interconnects upon the cells have been optimized along with the introduction of two cell designs to aid bundling of cells in series. In addition, the spray methodology and powders have been successfully optimized for cell performance and cost.

3.3 – Generator (Fuel Cell Module) Design

In Phase II of the program, Acumentrics optimized the generator design taking into account performance and configuration changes afforded by the higher power density, chromite interconnect cells.

The increases in cell power density and changes in current collection methods over the course of the project provided an opportunity to improve the overall fuel cell module configuration. Among the changes made to the stack design compared to the SECA Phase I generator are:

- Cemented, isolated cap/cell connections
- Axial cathode air flow
- Vertical or Horizontal Cell Orientation
- Sintered cell to cell current collection
- Offgas collection
- Single Cell Series Connection

Extensive analysis was performed to determine the optimum cathode flow configuration. Since in the POX system the cathode air is the primary means of stack thermal management, good air distribution and good heat transfer rates are critical to maximize cell performance. Cathode flow axial to the cell compared to the cross flow utilized in the SECA Phase I generator was found to be superior. In addition to enhancing thermal management, the inlet and outlet plenums were considerably simpler and also allowed for simplified integration with the cathode air recuperator. Figure 38 illustrates the axial flow stack configuration.

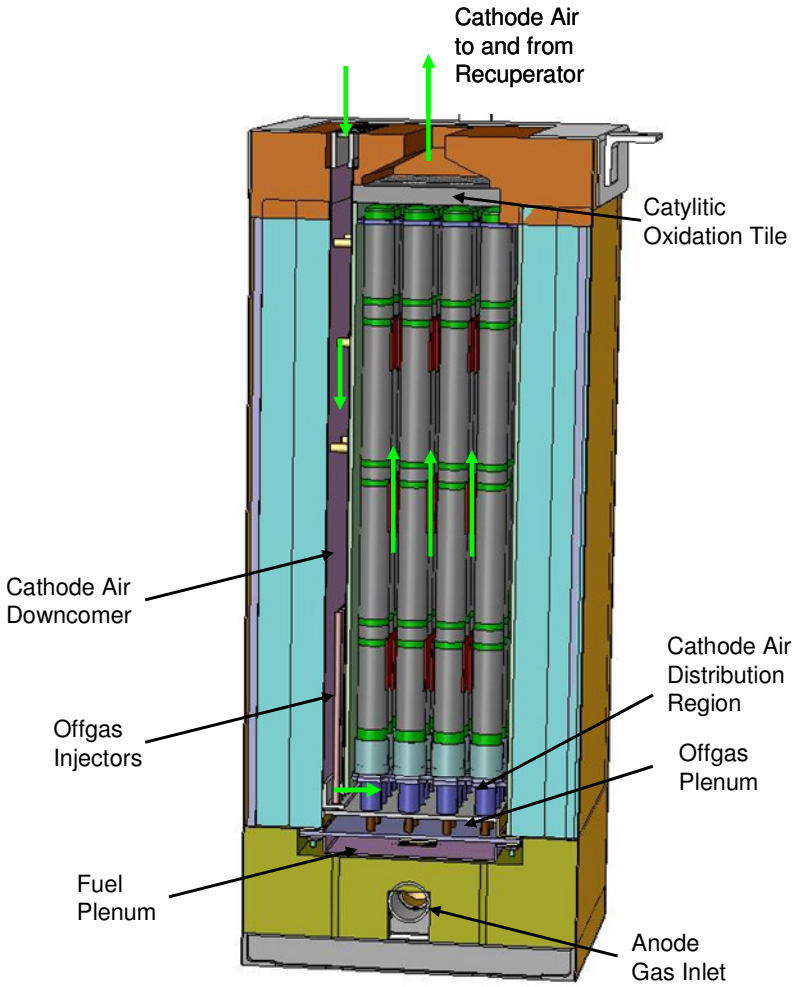


Figure 38 Axial Flow Stack Configuration

A CFD simulation of the cathode air side was utilized to determine if cathode air flow and temperature distribution may be adversely effecting stack performance. As the main cooling mechanism, the cathode air flow significantly impacts the temperature distribution within the stack. The temperature distribution in turn significantly impacts the performance and the reliability.

Figure 39 shows the stack flow model and Figure 40 gives the corresponding mesh used for the analysis. The CFD analysis was used to determine the size and spacing of the cathode plenum distribution ports to achieve uniform air flow, required side wall clearances and baffling to prevent stack bypass and plenum geometry to ensure good mixing between the anode offgas and cathode air.

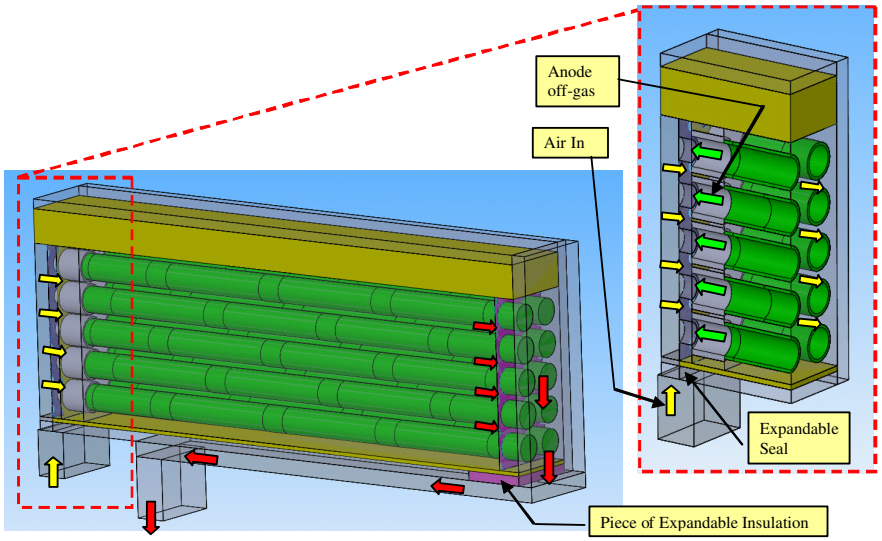


Figure 39 Stack Flow Simulation Model

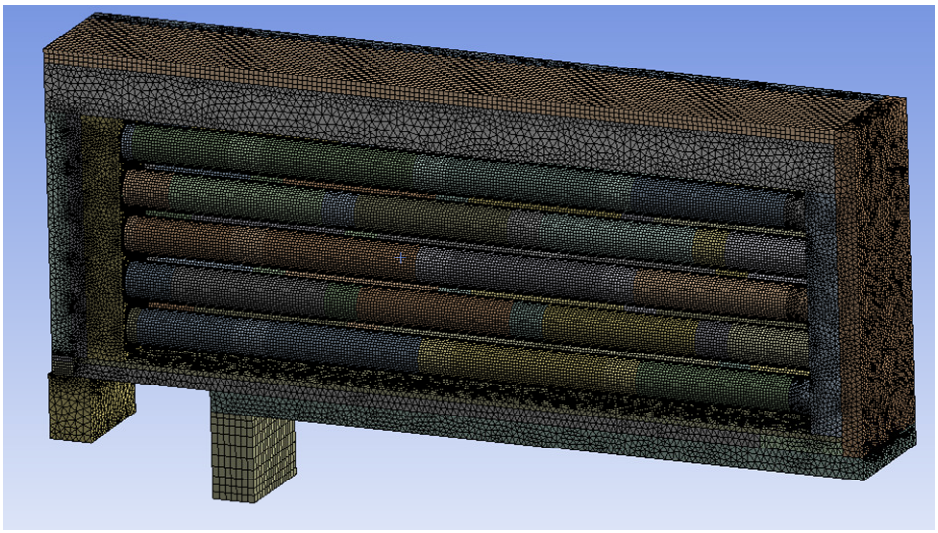


Figure 40 CFD Mesh

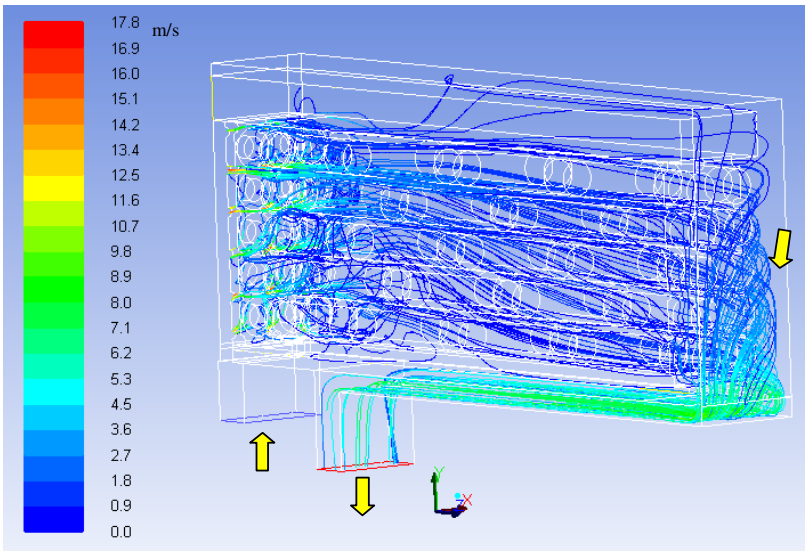


Figure 41 Typical Flow Model Result

Another key design change made during Phase II of the program was the implementation of a fuel cell module configuration which allows for the quick removal of the fuel cell bundle. This was achieved by incorporating all connections to the bundle on a front flange plate including anode fuel connections and power leads. A stack box was also designed which could allow for easy insertion of the bundle into the cathode flow chamber with all auxiliary components such as the startup burner, cathode air recuperator and thermal insulation being an integral part of the stack box.
Figure 42 shows the fuel cell module configuration along with a photograph of the fuel cell bundle being removed from the stack box assembly.

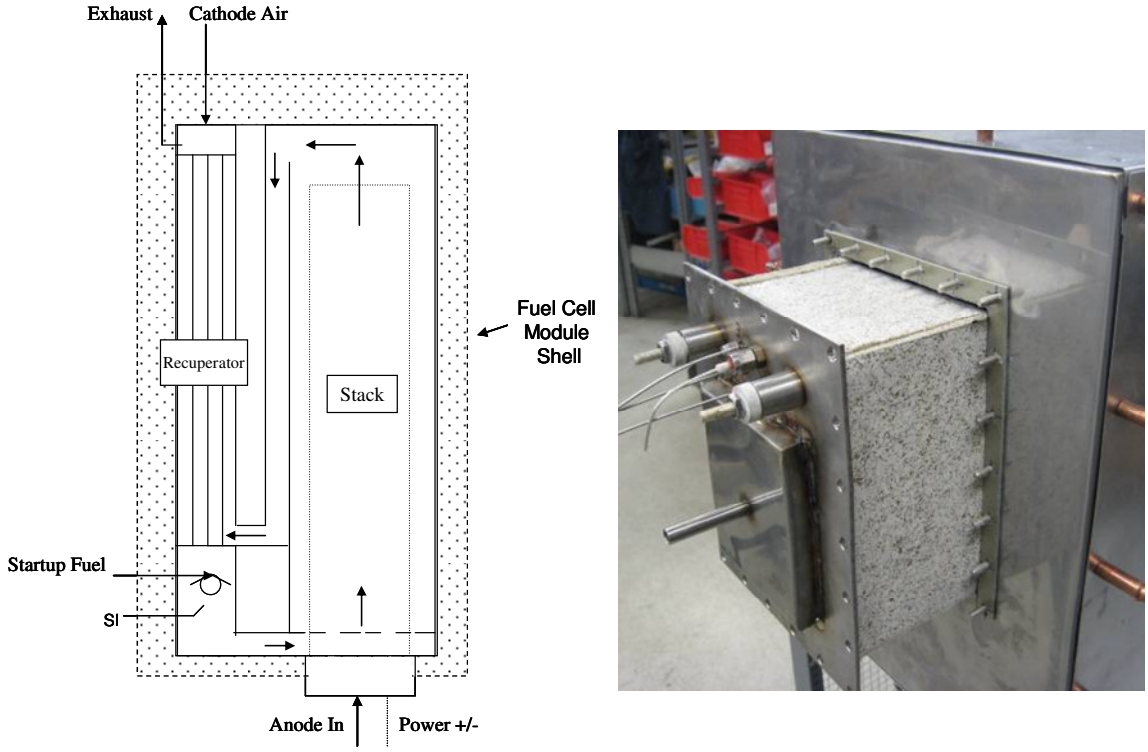


Figure 42 Fuel Cell Module Removable Cell Bundle Configuration

Physical and CFD models were developed to design the fuel cell module package to obtain acceptable heat losses and component operating temperatures. In particular, several power lead geometries were investigated to ensure that connections to external power lead cables were at acceptable temperatures to prevent long term oxidation and degradation of these connections. Cooling fins were sourced which can allow the cooling system to operate with or without active cooling. It is predicted that at low power or when the ambient temperature is low, natural convection can provide sufficient cooling of the power leads. This will reduce the parasitic load of the system by allowing the ventilation fan to operate at lower speed or to be shut off. Pin heat sinks were therefore obtained which could work effectively either when the fan is on and there is a cross flow of air or when the fan is off. Alternative designs were also developed that do not require cooling fins. In this case the power leads themselves were designed to minimize heat transfer to the connections.

3.4 – Manifold and Cap Development

During Phase I, a method of joining the tubular fuel cells to a fuel manifold was developed and successfully implemented. This included development of a process to inductively braze inlet and end caps onto to the cell. These caps allow the cells to be screwed or press fit into the fuel manifold while maintaining gas tight integrity between the anode fuel and cathode air streams. For the original single ended current collection cells, the caps and braze joint also allowed current to flow to the manifolds which served as the anode bus. A

manifold geometry was developed which enables through the use of a fuel injection orifice the uniform fuel distribution to each cell and the collection of the unspent fuel in a single manifold. For both the manifolds and inlet caps, metal injection molding (MIM) was utilized to reduce material consumption by over 50% while greatly reducing post machine processing over alternative fabrication methods. This significantly reduced the part costs compared to machined parts from bar and round stock. A deep drawn cap was also manufactured and used as an end cap. Brazing of this cap to the cell was successfully demonstrated.

In Phase II, a refinement to the manifold and caps was made taking advantage of design changes afforded by the chromite interconnect cells which do not require current to pass through the caps and manifold. Since the fuel cell manifolds are no longer required to be an integral part of the current path, a joining method between cell and cell cap was developed which would allow electrical isolation of the cell at the cap. This isolation method allows for the use of a common fuel plenum which greatly reducing component costs and complexity.

A ceramic based joining techniques was developed. Of critical importance was the selection of cement and cap materials that have thermal expansion properties similar to the cell and to design the components to tolerate slight mismatches in expansion at temperature. Fixturing and application methods were developed to ensure proper cell/cap alignment, electrical isolation, and joint permeability.
Figure 43 shows a cemented connection after over 9,000 hours of operation. A hybrid seal was also developed which incorporated a glass component resulting in improved permeability. This seal although more expensive than the baseline seal has application where offgas collection is required such liquid fuel systems utilizing offgas water recovery for fuel reforming.

Figure 43 Cemented Joint after 9000 hrs

The electrical isolation of the cell at the cell cap allowed simplification of the fuel plenum geometry. Sheet metal plenums were developed that can be massed produced using conventional stamping or bending operations. The chromite

interconnect cells also allowed for a single plenum geometry. A typical plenum arrangement is illustrated in Figure 44.

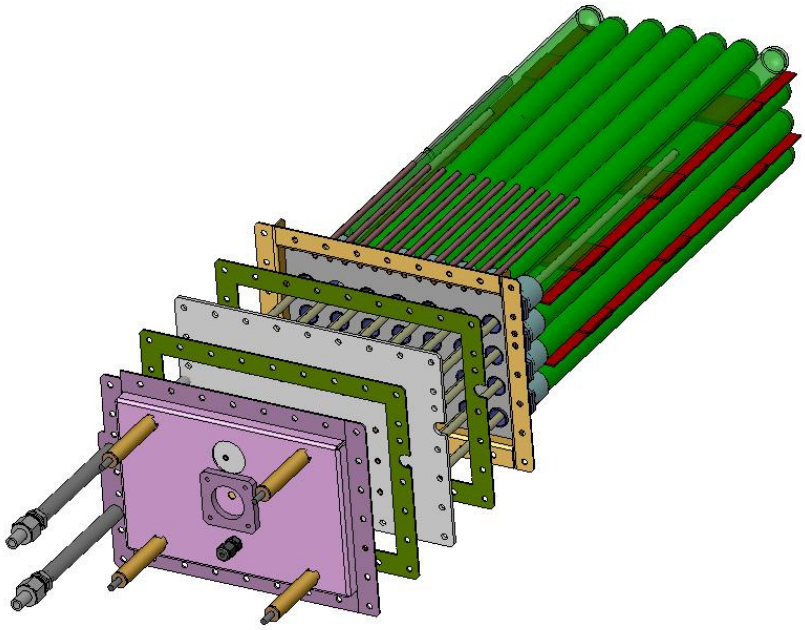


Figure 44 Single Fuel Plenum Geometry

4.0 – Fabrication and Processing Technology Development

4.1 Electrolyte Deposition

During Phase I, a number of different 8mol% YSZ electrolyte powders were evaluated from different manufacturers with the goal of reducing the sintering temperature. This in turn has the knock-on effect of minimizing electrolyte film contamination generated through solid-state interactions while firing at high temperatures on kiln furniture. From these initial studies, it was noted that electrolyte sintering temperatures in the region of 1400°C could be achievable for certain YSZ/anode formulations. Also determined during Phase I was the significance of a simultaneous approach with regard to both electrolyte and anode when trying to minimize sintering temperature.

Through building upon the work conducted in Phase I, further investigation was made of the nature of the electrolyte and the electrolyte dipping process to make possible an electrolyte sintering temperature in the region of 1400°C, which is robust enough for implementation into a real process environment. Therefore, a number of sintering trials took place and the resulting electrolyte/anode interface probed by microscopy to ensure optimal cell performance. Trials were performed to determine leak rate and electrical performance of the resulting cells.

A further area of investigation was with firing the alternative oxide films developed in subtask 2.2 at lower temperatures which allowed a reduction in

both generator and cell fabrication costs due to the materials that become available for use at the lower generator operating temperatures.

In accordance with the statement of work, the process with which to coat electrolyte upon Acumentrics tubes was initially evaluated to determine where improvements in coating consistency may be realized. Since the electrolyte is required to be dense, it is important to eliminate defects and apply a coating that is as uniform as possible. These facts are especially important when trying to minimize firing temperature as the effects of any non uniformity which may be present are magnified at lower firing temperatures. As a result a number of upgrades to the dipping fixture were initially sought to try to lay down a coating which was as free of defects as possible and which eliminated as much human error/variation as possible. To this end a semi automated dipping system was designed and fabricated which had the following advantages over the incumbent system:

- Improved coating consistency – dip time constant for all tubes
- Filtering system for the slurry to remove agglomerates/contaminants
- Greater than 99% yield through the process - no human error handling delicate tubes
- Reduced set-up and clean down times

The next area which was addressed was the kiln furniture. This was particularly important to resolve as significant contamination was coming from this source due to the fact that all firings involved laying down the tube on to the furniture in a horizontal fashion. This then leads to contamination being picked up by the tube especially at the electrolyte sintering stage resulting in pin holes in the electrolyte. Through redesigning the kiln furniture and conducting the high temperature electrolyte firing in the vertical direction where only the end of the tube which is not coated with electrolyte is in contact with the kiln furniture it has been possible to achieve the following.

- Contamination from furniture has been eliminated
- Significant yield improvement
- Significant furniture design improvements, easier to load and unload product
- Green to electrolyte sintered tubes kept on common furniture saving time

Through making these modifications to the dipping process and the kiln furniture, an electrolyte coating which is significantly more uniform in nature and which is far less prone to contamination has been realized. This in turn has lead to superior leak properties for the electrolyte layer and therefore a more stable cell.

While the overall leak of the cell improved by automating the dipping and moving from horizontal to vertical firing, a significant reduction in the high firing temperature can not be realized by these measures alone. To achieve a significant reduction in firing temperature it was quickly realized that a move to

spray coating of the electrolyte was required. This is because the incumbent process requires that the green tubes initially undergo a bisque fire to allow dipping of the electrolyte which is then followed by a second firing, electrolyte sintering. This in turn means that some of the total tube shrinkage which is important to the densification of the electrolyte is lost in the bisque fire. If the bisque fire can be eliminated and all the shrinkage of the tube now occurs when electrolyte is present in the electrolyte sintering, then the high firing temperature may be reduced. Dipping the electrolyte directly upon a green tube is not possible due to run off resulting in coating thickness variations along the tube length and as such introduction of the electrolyte must be completed by spraying. Spraying of the electrolyte then allows for co-sintering of the anode tube and electrolyte in one firing. This in turn leads to a reduction in the temperature required to densify the electrolyte.

To implement spraying of the electrolyte, a fixture was designed and fabricated at Acumentrics which incorporated a spray head on a linear track which passes over the tube while rotating. A sprayable slurry was developed and spray trials undertaken to optimize the coating uniformity and thickness. As detailed in section 2.2, a reduction in electrolyte thickness to 10 microns was achieved which also helps the sintering process. Co-sintering trials for the green tube and electrolyte were then undertaken which, as stated earlier, incorporated an extra few percent of tube shrinkage over the incumbent process leading to a denser electrolyte. Optimization of the YSZ material in the anode tube substrate which was detailed in section 2.0 has lead to even higher base tube shrinkage for a given temperature. Through these two factors in conjunction, it has been possible to realize a significant reduction in the temperature required to achieve a dense electrolyte. Indeed, sintering temperatures for production cells have been successfully reduced over the course of this project by 80°C and are now close to 1400°C, a key goal for this work.

In summary, a significant reduction in electrolyte firing temperature has been successfully realized through moving to a spray application of the electrolyte and modification of the YSZ in the anode cermet formulation. As a result of this work, the firing temperature for production cells has been successfully reduced by 80°C while still maintaining electrolyte density and consequently cell performance.

5.0 – Fuel Processing Technology Development

5.1 Reforming Technology- Light Hydrocarbons

In Phase I, a great deal was learned about the control and basic operating points on both natural gas and propane. In Phase II, work was focused on developing a fuel reforming technology capable of 1) eliminating complex components while maintaining or increasing reliability 2) increasing system efficiency and 3) simplifying designs so that they are conducive to mass production through automation and 4) reducing the number of different parts between different product lines. Acumentrics has developed a reformer that is thermally, materially

and structurally integrated within the SOFC stack and able to operate on natural gas and LPG.

The technology integrates each cell with a mini- integral reformer. The mini reformer utilizes the fuel delivery tubes used to supply fuel to the ends of the cells but the internal wall is coated with a thin layer of precious metal catalyst. Instead of always building highly integrated *external* reformers which are typically targeted to individual fuels and specific fuel cell duties, with this technology the reformer is incorporated into one of the stack components. An important aspect of the technology is that the water required for the reforming of complex hydrocarbons is recycled inside the cell. Expensive water carriage and softening or offgas recirculation blowers or compressors are not required. The mini-reformers are also capable of operating at low fuel pressures typical of residential natural gas systems.

The integral reformer technology has been demonstrated at the individual cell level, in subscale bundle tests and in full scale generators. Operation for over 10,000 hours has been demonstrated without a reduction in system performance due to reformer degradation. The reformer technology has resulted in reduced system cost based on the following attributes:

1) Simple design – while attention must be given to the engineering of the reformer, *e.g.* the optimization and grading of the catalyst, once complete the design is very amenable to automated techniques such as slip casting. Manufacturing procedures have been developed and are now utilized in the manufacture of production generators.

2) Scalable – higher rated SOFCs do not require the re-design of larger external reactors as each tube contains in effect its own reactor. Larger fuel cells systems will require more cells, but the reactor stays the same. Similarly as stacks get smaller the reformer cost proportionally vanishes.

3) Inexpensive – the catalyst coating at loadings ~1% of the catalyst weight cost ~$10-20 for a 1kW stack compared with $1000 for parts for an external CPOX or ATR reactor. The fuel delivery tube, which is essentially the catalyst support, is already a stack component.

4) Fuel flexible – the general rule for fuel processing is to have the fuel and oxidant over a catalyst before the decomposition temperature of the fuel. Since high temperatures are only approached in the reformer tube, above ~100^{o}C the fuel is always over a catalyst. Most importantly, since the temperature of the fuel cell is actively controlled at ~750-850^{o}C, the integral reformer is approximately *isothermal*, and always at the ideal temperature even for endothermic reforming.

5) High efficiency – because the temperature is moderated by the fuel cell and the catalysts do not promote carbon formation, the fuel cell can be run at the minimum O/C ratio in the case of partial oxidation. This is in contrast to external reactors, where high O/C ratios are employed to keep the effluent hot so as to mitigate reformer heat loss and to avoid carbon deposition in plenums. In fact in

this concept, reformer efficiencies can be greater than 100% since endothermic reforming reactions are enabled by the high heat transfer rates.

5.2 Light Fuel Desulfurization

Sulfur, ubiquitous in petroleum fuels, is a particularly acute poison to fuel cell anodes and reforming catalysts alike and thus is always to be considered when using hydrocarbon fuels for fuel cells. Fortunately, compact desulfurization solutions do exist for NG and LPG; the cost of these depend on fuel cell sulfur tolerance. Of all the fuel cells, the low temperature polymer electrolyte fuel cell generally has the strictest requirement for sulfur (<0.2ppmV) while SOFC is generally accepted to have the highest tolerance to sulfur at ~1ppm V mostly due to its high operating temperature.

It is universally accepted that sulfur will efficiently bind to active sites on most metals, poisoning the catalyst function. This effects the SOFC primarily in two ways: it poisons the reforming catalyst so that hydrocarbon carbon conversion to syngas is incomplete increasing the risk of carbon fouling of pipes and manifolds, and it poisons the nickel anode so that water gas shift reaction and electrochemical oxidation kinetics are retarded. The effect of sulfur on the cell is demonstrated in Figure 45. With ~1ppmV H_2S the nickel anode is shown to be poisoned, in this case, over the time frame of 50 hours. Nevertheless the cell performance abruptly stabilizes, and if clean fuel is added a slow recovery occurs. Subsequent poisoning at ~2ppmV and 5ppmV results in only slightly lower poisoning. Thus low level sulfur poisoning results in a depreciation in performance, with the strongest effects occurring at the lowest levels, *i.e.* the relative poisoning effect at 1 ppm is substantially stronger than for 2ppm V . At 10ppmV it is noticeable that the cell performance does not appear to stabilize. Recovery from sulfur poisoning will start as soon as the sulfur is removed from the feed, and at least at the 0-10ppm V levels, the recovery has been shown to be complete.

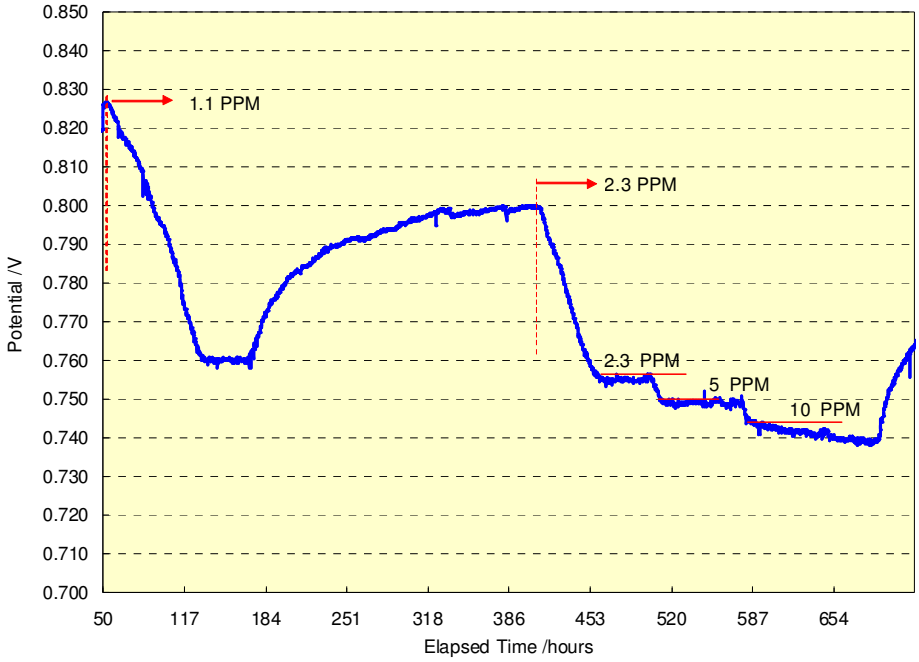


Figure 45 Sulfur poisoning of SOFC Ni based anode with H2S

Natural Gas: The sulfur species in residential natural gas are well controlled although they may differ dramatically around the world depending on local regulations. It is generally true that the sulfur in natural gas is due to an odorant. Federal Regulation 192.625 states "A combustible gas in a distribution line must contain a natural odorant or is odorized so that at a concentration in air of one-fifth of the lower explosive limit, the gas is readily detectable by a person with a normal sense of smell." In the US, the odorant will vary depending on the state. Thus, in the Northeast, the typical odorant is comprised of tert-butyl mercaptan and isopropyl mercaptan but, depending on the state, the odorant will be one or mixture of the following: t-butyl mercaptan (TBM), i-propyl mercaptan (IPM), n-propyl mercaptan (NPM), dimethyl sulfide (DMS), ethyl-methyl sulfide (EMS) and thiophane (THT). Of these species, DMS is recognized as the most difficult to remove. At Acumentrics, the odorants are a mix of TBM, IPM and NPM. Figure 46 shows the historical natural gas composition at the Acumentrics Westwood, MA manufacturing facility.

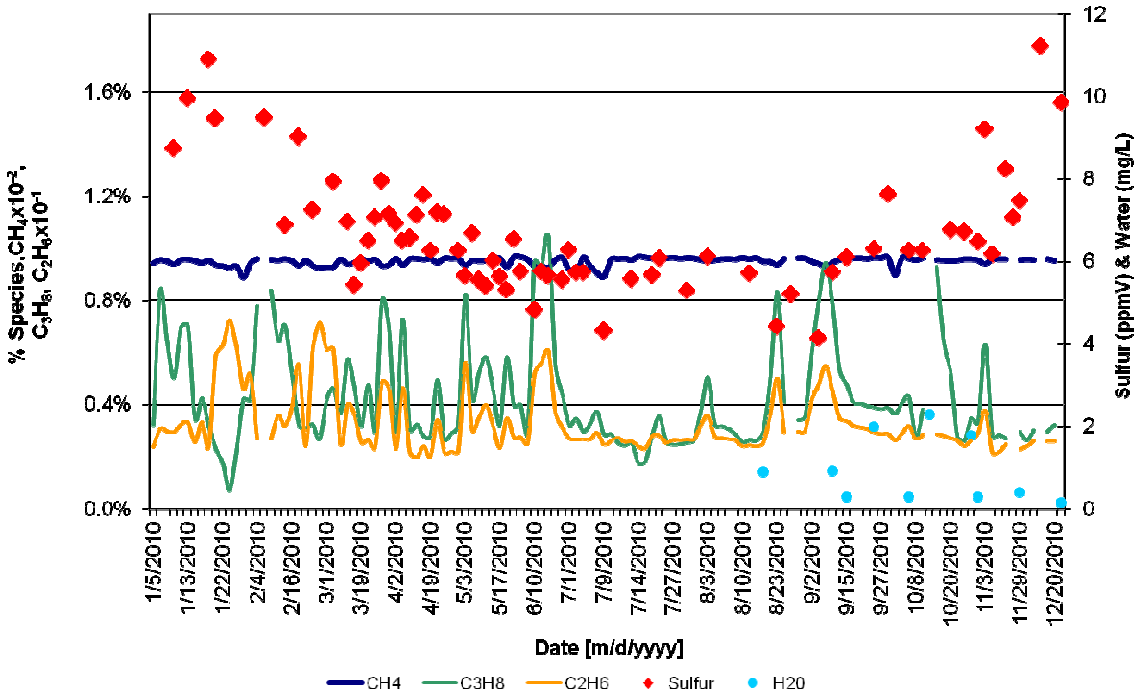


Figure 46 Acumentrics Utility Natural Gas Composition

LPG: The chemical composition of LPG differs around the world, although in all cases the physical property and thermodynamics requirements will limit it to a mixture of all or some of the following components: propane, propylene, butane and ethane, along with minor contributions of derivative olefins and di-olefins. There is no precise definition based on the final commercial application, which seldom require composition definition or gas purity, and commercial availability; the price of the different components in LPG are quite different around the world depending on the fuel sources and the local industry.

For the SOFC, the major potential issues in using such an unregulated fuel are: 1) metering of the fuel , 2) gumming of the reformer and 3) poisoning of the cell by sulfur. While most commercial LP gas in the United States is readily usable, as discussed above, there is no commercial reason for stricter regulation of LPG composition. The strictest specification for LPG in the US is HD-5, aimed at defining an LPG better suited for motor applications. Since the SOFC is still regarded as a nascent technology, Acumentrics currently limits the LPG used in their products to HD-5 specification. In the future, it is expected that the SOFC will be certified for both commercial and HD-5 specifications in the US, but in the meantime HD-5 is widely available and its adoption limits the possibility of anomalous fuel compositions, avoiding complications of the first two issues raised. HD-5, for instance, states that the propane content must also be at least 90% and limits the propylene content to 5% . The HD-5 specification also limits the sulfur content to ~125ppmW.

Various desulfurization unit operations have been used in the chemical process and petroleum industries in order to protect expensive catalysts, or to meet environmental standards for fuels. The standard method for desulfurization of hydrocarbon feed streams is based on hydro-desulfurization which uses hydrogen to help convert the organic sulfur to H_2S. The H_2S can be subsequently removed by a number of processes such as amine scrubbing or adsorption in a Zinc oxide (or mixed metal oxide) bed. The desulfurization challenge for small scale, commercial fuel cells is that it must occur *at the point of use* and the techniques available at large processing scales are not always practically possible or efficient at small scales. However, in contrast to the chemical process industries, the economics of sulfur adsorption in fixed *non-regenerable* beds are feasible in small fuel cells, due to the relatively low levels of sulfur in the fuel and the low fuel flows. Acumentrics performed an extensive literature and vendor search to identify commercially available sorbents that can cost effective remove sulfur from the incoming fuel stream. Vendor recommendations and in-house data was used to screen the potential sorbents and to design fixed, replaceable beds capable of ensuring adequate sulfur removal given a broad range of sulfur species, sulfur levels and ambient temperature conditions. Unique bed formulations were developed for natural gas and LPG systems. Figure 47 shows a typical breakthrough curve for a natural gas desulfurizer.

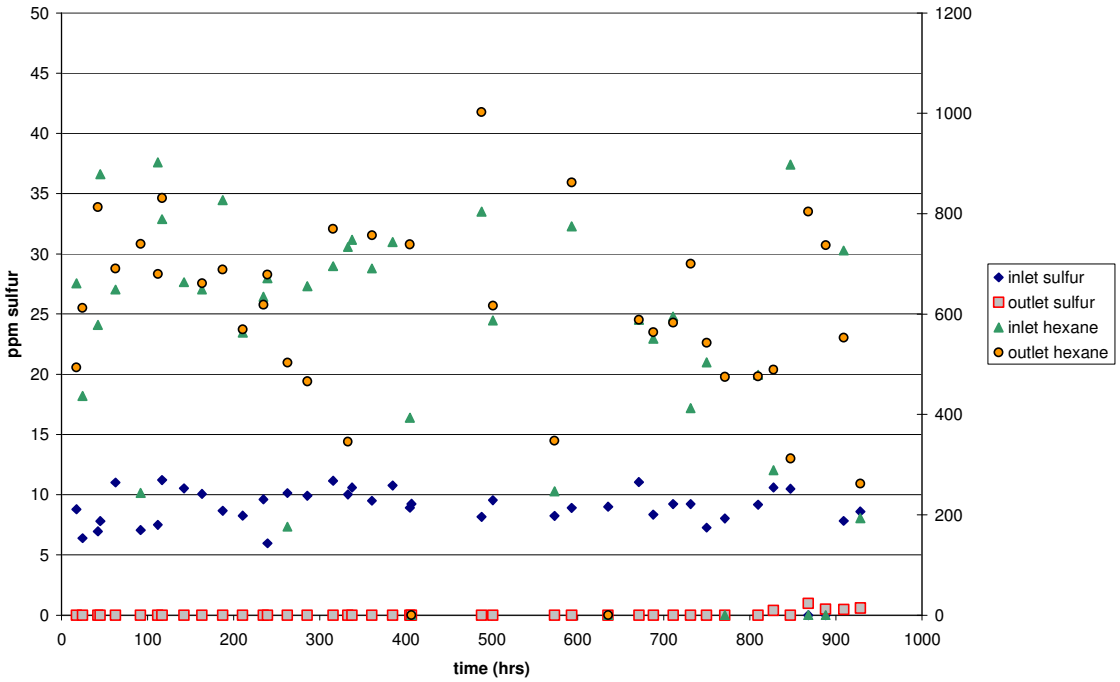


Figure 47 Low temperature (0℃) breakthrough curve operating on line NG at S.V. ~1400hr-1, 0.675 slpm NG with ~1% Hexane.

6.0 – Prototype Test and Evaluation

During Phase II several versions of the remote power generator were tested to evaluate the performance of the system and evaluate component reliable. Also, as discussed in Section 1.1 several units were placed in the field to acquire long term, "real world" operating data. A test plan was developed to test the prototype generators in a systematic fashion to acquire the necessary performance data and to ensure that all subsystems were functioning according to specification. The following is a typical Test Plan.

Test Plan

A. General Remarks

All system Design Verification Testing should be carried out with:

- All skins installed
- An independent outside fuel flow meter
- Additional shunts that are hand-measurable from the outside at:
    - Stack low side
    - Battery
    - Solar (if applicable)
    - Make output shunt measurable outside

Schedule:
4 days for Verification testing of Performance and Self Protection. 18 days for Ohmic Load, Gas Composition, Cycling and Environmental (outdoor) testing after ohmic load is completed (need the same load fixture).

Equipment:
1 bottle each of fat and lean gas (see below)
Passive load fixture for Ohmic load and environmental testing
Flow meters for indoor and environmental chamber testing
Additional shunts (see above)
Passive load fixture (2 ohm only) for other testing
Battery bus and constant current load (1.2)
2 fully assembled RP-20 systems with "good" stacks

B. Performance

Start up system from cold start. Verify that the system will fully charge the batteries and output full power 500W within 60 minutes.
Time to start charging batteries: _____min
Time to full power output: _____min
Full power output value: _____Watts
Maximum stack power: _____Watts

Output voltage: verify that the output voltage can be set from 5 to 48 volts.
Record min and max values:

Min voltage: _____V

Max voltage: _____V

Measure maximum output current = 30A: _____
Verify that the terminal block output connectors will accept 4 AWG wire:_____
Record the composition for the Natural Gas being used: _____
Measure the system efficiency. It should be > 25% net DC/LHV basis at 500W: %
Verify that the Ethernet communications are operating properly: _____
Verify the size and weight of the system: ____" W x ___" L x ___" H, _____ lbs
Verify that the fuel connection at inlet is ¼" MNPT: _____
Verify the following:
Fuel Flow Range: 1.5-5 LPM _____
Anode Air Flow Range: 5-15 LPM _____
Cathode Air Flow Range: 50-300 LPM _____
Measure and record the auxiliary power draw at:

System startup: _____

Battery charging before power output: _____

At full steady state 500W power output: _____

Verify that the fuel pressure at inlet is 2-3 psi: _____
Verify that the system is fitted with the standard features:

Fuel filter and regulator. Record the regulator pressure setting:_____

Low voltage alarm and shutoff. Verify that the system alarms and shuts down: _____

Volt and Ammeter: Verify that both are fitted and the values are labeled and correct: _____.

Lightning protection: Verify that the unit is fitted with lightning protection.

Automatic Fuel Shut-off (SO): verify that the unit is equipped and that the system operates correctly: _____
Measure fuel consumption at nominal 500W steady state load:

NG: < 7 ft3/hr (0.19m3/hr): _____.

Propane: < 0.08 gals/hr (0.3 liters/hr) OR 0.34 lbs/hr (0.15 kg/hr): _____.

Adjust the O/C ratio and record its value:_____
Remove and replace the Fuel Cell module (FCM) and verify that it can be replaced within 60 minutes:. Record the actual time from start to ready to restart the system: _____min
Verify the weight of the FCM: _____lbs
Verify that the Burner igniter can be replaceable in ½ hour starting with a cold FCM: _____
Verify that the Startup burner can be replaceable in ½ hour starting with a cold FCM: _____

Software algorithms that have to be verified on the System:

- Faults
- Loss of Communication between Fuel Cell Controller and FCIC
- Output Sequencer – Load Interruption. Setting of Load Interrupt flag.

- Output Sequencer – Local and Remote Load Setting
- Transition between load and battery charge based on Stack Voltage.
- Fuel Outage

C. Self Protection

Fuel System Failure
Test system response to low fuel pressure, lower input pressure from 12" in 2" increments and observe behavior GUM and of fuel pressure switch. Need to install functioning 0.5 psi rated Dwyer pressure switch

Anode Air Flow Degradation
Need to state which specification this is testing: over temp shut down? Then use this or other tests to verify proper operation. Partially block anode air intake filter, observe behavior GUM

Exhaust fan failure
Test response to exhaust fan failure while at 48 C ambient. Observe rise cabinet temperatures, power electronic efficiencies.

Cathode Air Flow Degradation
Reduce cathode air capability while operating at full load (condition 1.1 D).Observe whether shutdown is due to stack voltage or stack temperature.

- Block exhaust gradually until system shuts down.
- Block cabinet intake filters until system shuts down.

Short circuit at user load terminals
Set up passive ohmic load with a short circuit switch in parallel.

- Switch in short circuit before reaching "output enable" state
- Switch in short circuit while at steady state at 16 A (condition C)

System should stop feeding into short circuit within one minute

Low Battery
While at steady state create low battery situation by disconnecting battery charger from batteries (remove J407 from 269 board). System should disconnect from customer load, shut down and actuate its battery relay to shut down all power consumption. Record battery voltage at these events and observe how the battery voltage develops after the battery relay has tripped.

The RP-20 will need to be tested in two different load modes:

Ohmic Load

The FCIC delivers into an ohmic load such as a cathodic protection application. The RP-20 works in target current mode, where the output current is set as the reference for the top level "output current" loop. Test at each of the below load levels. During that period, disconnect the ohmic load for 1 minute and 5 minutes. System should detect load disconnect and latch out, need to reset via "manual load disconnect switch." Repeat this test for a 24 hour period during validation testing.

Condition	Load resistance (set value)	Output Current (set value)	Output Voltage (expected value)	Output voltage recorded	Output Power (expected value)	Output power recorded
A	0.5	20	10		200	
B	1	20	20		400	
C	2	16	32		512	
D	3	16	48		768	

Delivering into an external battery bus

The temperature compensated battery float voltage (e.g. 53 V to 54 V) will be set as the reference for the top level "battery voltage" loop. A simulated load pattern will draw current from the battery bus. Set up external battery bank of 2x4 MK M24 SLD Gel cell batteries 84 Ah (33-0015) and repeat above schedule for 4 consecutive days. Repeat this test for a 24 hour period during validation testing.

Minute	Load (W)	comment
0	200	Night
7	2000	Morning peak
7.25	600	Day level load
12	1000	Mid-day peak
13	600	Day level load
18	2000	Evening peak
18.25	200	Night

D. Validation testing

Repeat the above testing for longer term: Ohmic Load (4 Days) and Delivering into an external battery bus (4 days)

E. Gas Composition

Besides operation on Westwood line natural gas, generators need to be tested with fuel similar to extreme compositions possible at customer's site:

- Test with fat gas (85 % C1, 10 % C2, 4 % C3). Remove desulfurizer for this test only to avoid adsorption of higher hydrocarbons. Test burner light off. Then heat up using line gas to preserve bottle, switch

to special mix bottle and measure actual air/ fuel mix after flow meters and anode fuel valve. Evaluate change in cell voltages.

- Test with meager gas (85 % C1, 15 % N2). Test burner light off, measure heat up time and possible delay. Then heat up using line gas to preserve bottle, switch to special mix bottle and measure actual air/ fuel mix after flow meters and anode fuel valve. Evaluate change in cell voltages.

F. Cycling

Test unit through ten 24 hour cycles from room ambient to +48°C at condition C (512 W out, see part A). Repeat sequence 7 through 12 nine times for a total of 10 cycles.

Sequence Index	Hour	Expected ambient T	Insulation Box	Action
1	0	20	Put On	Start system
2	1	30	On	Reach “output enable”
3	2	48	On	Box fan starts to control temperature
4	5	48	Take off	
5	8	20	Put On	
6	16	48	On	Automated shutdown
7	24	48	Put On	Automated system
8	25	30	On	Reach “output enable”
9	26	48	On	Box fan starts to control temperature
10	31	48	Take off	
11	32	20	Put On	
12	40	48	On	Automated shutdown

G. Environmental

Install unit in environmental chamber and run through conditions outlined above with an environmental chamber temperature of 50 C.

Test Summary

Table 5 summarizes the performance data for an RP20 remote power generator system.

Table 5: RP20 Performance Summary

Adjustable Voltage Output:	5-60 VDC
Gross DC Power:	580
Stack Current :	33 amps
Ave Cell Voltage:	0.87
Fuel Utilization:	64%
Average Stack Temperature:	800 C

Parasitic Power:	65 Watts, 85% Eff
Load Power:	480 Watts, 95% Eff
Oxygen/Carbon Ratio:	0.8
System Efficiency:	32%

Acumentrics has achieved >40% gross DC Efficiency on a number of systems tested during the course of the program. In addition, when operating in a combined heat and power mode, overall thermal efficiencies of >80% were demonstrated. Several different heat recovery geometries were utilized ranging from custom built hydronic water coils placed in the exit of the flue gas leaving the fuel cell stack to complete integration of the fuel cell exhaust with a high efficiency condensing residential boiler.

The electrical efficiency target was met on generators utilizing three distinct fuel reforming technologies. In the first case, steam reformation via hot offgas recirculation was utilized and a DC efficiency of 52% was achieved, see Figure 48. This efficiency was obtained when operating at 8.5 kW DC. The overall AC efficiency was 42% and the overall thermal efficiency was 83%.

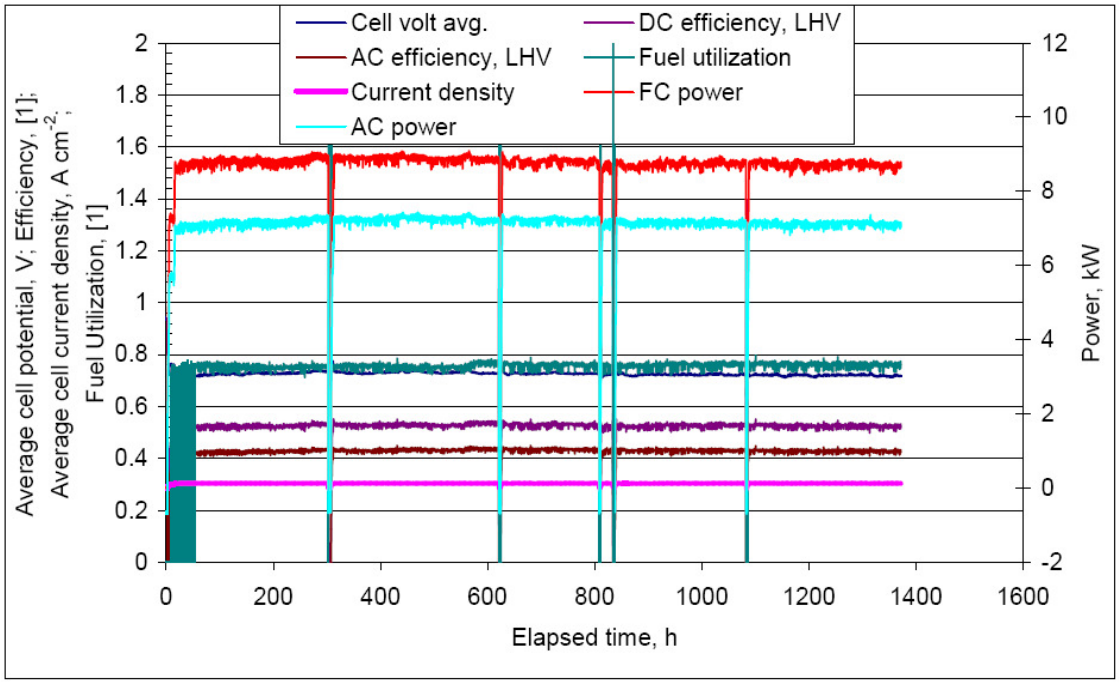


Figure 48 Hot Gas Recirculation Configuration

In the second configuration, steam reformation via water vaporization was utilized and a DC efficiency of 47% was achieved, see Figure 49. Operation was demonstrated with water recovered through condensation of the water rich flue gas and by reverse osmosis filtration of potable water.

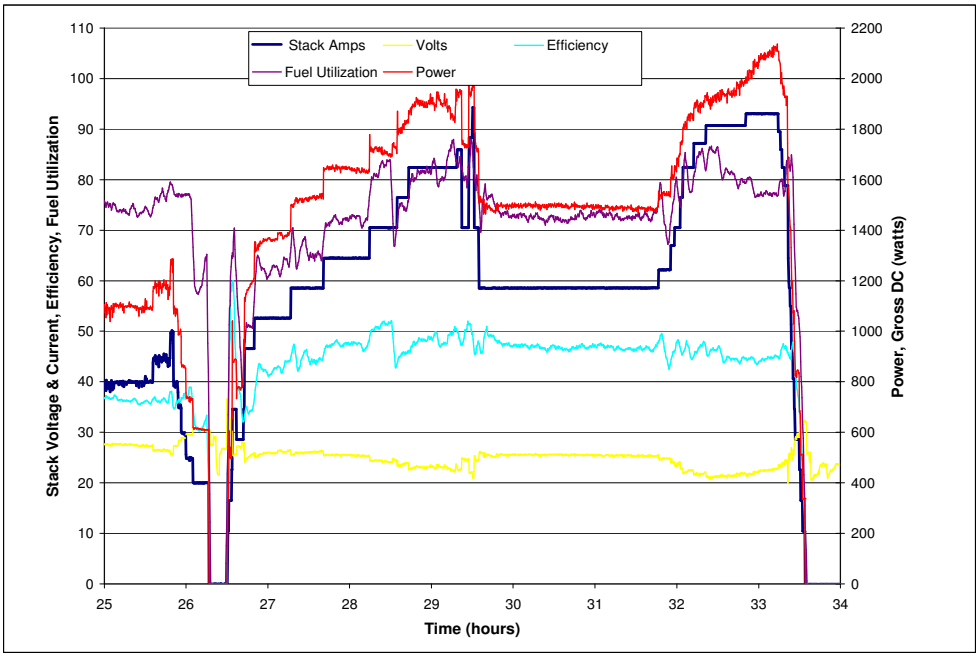


Figure 49 Steam Reformation Configuration

For the final configuration, a proprietary high efficiency partial oxidation fuel reforming technology developed during the program was utilized. With this technology, simplified, low cost, balance of plant components can be utilized to achieve a degree of steam reformation within the cells. With this system configuration, gross DC efficiencies slightly greater than 40% were achieved, see Figure 50. It is important to note that this was accomplished without the use of high cost recirculators or water handling equipment. This is extremely important for the remote power market which is Acumentrics' early market entry point since potable water is not available, overall system cost is important and system reliability is essential.

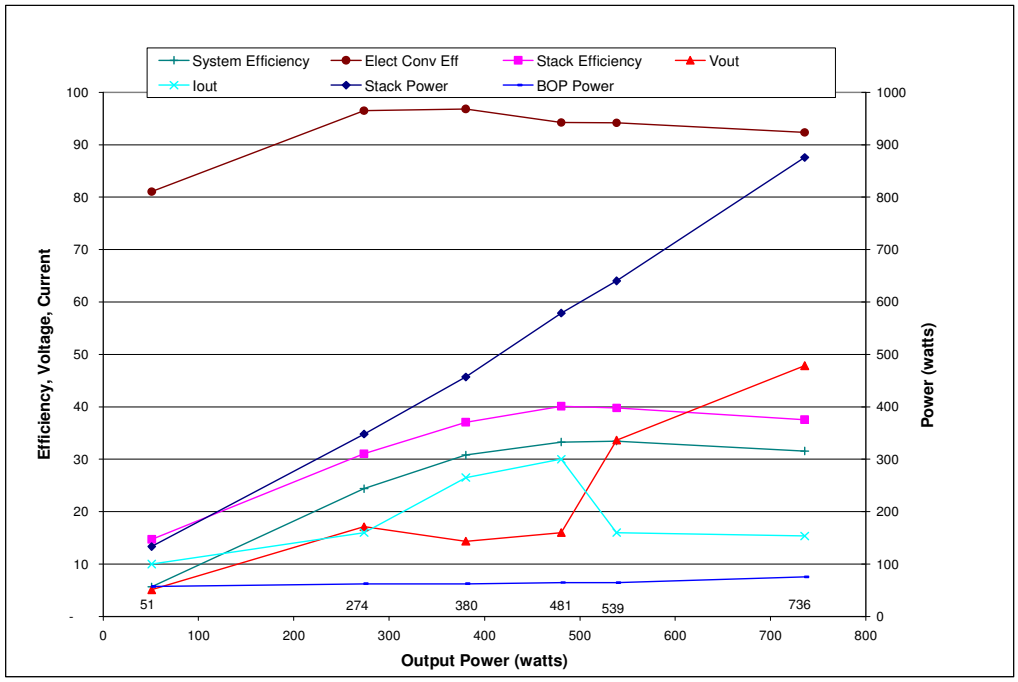


Figure 50 High Efficiency Partial Oxidation Configuration

Final Results

This development program funded from 2003 through early 2013 has brought the Acumentrics SOFC program from an early stage R&D program to an entry level commercial product offering. The development work started as one of the main core teams under the DOE Solid State Energy Conversion Alliance (SECA) program administered by the National Energy Technology Laboratory (NETL) of the DOE. During the first phase of the program, lasting approximately 3-4 years, a 5kW machine was designed, manufactured and tested against the specification developed by NETL. This unit was also shipped to NETL for independent verification testing which validated all of the results achieved while in the laboratory at Acumentrics. The Acumentrics unit passed all criteria established from operational stability, efficiency, and cost projections.

During Phase II, the overall objective was to further refine the unit meeting a higher level of performance stability as well as further cost reductions. To achieve this goal, further enhancements in power, life expectancy and reductions in cost were made. The past 5 years have shown that Acumentrics has achieved these goals with machines that can now achieve over 40% electrical efficiency and field units that have now operated for close to a year and a half with minimal maintenance. Over the course of Phase II, approximately 50 remote power generators were built and tested. Along with several laboratory units, generators were placed in the field under a variety of applications and test conditions. Among these are: pipeline and well head catalytic protection, chemical injection pumps, cell towers, wind assessment units (LIDARS), outdoor lighting, and a

National Park Service visitor center. Acumentrics is now offering these remote power units commercially and the units are being purchased against incumbent technologies for the benefits provided by the higher efficiency, lower maintenance SOFC technology.

Patents: Nothing to report.

Publications / Presentations:

5th Annual SECA Workshop
"Status of the Acumentrics SOFC Program"
Norman Bessette
Acumentrics Corporation
5/11/2004

7th Annual SECA Workshop
"Status of the Acumentrics SOFC Program"
Norman Bessette
Acumentrics Corporation
9/12/2006

2006 Fuel Cell Seminar
"Advancements of the Acumentrics Solid Oxide Fuel Cell Program" (Abstract 241)
Doug Schmidt
Acumentrics Corporation
11/14/2006

8th Annual SECA Workshop
"Progress in Acumentrics' Fuel Cell Program"
Doug Schmidt
Acumentrics Corporation
8/7/2007

2007 Fuel Cell Seminar
"Progress in the Acumentrics Solids Oxide Fuel Cell Program" (Abstract 452)
Doug Schmidt
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10/16/2007

2008 Fuel Cell Seminar
"Progress in Acumentrics' Fuel Cell Program" (Abstract 1774)
Doug Schmidt
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10/28/2008

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“Advancing Solid Oxide Fuel Cells at Acumentrics” (HRD41-1)
Doug Schmidt, Norman Bessette, Anthony Litka, Rhys Foster, Jolyon Rawson
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11/19/2009

DOE Fuel Cell Pre-Solicitation Workshop
Solid Oxide Fuel Cell Balance of Plant & Stack Component Integration
Norman Bessette
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3/16/2010

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“Development of a Low Cost 3-10kW Tubular SOFC Power System”
Norman Bessette
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“Progress in Tubular SOFCs at Acumentrics”
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10/20/2010

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Norman Bessette
Acumentrics Corporation
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