

MOLTEN CARBONATE FUEL CELL PRODUCT DESIGN IMPROVEMENT

**SEMI-ANNUAL TECHNICAL PROGRESS REPORT
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**H.C. MARU, PROGRAM DIRECTOR
M. FAROOQUE, ASSOCIATE PROGRAM DIRECTOR**

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**FuelCell Energy, Inc.
3 GREAT PASTURE ROAD
DANBURY, CT 06813**

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FuelCell Energy, Inc., the overall project coordinator provided the lead role in the execution of program tasks. The program activities are organized under seven tasks. The task leaders are A. Leo (Tasks 1 through 3 and Task 5), T. Lucas (Task 4), J. Daly (Task 6), and M. Farooque (Task 7). Numerous FuelCell Energy engineers have contributed to this report.

Interactions and guidance of Technical Representative Richard Dennis of DOE/NETL is acknowledged.

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EXECUTIVE SUMMARY

Under the cooperative agreement DE-FC21-95MC31184 with DOE/NETL, FuelCell Energy, Inc. has been developing its direct fuel cell (DFC[®]) technology for stationary power plants. The objective of the program is to develop and demonstrate a cost-effective, market responsive DFC[®] power plant design(s) and make it ready for commercial entry. Significant progress has been achieved during the reporting period, January through June 2002, as highlighted below.

- Cell and stack designs were refined to reduce cost and further enhance endurance capability.
 - New inactive end cell design, used for aiding stack electrolyte management and providing transition from end plate to cell packages, was verified in subscale stacks, showing very low, stable end cell resistance through stressed testing (20 thermal cycles). The design has been incorporated in product stacks.
 - Alternate low-cost bipolar plate material promising at least six times lowering of material cost has been successfully evaluated in subscale stacks, showing very low corrosion in post-test examination. Full-size stack evaluation is planned next.
- The full-height Stack FA-100-2 test was continued, demonstrating excellent endurance characteristics, operability under all conditions in the DFC/T hybrid system, and excellent performance of the low-cost stack hardware. Based on these test results, the MW-class power plant stack module M10 design has been finalized and the module fabrication has been launched.
- The manufacturing facility expansion at Torrington was continued to increase the production rates toward the commercial goals, while hiring and training new employees. The Stack Final Assembly facility is now capable of assembling two stacks simultaneously and handling six stacks in various stages after cell stacking.
- Progress in resolving technology and cost issues related to the balance-of-plant (BOP) components was also continued;
 - An advanced low-cost adsorbent with three times higher capacity (than the baseline material) for sulfur removal from pipeline natural gas has been identified for further verification in field trial operations.
 - FuelCell Energy has evaluated four alternate inverter systems and qualified three designs for DFC[®] power plants. Operation of one of the designs in grid-connected and grid-independent modes has also been successfully verified in conjunction with the 250 kW DFC/T test.

INTRODUCTION

The carbonate fuel cell promises highly efficient, cost-effective and environmentally superior power generation from pipeline natural gas, coal gas, biogas, and other gaseous and liquid fuels. FuelCell Energy, Inc. has been engaged in the development of this unique technology, focusing on the development of the Direct Fuel Cell (DFC®). The DFC® design incorporates the unique internal reforming feature which allows utilization of a hydrocarbon fuel directly in the fuel cell without requiring any external reforming reactor and associated heat exchange equipment. This approach upgrades waste heat to chemical energy and thereby contributes to a higher overall conversion efficiency of fuel energy to electricity with low levels of environmental emissions. Among the internal reforming options, FuelCell Energy has selected the Indirect Internal Reforming (IIR) – Direct Internal Reforming (DIR) combination as its baseline design. The IIR-DIR combination allows reforming control (and thus cooling) over the entire cell area. This results in uniform cell temperature. In the IIR-DIR stack, a reforming unit (RU) is placed in between a group of fuel cells. The hydrocarbon fuel is first fed into the RU where it is reformed partially to hydrogen and carbon monoxide fuel using heat produced by the fuel cell electrochemical reactions. The reformed gases are then fed to the DIR chamber, where the residual fuel is reformed simultaneously with the electrochemical fuel cell reactions.

FuelCell Energy plans to offer commercial DFC® power plants in various sizes, focusing on the subMW as well as the MW-scale units. The plan is to offer standardized, packaged DFC® power plants operating on natural gas or other hydrocarbon-containing fuels for commercial sale. The power plant design includes other fuel processing options to allow multiple fuel applications. These power plants, which can be shop-fabricated and sited near the user, are ideally suited for distributed power generation, industrial cogeneration, marine applications and uninterrupted power for military bases.

FuelCell Energy operated a 1.8 MW plant at a utility site in 1996-97, the largest fuel cell power plant ever operated in North America. This proof-of-concept power plant demonstrated high efficiency, low emissions, reactive power control, and unattended operation capabilities. Drawing on the manufacture, field test, and post-test experience of the full-size power plant; FuelCell Energy launched the Product Design Improvement (PDI) program sponsored by government and the private-sector cost-share. The PDI efforts are focused on technology and system optimization for cost reduction, commercial design development, and prototype system field trials.

RESULTS/ACCOMPLISHMENTS

Progress continued in stack and balance-of-plant (BOP) equipment technology improvement and cost reduction, in power plant manufacturing process development, and in manufacturing facility expansion. Key program accomplishments during the first half of year 2002 are discussed below:

End Cell Design Improvement

A fuel cell stack comprises of hundreds of individual cell packages stacked together. The end cells provide structural termination at the two ends. There is a tendency for liquid electrolyte to slowly move along the surface of the stack from the positive end toward the negative end. This movement of the electrolyte may affect electrolyte inventory in the end cells. This results in an increase in internal electrical resistance and electrode polarization of the end cells. Furthermore, the end cell electrical contact can change due to changes in cell components and thermal deformation of the end plate at stack operating temperatures or during thermal cycling.

FCE has developed an advanced end-cell assembly that contains electrolyte source/sink and compliant members to mitigate electrolyte and contact loss concerns. The design was first verified in out-of-cell testing (>10 thermal cycles), showing an order of magnitude improvement in maintaining contact resistance. The electrolyte reservoir/sink near the end cell has increased electrolyte storage or absorbing capacity by >2 folds. The advanced design was then tested in subscale Stacks FA-20-7 (30 cells) and FA-5-9 (10 cells), verifying the functional enhancement. Figure 1 shows stability of low end cell contact loss through 20 thermal cycles in Stack FA-5-9. Test results are further discussed under Subscale Stack Tests section of this report. The design is now implemented in all field trial stacks.

Cell Performance Model Development

A simple spread-sheet based performance and thermal model has been developed to obtain quick and fairly accurate estimates of the stack performance, and the temperature and current distributions. The temperatures can be predicted within 15°C of the actual value. This model is being used for evaluating new RU and DIR designs to obtain the desired thermal characteristics (reduced thermal gradients) in the stack and hence for optimizing the stack design. Progress is further summarized under Subscale Stack Tests section later.

In parallel, a program was initiated to develop a comprehensive computational fluid dynamic (CFD) model using commercially available Fluent software. The work is being performed in collaboration with a consultant. The objective is to study in detail the effects of stack design on performance and the temperature, current and fluid flow distributions in full-area stack. The model development has been completed. The model is three dimensional and considers the fluid flow, pressure drop, conservation of mass and species, conductive and convective heat transfers, and electrochemical

reaction in each cell. The electrochemistry is included by using a simplified form of Butler-Volmer equation with empirically derived constants. The model includes both direct and indirect internal (steam) reforming of hydrocarbons, one of the main features of the DFC stack. The reformers and cells in the stack are integrated thermally and by gas flows. The model is capable of simulating various operating conditions. This model will be used to optimize the stack design and determine the design tolerances that will be acceptable. With the development of the model, FCE expects to save time and cost in its development efforts. The model validation is currently in progress.

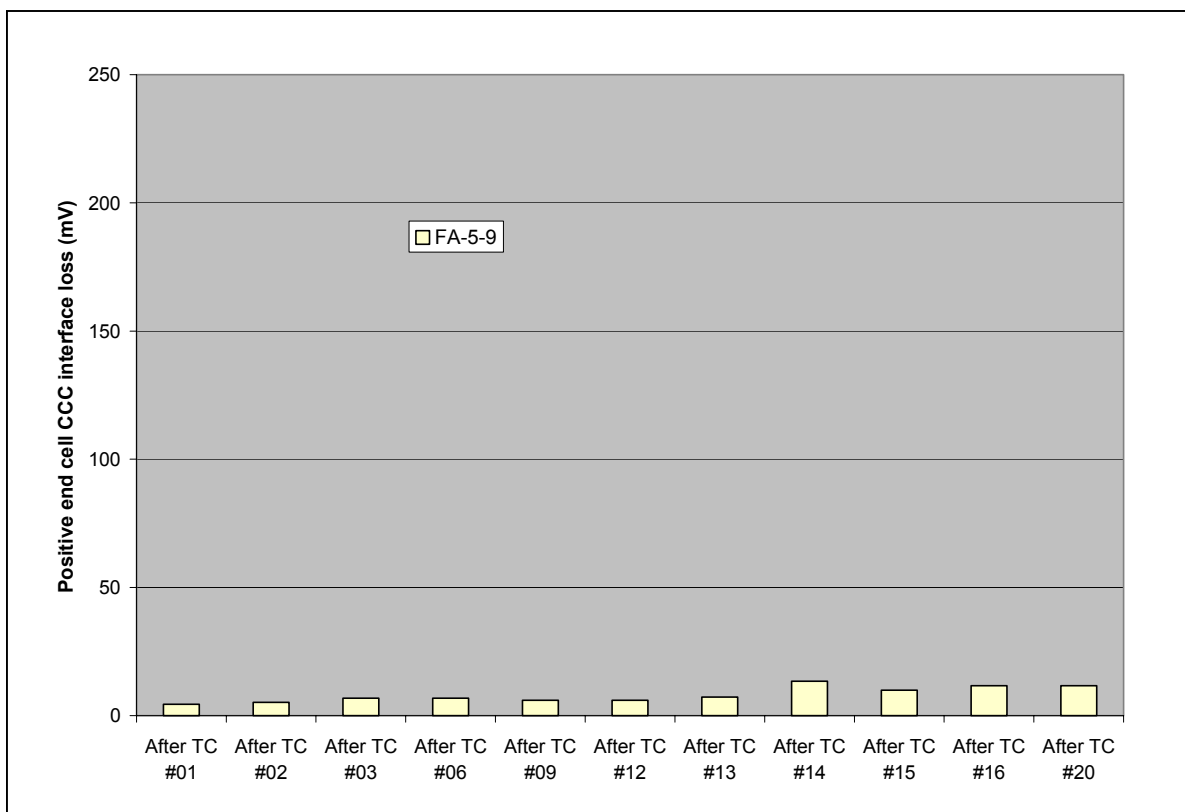


Figure 1. END CELL PERFORMANCE STABILITY:
Significant Enhancement in End Cell Thermal Cycleability
Achieved by the Advanced Design

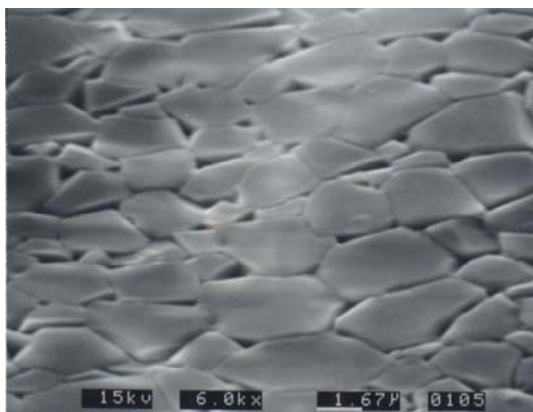
Performance Improvement

It is desirable to enhance the performance of carbonate fuel cell for further increasing efficiency. Voltage loss at the porous anode is caused mainly by the low electrolyte fill level (due to its low wettability) and by the low catalytic surface area. Several modification approaches to the baseline anode have been initiated to increase wettability and surface area. Two modified anodes have shown cell performance improvement in 3 cm² labscale cell testing. Bench-scale single-cell testing will follow.

Another factor affecting the performance of the carbonate fuel cell is the slow oxygen reduction kinetics of the NiO cathode. Material additives to the baseline cathode to enhance the cathode kinetics are being evaluated. The selected materials were successfully synthesized. Analyses of the processed cathodes by XRD, EDS and SEM showed the presence of the desired dense film on the cathode surface. The film was uniform in thickness. The modified cathodes will now be tested in 3 cm² lab-scale cells and 250 cm² bench-scale single cells.

Hot corrosion of the bipolar plates and the corrugated current collectors is an important cell endurance controlling factor. Approximately 25% of the internal cell resistance could be attributed to the formed interfacial oxide layer on the stainless steels used for the bipolar plate and cathode current collector (CCC). Current research thrust at FCE is aimed at increasing the corrosion resistance of these components by applying a dense, conductive coating that protects the underlying stainless steel. Coatings of desired thickness were successfully prepared. Figure 2 shows CCC coatings prepared at FCE. Out-of-cell and single cell testing are being conducted to evaluate the performance of these coatings. Preliminary results indicate stable contact resistance. Optimization of the coating preparation condition to achieve denser coating is in progress.

Material A



Material B

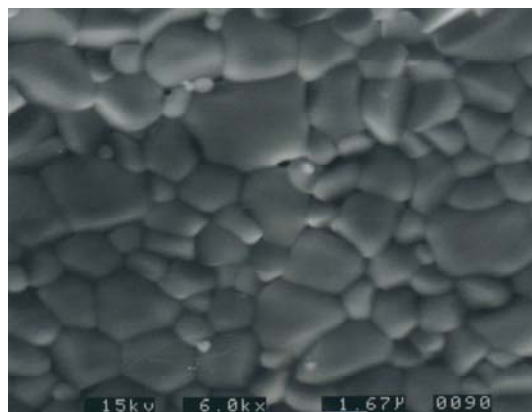


Figure 2. CORROSION PROTECTION OF CATHODE CURRENT COLLECTOR:
Dense Coatings Have Been Successfully Prepared

Cell Component Cost Reduction

Tape casting is a well-established technique used for large-scale fabrication of key thin carbonate fuel cell components such as anode and cell matrix. Organic solvents have traditionally been used as the liquid medium but water based tape casting is more desired based on cost, and environmental considerations. Efforts are now directed at FCE towards developing water-based tape casting process for the anode and matrix. Preliminary experiments have indicated that water based tape casting process for

matrix is not only possible but also can offer acceptable drying rate. Optimization of the formulation is underway. Also water-compatible materials for further strengthening the matrix are being pursued.

Preliminary tape casting has shown that the current anode material does not experience any instability in the aqueous system. The main consideration is the drying rate of the tape for application in current manufacturing procedures. Several aqueous-based slurries have been prepared, and small samples have been successfully cast and dried. Future experiments will be performed to optimize the aqueous-based binder composition, drying procedure and scale-up. Alternate methods such as calendaring process are also being pursued.

Current bipolar plate uses corrosion protected stainless steel. FCE has devised a cell design using an alternate material that eliminates the processing need for corrosion protection. This alternate bipolar plate material offers a significant cost reduction by lowering it to a sixth of the baseline material cost. The cell design has been evaluated in long-term single cell and subscale stack tests. The contact resistance and corrosion of the alternate bipolar plate have been found to be similar to the baseline design. The negligible corrosion was verified in a 6,200h full-area stack test (Figure 3). The internal reforming catalyst that is placed right next to the bipolar plate is also not affected. Therefore, the improved design is qualified for use in full-size Stack FA-100-3.

Subscale Stack Tests

New inactive end cell (assembly) design was implemented in Stacks FA-5-9 and FA-20-7 to reduce loss of contact and increase electrolyte inventory in the stack. Thermal cycling is known to accelerate increase in cell resistance. To evaluate the new end cell design under severe conditions, Stack FA-5-9 was repeatedly thermal cycled. Twenty thermal cycles were carried out. A performance drop of only $<0.5\%$ could be attributed to each cycle. The end cell resistances did not show any significant increase during operation or thermal cycling. Low gas crossover and good matrix strength to withstand thermal cycling were also confirmed. The open circuit voltages of all the cells were within 5 mV of each other after a number of thermal cycles. The new end cell design was considered a success based on these results and has been incorporated in the upcoming stacks.

Low-cost bipolar plate materials were tested in Stacks FA-5-8 (10 cells) and FA-20-6 (30 cells). No performance change and resistance increase were observed. The post-test examinations indicated very low corrosion. The design was implemented in Stacks FA-5-9 and FA-20-7 for further verification.

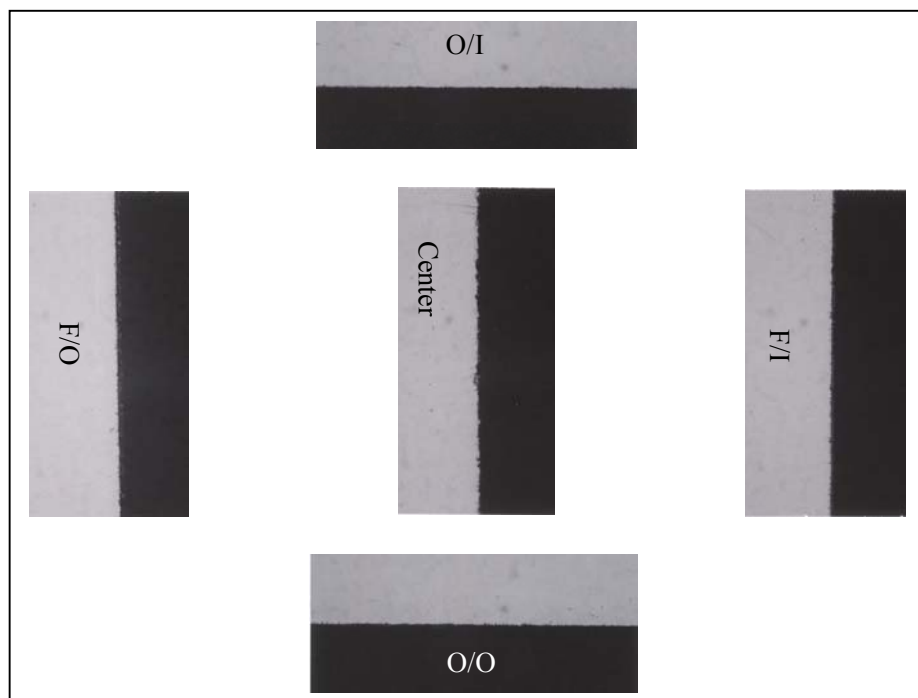


Figure 3. CORROSION RESISTANCE OF BIPOLAR PLATE IN NEW DESIGN:
Excellent Resistance of Advanced Plate Sections Verified
in a Full-Area Stack Tested for 6,200h

Low-cost production method cell matrices were evaluated in Stacks FA-5-8 and FA-20-6. The cell resistance and gas crossover for the matrix produced using the new method were found to be similar to the baseline matrix. The design has been implemented in the product stacks.

New manifold gasket design was implemented in Stack FA-20-7. Improved gas sealing was observed at the beginning of life compared to the baseline design. Further evaluation is being carried out to check the durability of the seals.

A program has been established for further improving the thermal uniformity in the DFC[®] stacks, to reduce thermal stress and improve performance. Analysis of the thermal characteristics for different designs is being carried out using mathematical models discussed earlier. New RU and DIR designs are being evaluated in Stacks FA-5-9 and FA-20-7. The number of reforming units in Stack FA-20-7 was modified to increase the thermal uniformity in the stack. Uniform cell voltages were observed with significantly reduced cell-to-cell variation of $<\pm 10$ mV (Figure 4) at 160 mA/cm². The new design reduced thermal stress near the fuel inlet area of the stack and resulted in a performance improvement of 10 mV over Stack FA-20-6 (current baseline). Further design optimization is underway, and the optimized design will be evaluated in the next 30-cell stack.

Ability of stack to undergo electrical load and thermal transients was evaluated in Stack FA-20-6. New more compliant bipolar plate wet-seal designs have since been developed and are being investigated in Stacks FA-20-7 and FA-15-1 (22 cells) to further increase load ramp rate capability and the load following capability. Improvements in load ramping capability have already been observed in Stack FA-20-7.

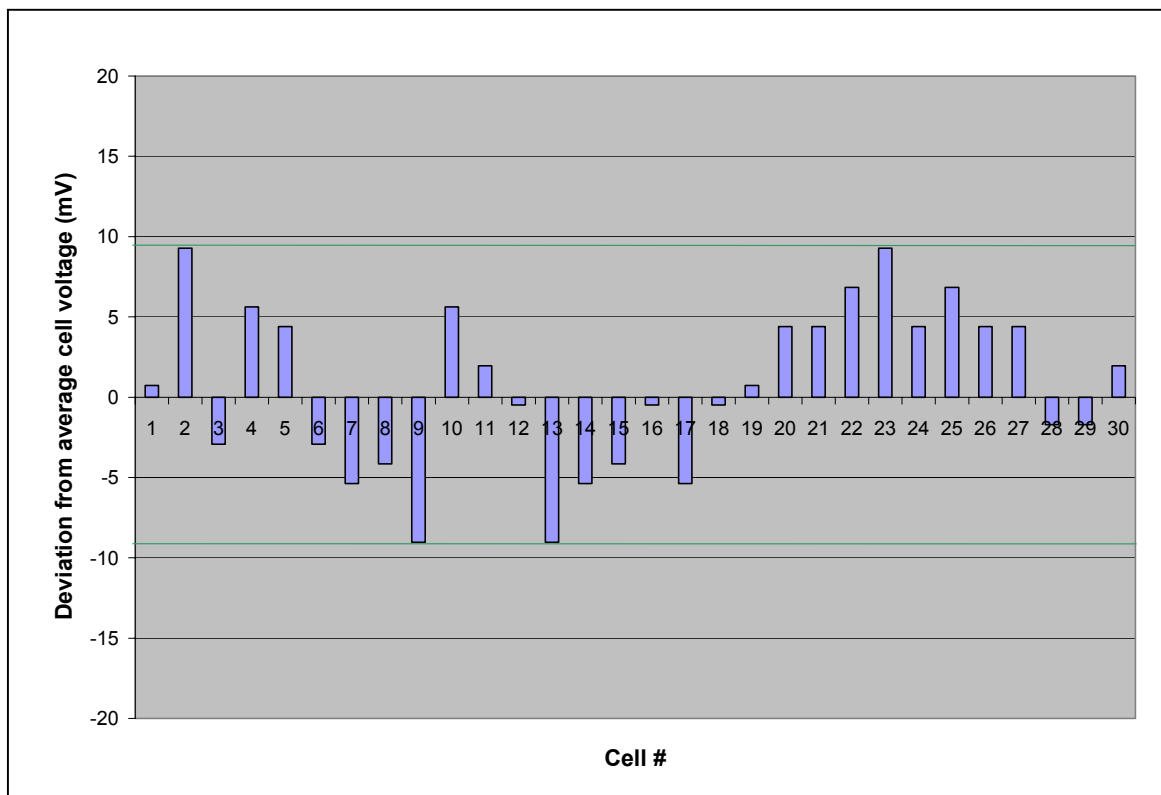


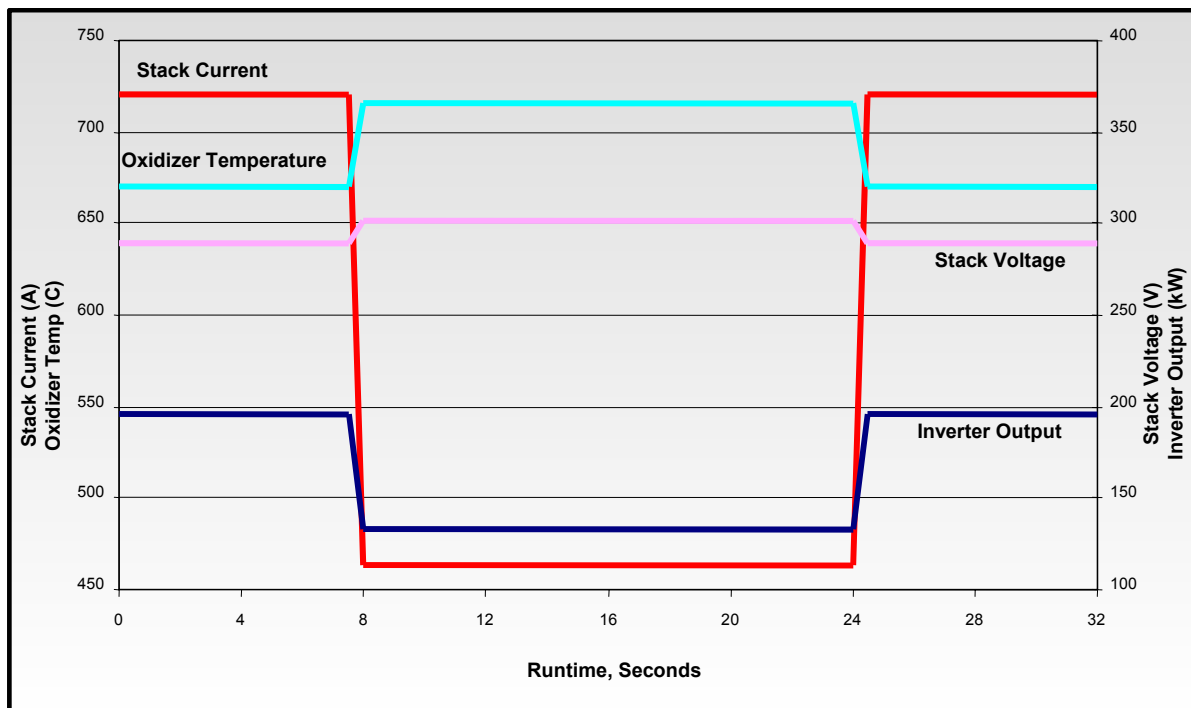
Figure 4. CELL VOLTAGE VARIATION IN STACK FA-20-7 AT 160 mA/cm²:
Total Cell-to-Cell Variation Reduced to only ± 10 mV

Full-Size Stack FA-100-2 Test Continuation

The full-height Stack FA-100-2 operation in the 400 kW-class power plant was continued. So far, two thermal cycles have been completed with no significant performance loss. The stack performance over the test period was analyzed for performance decay, meeting the expectations and the performance goal. Methane reforming conversion remained stable indicating little or no degradation of the DIR catalyst.

Load-step capability of Stack FA-100-2 and the 400 kW-class power plant was tested wherein a portion of the electrical load was instantaneously dropped for up to 20 sec and then brought back. The purpose was to see how the stack and system pressures and temperatures react to a load step/fluctuation concurrent with an inverter transferring

from a grid-connected to a grid-independent mode of operation (e.g. during a grid disturbance). Ability to accept large instantaneous load fluctuations was successfully demonstrated with up to 35% load fluctuation from 200 kW (Figure 5) and up to 50% load fluctuation from 150 kW power level. No process adjustment is required for grid disruption lasting 5 sec or less. For longer disruptions, the fuel flow rate needs to be adjusted to match critical bus load ('fuel following'). This helps control temperatures in the anode exhaust oxidizer. Additional load step and fuel following tests will be conducted on the next full-height Stack FA-100-3.



**Figure 5. LOAD STEP TEST ON STACK FA-100-2 OPERATING
IN 400 kW-CLASS POWER PLANT:**

Effects of Instantaneous Load Change from 200 kW to 135 kW Lasting 16 Sec

NO_x emissions from the DFC[®] plant were measured and were found to be low (~0.1 ppm). NO_x is produced in the anode gas oxidizer (AGO). At normal catalyst temperatures, a level of 0.3 ppm was observed in the cathode inlet gas. Upon passage through the fuel cell cathode, the concentration drops to about 0.1 ppm.

The stack continues to operate in conjunction with the micro turbine, at 200 kW net AC power endurance condition, in the grid-connect mode. Based on the test results, the MW-class power plant stack module M10 design was finalized and fabrication of the module was launched. A modification of the 400 kW-class power plant to change to a low mean temperature difference humihex and a larger 60 kW micro turbine is planned after the FA-100-2 test is voluntarily terminated.

Natural Gas Clean-up Subsystem Design Improvement

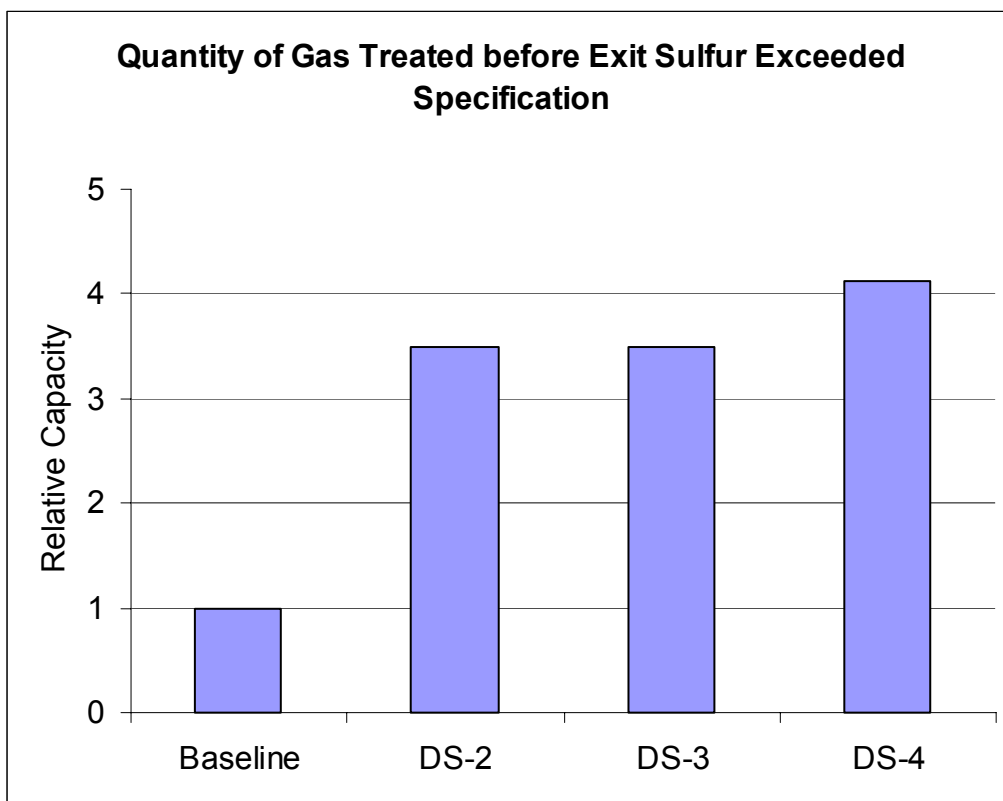
Natural gas may contain sulfur impurities in the forms of H_2S and COS . Furthermore, odorants such as mercaptan, alkyl sulfide or thiophene are added in ppm levels to the gas for leak detection purposes. Sulfur compounds present in natural gas fuel are detrimental to reforming catalysis. Use of the pipeline quality gas in the reformer requires that the sulfur be reduced to below sub-ppm level.

Presently, a treated activated carbon (baseline DS-1 adsorbent) is used to remove sulfur from natural gas at ambient conditions. However, the capacity of this adsorbent is much lower for long-term operation. Efforts were made to identify high capacity, low-cost adsorbent that meets commercial design goals with existing desulfurizer vessel configuration. Various commercial, high capacity adsorbents were evaluated during Stack FA-100-2 test. The results are presented in Figure 6. Advanced adsorbents (DS-2, DS-3 and DS-4) were found to have three times higher sulfur removal capacity than the baseline DS-1 adsorbent under similar conditions. An advanced desulfurized bed was recommended for field trial verification. This advanced bed configuration is expected to trap all sulfur species including dimethyl sulfide which can not be removed by the baseline adsorbent. The advanced bed design is expected to provide three times longer life than the baseline design and reduce cost per volume of treated gas to less than half.

Inverter Evaluation

An alternate inverter capable of grid-independent operation was installed and placed in operation in conjunction with the 400 kW-class power plant. The inverter worked well in grid-connect mode, except for some trips from hypersensitivity to grid fluctuations. Adjustments to the inverter sensitivity were made. Tests to transfer the plant operation from grid-connected to grid-independent mode were successfully completed. The results indicated that the two-stage inverter was in compliance with FuelCell Energy specifications.

Another inverter from a different vendor was also installed and operated in grid-connect mode. This inverter was designed for operation in grid-connect mode only. Successful operation of the inverter qualified the supplier as an alternate vendor for FuelCell Energy. To date, FCE has evaluated inverters from four different vendors and found the overall inverter conversion (DC to 480 VAC) efficiency to range between 93 to 95% for the different units. Three of these vendors have been qualified for supply of inverter for the DFC[®] products. Additional suppliers have been identified for testing of their inverters at FuelCell Energy site.



**Figure 6. PERFORMANCE OF ADVANCED ADSORBENTS
DURING STACK FA-100-2 TEST:**
High Capacity and Low-Cost Desulfurization Adsorbent Identified

Manufacturing Process Development

Manufacturing processes continue to be developed while more employees are added and the production rates increase toward the commercial goals. In the first half of Year 2002, major focus was placed on the Final Assembly department where the cell stacking and module assembly operations are preformed. Equipment and processes were developed to allow for assembling multiple horizontal and vertical-type power plants simultaneously. FCE is now capable of stacking two stacks simultaneously (See Figure 7) and handling six stacks in various stages after the stacking. The cranes for loading four stacks to a single base and assembling the module vessel are ready for the first megawatt class power plant field trial this fall.

The Cathode Electrolyte Filling furnace line was completed with the addition of material handling equipment. The equipment automatically loads and unloads the furnace with cathodes on carrier plates. It also separates, returns and stacks the carrier plates for reuse.



Figure 7. STACK FINAL ASSEMBLY FACILITY:
Capable of Assembling Two Stacks Simultaneously

Anode and cell matrix tape casting equipment has been modified with combustible gas sensors, improved safety interlocks, and a back-up exhaust fan (to empty the tape caster of vapors in case of a failure). The casting process has been improved to yield 100% more parts from a given slurry batch. An additional tape caster has been ordered with a feature to allow for more effective drying of the matrix and anode products. A second high volume slurry preparation system has been installed and qualified. Anode and matrix trimming equipment has been installed in the product flow line to automatically final size the parts.

Bipolar plate-wet seal attachment process development has achieved a 20% increase in speed with a 22% decrease in defects. An automatic inspection system is being developed to replace the manual visual inspection currently used. The vision system camera is in place and currently gathering data on defect characteristics. Alternate wet seal attachment processes are currently under evaluation. Corrugation current collector (CCC) flatness improvement has been approached in two ways. First, the current stamping die and press have been analyzed and improvements made in tool stiffness.

The stiffer die and press bolster plate achieved a 50% reduction in edge wave of the stamped part. Further flatness improvement may be possible with micro shimming of the die. The second approach utilizes ultra-high speed forming principles and an electromagnetic press system. This system has been developed on a small scale and is currently being scaled up for laboratory-scale fuel cell tests. This type of tool allows better dimensional control. The process holds promise for improvement in CCC flatness.

Fuel Cell Module Conditioning and Performance Verification Facility

The construction of the Megawatt Testing and Conditioning Facility (MTCF) was completed in late 2001. The purpose of the facility is to allow for conditioning and performance verification (acceptance) testing of MW-class fuel cell modules.

After construction was completed, numerous tests including process and control (PAC) tests were conducted to verify the operability of installed components, system integration, and Distributed Control System (DCS) compatibility with the plant. Issues encountered during the tests were corrected. In addition to the verification of conditioning and operating procedures, these tests provided all operators with invaluable training and experience.

While the hot testing of the facility continues at present, conditioning of the first MW-class module M10-1 is planned during the second half of 2002. A photograph of the facility is shown in Figure 8.



Figure 8. MEGAWATT TESTING AND CONDITIONING FACILITY:
PAC Testing is Currently in Progress

Balance of Plant Cost Reduction

BOP costs represent a major portion of total fuel cell power plant cost. This is especially true in small plants where scale is a significant factor. In large power plants, output is increased by adding fuel cell modules and BOP costs naturally shrink as a percent of total cost. FuelCell Energy has developed a strategy for reducing BOP costs. Current efforts are focused on the sub-megawatt power plant because of the scale factor, mentioned above, and because this product is first to market.

The strategy that FCE has developed for sub-megawatt products is: 1) Perform value engineering on the initial design, 2) Purchase electrical BOP as a turnkey product, 3) Procure mechanical packaging to assemble the entire BOP including the integration of the electrical BOP and 4) Procure all major sub-components directly and drop ship to packagers/assemblers. Progress in implementation of the strategy is further summarized below.

Value Engineering – A one-week meeting was held to value engineer the sub-megawatt power plant. This effort was led by a third party consultant and included all of the entities that participated in the design, engineering, construction and operation of the initial product. It also included the firm that has been contracted to engineer the improved product. Eighty percent of the design review has been completed and major component specifications are now available for the procurement process.

Electrical BOP – Three sources have been qualified for EBOP and others are in the qualification process. Competitive proposals will be maintained for all qualified sources and supply agreements will be developed to maximize value.

Mechanical Packaging – Three mechanical packagers have been qualified and others are being surveyed. Competitive proposals will be maintained for all qualified sources and supply agreements will be developed to maximize value.

Sub-components – All sub-components will be purchased directly by FCE to avoid mark-up by the packager and to benefit from volume leverage when using multiple vendors. This strategy further allows for volume leveraging of common parts that are used in megawatt-class products. Commodities will be grouped (i.e. valves) and supply agreements created to drive to the lowest cost (best value).

FCE believes that sustained progress on the strategy outlined above will help insure that we achieve our goal of cost competitive products. We expect to capture the benefits of these efforts in our product BOP cost in the second half of 2002.