

# ***MOLTEN CARBONATE FUEL CELL PRODUCT DESIGN IMPROVEMENT***

**TECHNICAL PROGRESS REPORT FOR PERIOD  
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**Submitted to:**

**MR. RICHARD DENNIS, PROJECT MANAGER  
U.S. DEPARTMENT OF ENERGY  
NATIONAL ENERGY TECHNOLOGY LABORATORY  
P. O. BOX 880, 3610 COLLINS FERRY ROAD  
MORGANTOWN, WV 26507-0880**

**Submitted by:**

**FuelCell Energy, Inc.  
3 GREAT PASTURE ROAD  
DANBURY, CT 06813  
H.C. MARU, PROGRAM DIRECTOR  
M. FAROOQUE, ASSOCIATE PROGRAM DIRECTOR**

## ACKNOWLEDGEMENT

The activities reported here were sponsored by DOE/NETL and DOD/DARPA, and cost-shared by the FuelCell Energy, Inc. (formerly Energy Research Corporation) team. The key team members are: FuelCell Energy, Inc. (FCE), Fluor-Daniel, Jacobs Applied Technology, and DaimlerChrysler affiliate MTU. Numerous employees of FuelCell Energy and these organizations have contributed to the project. The role of each organization, and its principal project leaders are: **FuelCell Energy, Inc., Danbury, CT** - coordination of efforts under all program areas (H. Maru); - product definition oversight, overall plant construction management and customer service (T. Leo); - manufacturing process development and stack module fabrication (C. Bentley); **Fluor Daniel, Inc. (FDI)**, Irvine, CA - assisting in power plant design (C. Newlander); **Jacobs Applied Technology (JAT)**, Orangeburg, SC - assembly and packaging of fuel cell stack and balance-of-plant modules (H. Rast); Motoren-Und Turbinen Friedrichshafen (MTU), Ottobrunn, Germany - parallel technology efforts.

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 Representatives 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 carbonate fuel cell (DFC<sup>®</sup>) technology for stationary power plants. The objective of the program is to develop and demonstrate a cost-effective, market-responsive DFC<sup>®</sup> power plant design(s) and make it ready for commercial entry. Significant progress has been achieved during the reporting period, as highlighted below.

- Cell and stack designs were refined to enhance endurance capability and reduce material costs. The direct internal reforming catalyst life is projected to increase to >5 times over the baseline catalyst. Alternate, low-cost bipolar plate wet seal material was verified in 6,200h Stack FA-5-7 test and >40,000h life is projected based on stack and simulated test results.
- The full-height Stack FA-100-2 built with low-cost components completed the first phase of operation, demonstrating a power level of 250 kW net AC. This product building-block stack with low-cost value-engineered non-repeat hardware performed as designed. The MW-class stack design was finalized based on these results.
- The equipment necessary to produce 50 MW of fuel cells per year has been successfully installed at company's new Torrington manufacturing facility building. Each of the process lines has been tested at and has achieved the 50 MW run rate.
- The construction of MW-class and sub MW-class conditioning and performance acceptance test facilities at Danbury site is complete. The hot test of the MW-class power plant simulator has been planned and will start in 2002 beginning.
- The truck transportable 4-stack module enclosure with internal insulation was fabricated and transported to FuelCell Energy, successfully hot tested at Danbury site and is now ready for MW-class power plant test. The field handling and installation of the module enclosure were verified.

The 4-stack module enclosure internal gas distribution/collection design was further verified using full-scale hardware. The flow simulation test results projected stack-to-stack flow variation to be within  $\pm 0.5\%$ .

- Sub MW-class field trials were started in US and Europe, and are currently ongoing.

## 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<sup>®</sup>). The DFC<sup>®</sup> 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<sup>®</sup> power plants in various sizes, focusing on the subMW as well as the MW-scale units. The plan is to offer standardized, packaged DFC<sup>®</sup> 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. Year 2001 program accomplishments are discussed in this report.

## OBJECTIVES AND APPROACH

The FuelCell Energy, Inc. PDI program is designed to advance the carbonate fuel cell technology from the full-size proof-of-concept field test to the commercial design. The specific objectives selected to attain the overall program goal are:

- Define power plant requirements and specifications,
- Establish the design for a multi-fuel, low-cost, modular, market-responsive power plant,
- Resolve power plant manufacturing issues and define the design for the commercial-scale manufacturing facility,
- Define the stack and balance-of-plant (BOP) equipment packaging arrangement, and module designs,
- Acquire capability to support developmental testing of stacks and critical BOP equipment to prepare for commercial design, and
- Resolve stack and BOP equipment technology and cost issues, and design, build and field test a modular prototype power plant to demonstrate readiness for commercial entry.

## PROJECT STATUS

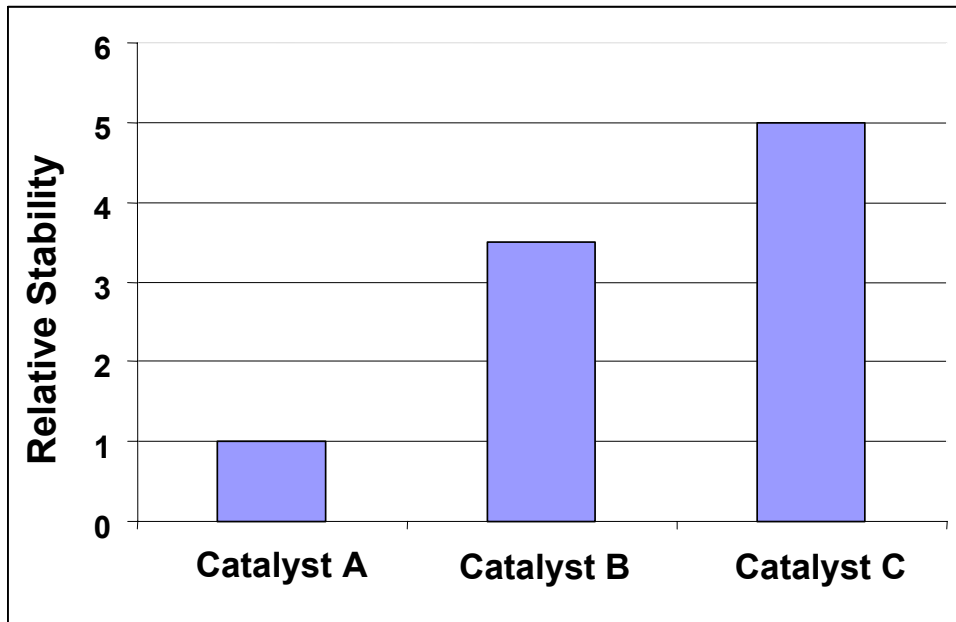
FuelCell Energy, Inc. is currently in the later stage of the multiyear program for development and demonstration of a MW-class power plant supported by DOE/NETL with additional funding from DOD/DARPA and the FuelCell Energy team. Figure 1 shows key program elements (shaded) and their interrelationships. The product definition and specifications have been derived with input from potential users. The baseline power plant final design has been completed. Detailed power plant system and packaging designs are being developed using stack and BOP development results. A prototype modular power plant field trial, representative of the commercial design, is currently in the early stage. In parallel, stack and BOP equipment development efforts are being carried out for achieving commercial market entry cost and performance goals. Based on the experience and data generated in the current program, FuelCell Energy is in the process of acquiring manufacturing as well as factory check out capabilities for market-entry products.

## RESULTS/ACCOMPLISHMENTS

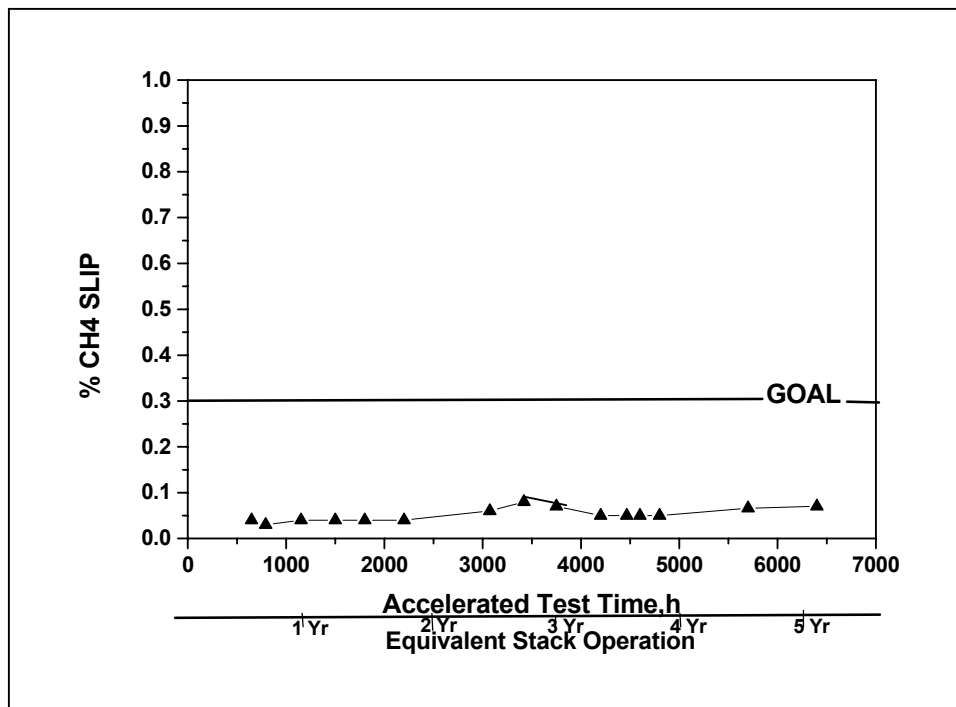
In the past year, the FuelCell Energy team has made steady progress in resolving technology and cost issues, manufacturing process development, manufacturing facility expansion, packaging design development and preparing for system design, analysis and verification. Major accomplishments in these areas are discussed below:







**Figure 2. DIR CATALYST STABILITY ENHANCEMENT:**  
Advanced Catalyst C Offers Stability Five Times Higher Than Baseline Catalyst A



**Figure 3. STABILITY OF ADVANCED DIR CATALYST C:**  
Excellent Endurance Capability Demonstrated in Accelerated Cell Test

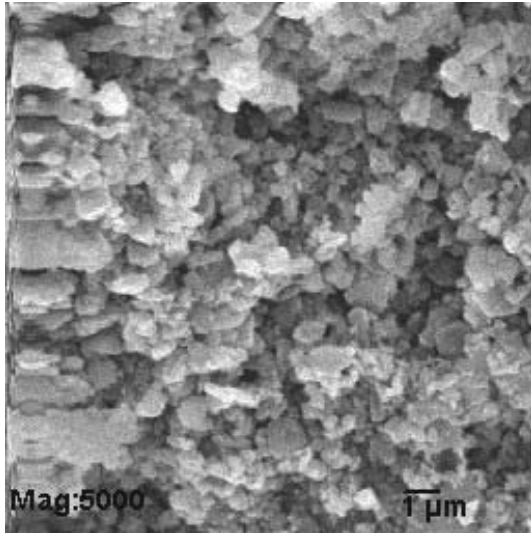
The inactive end cell development work included investigating the contact resistance increase observed during thermal transients. The stack test data indicated increase in contact resistance, which was found to be localized in the inactive end cell. A modification to the inactive end cell was incorporated to resolve this issue. With the modified design, resistance significantly more stable than the baseline design was observed in out-of-cell evaluation tests. Full-scale components were fabricated for verification tests in Stacks FA-5-9 and FA-20-7.

Material selections for improved stability were carried out for cell matrix support, bipolar plate wet seals and RU feed tubes. Long-term (~19,000h) out-of-cell tests (OCT) showed no phase conversion of the selected matrix support material. No significant particle size change was observed (Figure 4) in post-test examination of matrices from full-height Stack Test FA-100-1 (~12,000h) and Stack FA-5-6 (~18,000h). A low-cost, alternate wet-seal design was developed and evaluated in out-of-cell and stack tests. Figure 5 includes the photomicrographs showing the test results. Very little or no corrosion of test samples showed stability of wet-seal against corrosion. Excellent corrosion resistance of the selected alternate wet-seal material was verified in 6,200h Stack FA-5-7 test. Greater than 40,000h life is projected based on these results. The design has been incorporated in the product stacks. The high carburization resistance of RU feed tube material was verified in Stack FA-20-6. FuelCell Energy's atmospheric operation approach and Stack FA-100-1 post-test results ensure no shorting of cell matrix from NiO cathode dissolution/deposition in desired 40,000h lifetime.

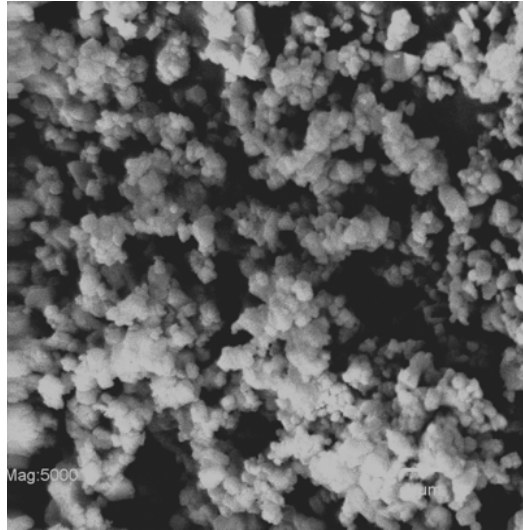
Material cost reduction activities were mainly related to the anode support, manifold-seal gasket assembly. An alternate approach for low-cost anode support, maintaining current functionality, was identified. Initial fabrication runs were successful. Cell test results have been promising. Additional optimization is in progress. An advanced design for the manifold-seal gasket assembly was developed and is being evaluated in Stack FA-20-6. In addition to lowering cost, the new design offers electrolyte transport rates much lower than the baseline design and improves gas-seal efficiency. The design is expected to improve manifold dielectric isolation properties. The advanced design has been verified in OCT. OCT endurance test and 30-cell stack test will qualify it for implementation in product stacks.

There were several accomplishments in the area of building-block stack design development. All major component designs for the full-size stack have been value-engineered for improved functional performance and reduced cost. The full-height Stack FA-100-2 was assembled with several of these value-engineered components. Enhanced involvement by the procurement team has led to multiple approved vendors for key stack components. An interdisciplinary team has also been formed to conduct failure mode and effects analyses (FMEA) for all major component designs.

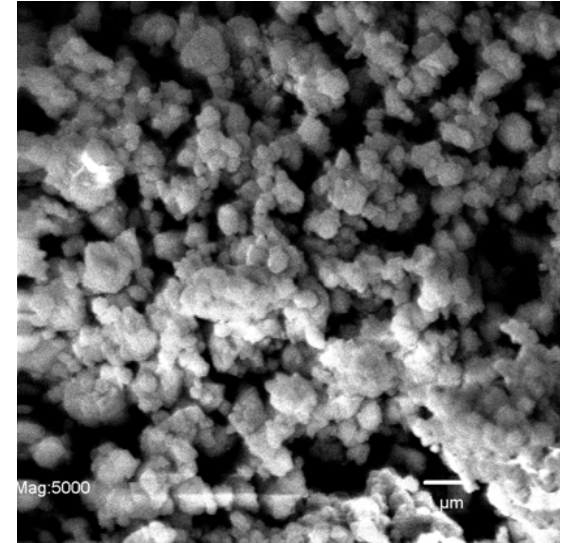
All stack design drawings were upgraded to comply with ASME and ANSI standards. Also the drawing graphics are now constructed using 3-D models, providing initial stack design verification in virtual reality by checking for interference-free fit. The bill-of-materials for sub-MW and MW market entry stacks are near completion.



a) Matrix Sample – Beginning-of-Life



b) Matrix from FA-100-1 cell 171, 12,000h

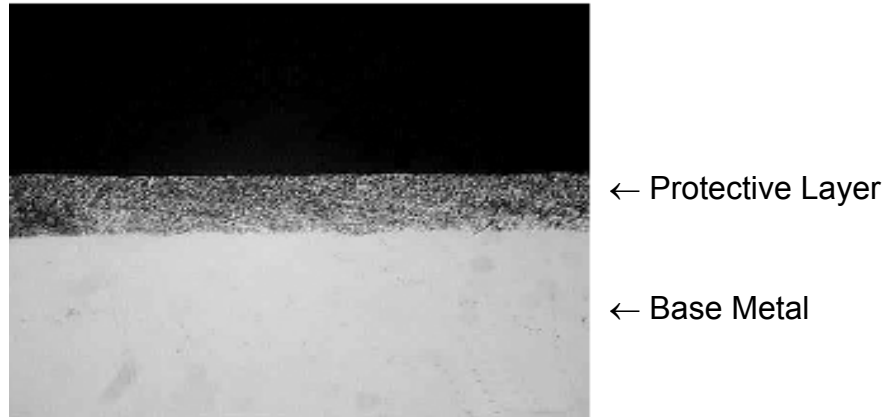


c) Matrix from FA-5-6 cell 9, 18,000h

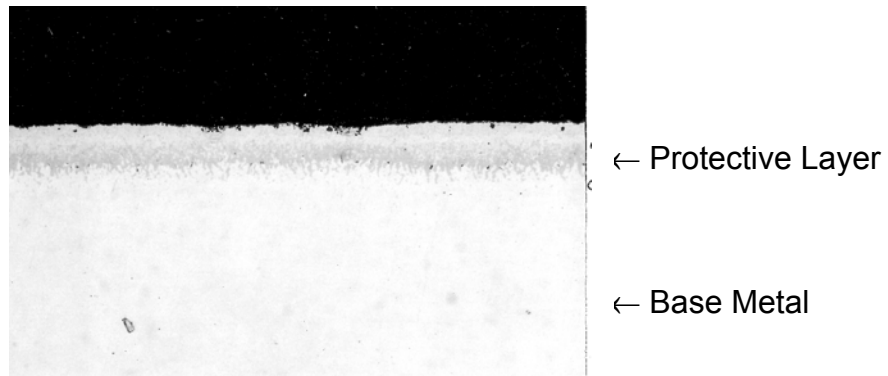
**Figure 4. CELL MATRIX SUPPORT MATERIAL STABILITY:**

Post-test Evaluation of Stack FA-100-1 and Stack FA-5-6 Matrices Showed No Significant Particle Size Change in Matrix

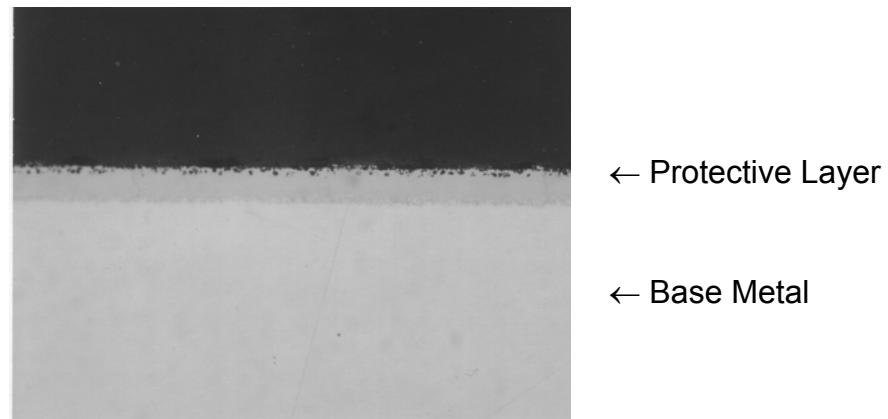
a) As received material



b) After 10,000h of out-of-cell testing



c) After 6,000h of operation in Stack FA-5-7



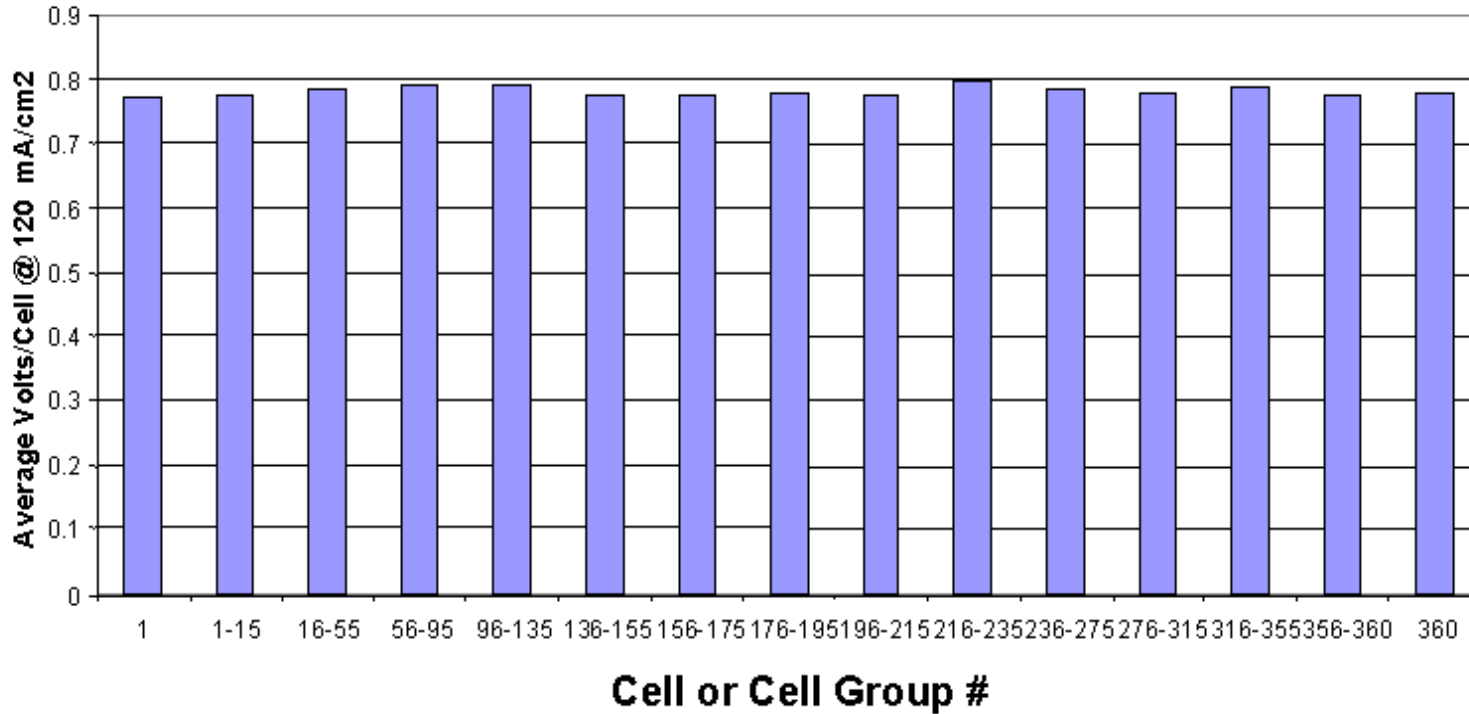
**Figure 5. ALTERNATE LOW-COST BIPOLAR PLATE WET-SEAL:**  
Excellent Corrosion Resistance Observed in Out-of-Cell and Stack Tests

The first phase of operation for Stack FA-100-2 test in conjunction with microturbine in the 400 kW-class power plant (Figure 6) has been completed. An excellent cell-to-cell performance uniformity at  $120 \text{ mA/cm}^2$  was achieved as shown in Figure 7. The major highlights of the system operation include attaining power level of 250 kW net (equiv.) AC, and LHV based efficiency of  $\sim 51\%$  at 208 kW net (equiv.) AC. Other accomplishments included successful operation of preconverter on  $\text{H}_2$ -free fuel feed and grid-connected operation using inverter from an alternate supplier. The alternate inverter provided smooth operation after initial commissioning. FuelCell Energy now has an alternate vendor to supply inverters. The test operation was shutdown for evaluation of stack non-repeat hardware (low-cost value-engineered components) performance, required for finalization of the MW-class stack design. All new-design components were examined and found to have operated as designed. Based on these findings, the MW-class stack module M10 design was finalized. The stack was successfully restarted in the 400 kW-class facility and the on-load operation was resumed. The stack to-date has operated for  $>2200\text{h}$ , produced  $>290,000 \text{ kWh}$  of electricity, completed one thermal cycle and has shown no measurable performance decay since the start of operation in July 2001. The test operation will continue.



**Figure 6. STACK FA-100-2 TEST IN 400 kW-CLASS POWER PLANT:  
DFC/T Proof-of-Concept Demonstration**

### Cell Voltages



**Figure 7. STACK FA-100-2 PERFORMANCE UNIFORMITY AT 265 kW DC:**  
Uniform Performance Achieved ( $\pm 1.6\%$ ) In Product Building-Block Stack

The subscale stack tests to verify design improvements included 30-cell Stacks FA-20-5R and FA-20-6. Stack FA-20-5R test included 1800h operation with two thermal cycles and provided performance bench-mark for cell components from the new manufacturing facility at Torrington. Operation at field trial conditions was characterized. Maximum power of 0.87 kW/cell was generated. Operation at 80% fuel utilization was also demonstrated. Approximately 40% improvement in cell-to-cell performance uniformity over the previous stack was observed. Design improvements to reduce stack thermal gradient were defined and implemented in next subscale Stack FA-20-6. Some of the design changes made included new RU and DIR catalysts with modified catalyst loadings, and new improved inactive end cells. Stack FA-20-6 test results showed ~30% reduction in stack temperature differential compared to that observed in Stack FA-20-5R. An improved stack load ramp procedure was developed based on results from transient tests and implemented in the load ramp procedure for the field trial stacks.

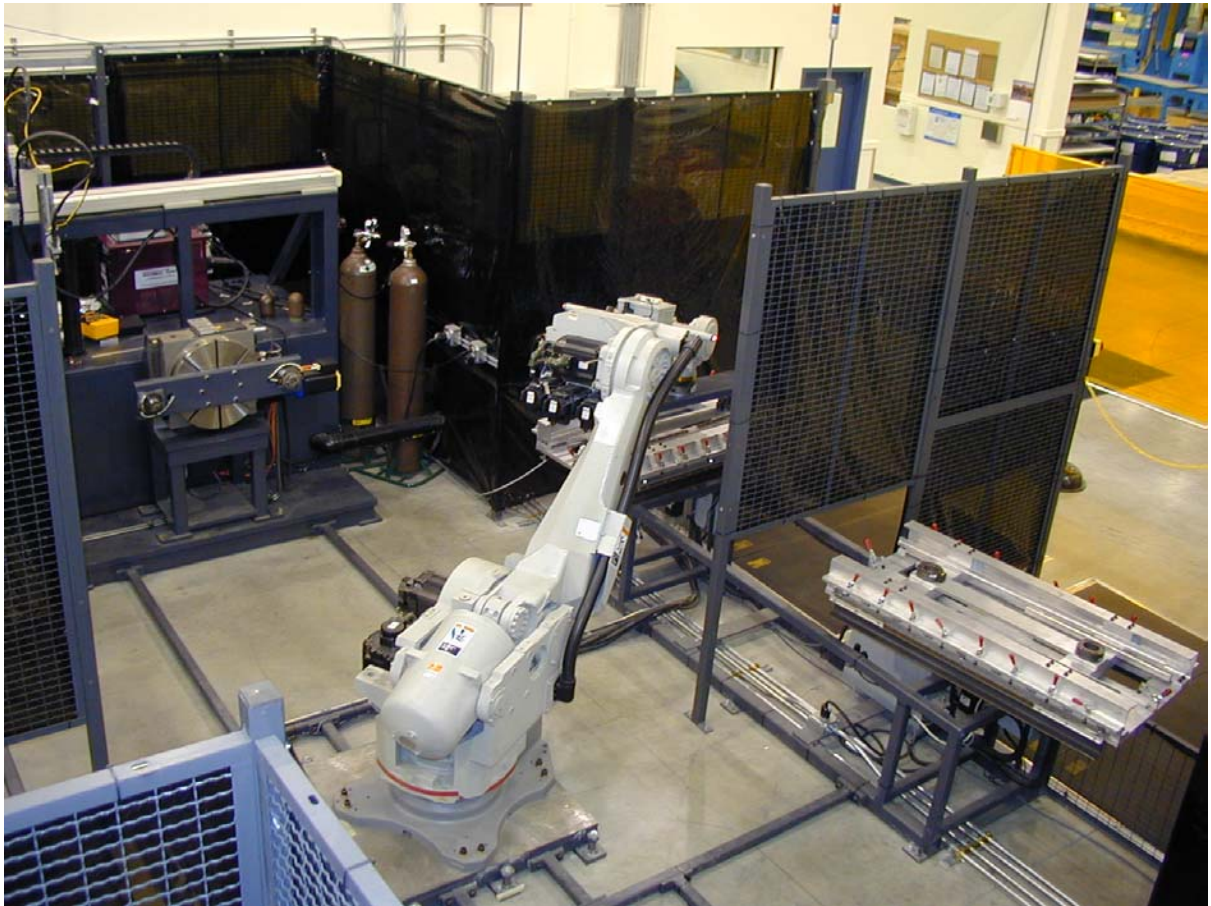
### **Manufacturing Process Development**

Information required for commercial manufacturing facility design is being developed. In addition to cost reduction, process refinement and yield improvement, focus was on attaining >50 MW/y manufacturing capacity at the Torrington facility. Equipment required to achieve this was specified and ordered. The existing plant equipment was moved to a new 65,000 ft<sup>2</sup> building and operation restarted successfully. New equipment received, installed and started in the facility included a 90-ft tape caster, a large continuous furnace for cathode electrolyte filling, a third rolling mill for anode lamination and high volume slurry preparation equipment. Other equipment installed included a hydraulic press for reforming unit (RU) assembly and a third direct internal reforming (DIR) catalyst extrusion system. In addition, the bipolar plate welding was automated with two robotic weld cells (Figure 8), 25 MW/y capacity each. The high volume slurry preparation equipment in use now consists of large, more aggressive mechanical mills and mixers and offers benefits of larger batch size and shorter processing time (Figure 9). The process for in-house manufacture of electrolyte was finalized and process enhancements on electrolyte and DIR catalyst loading in corrugations (Figure 10) were implemented.

The cell package assembly and inspection workstations now have added capacity and utilize conveyors and other material handling enhancements. The stack assembly area has been expanded to include two stacking stations and three stations for manifolding, instrumentation and final assembly. Thus the equipment necessary to produce 50 MW of fuel cells per year has been successfully installed at the company's manufacturing facility in Torrington, Conn.

Each of the process lines has been tested at and has achieved the 50 MW run rate. The facility which began construction a little over a year ago has been producing fuel cells for the company's all current commercial field trial projects. The Torrington facility has added more than 100 new employees. The company continues to hire and train staff for three shift operations and will assess production rates based on the market outlook.





**Figure 8. ROBOTIC BIPOLAR PLATE WELD CELL:**  
1 of 2 Automatic Weld Cells in Use





**Figure 9. HIGH VOLUME SLURRY PREPARATION EQUIPMENT:**  
Utilizes Large Mechanical Mills and Mixers

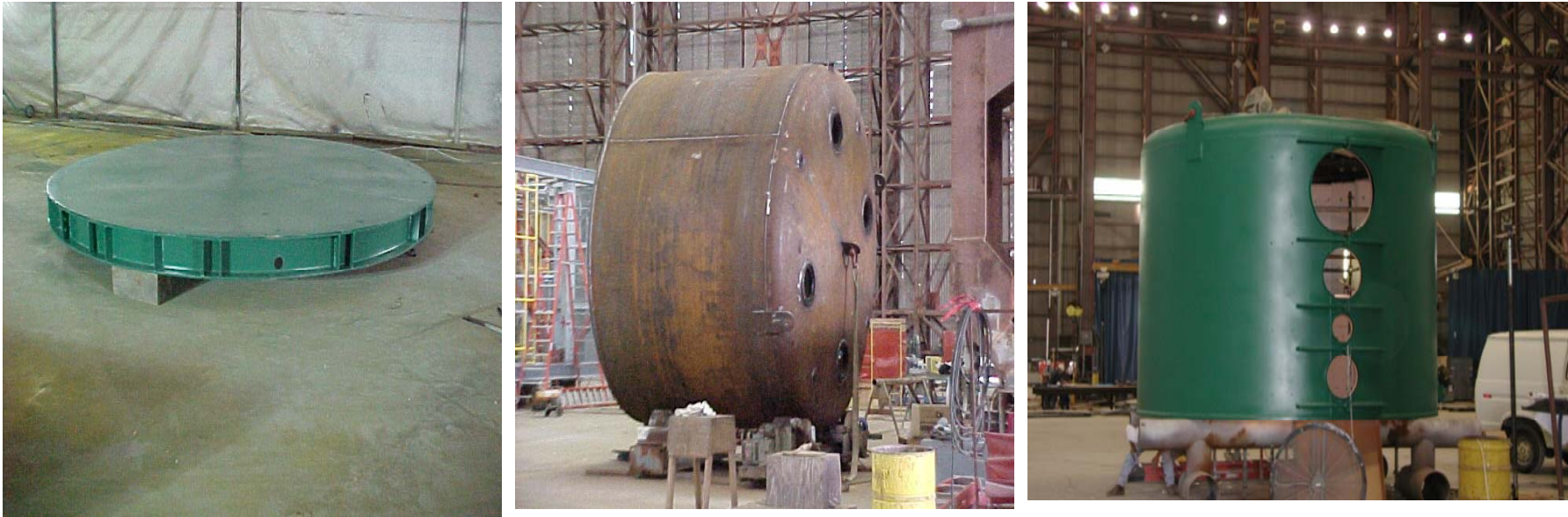


**Figure 10. IMPROVED CATALYST CORRUGATION LOADING:**  
2 of 3 Setups for Loading Extruded DIR Catalyst into Anode Corrugations

The construction of facilities for conditioning and performance acceptance test has been completed. The MW-class facility can have one module (1.5 MW) in operation while the other module is being connected/disconnected. The other facility can accommodate eight sub MW-class modules (250 kW) with one bank of four units in operation while the other bank of four units is being connected/disconnected. The two facilities together will provide a total capacity of 50 MW/year.

### **Module Assembly and Packaging**

The 4-stack (MW-class) module enclosure was fabricated to ASME code standards. Figure 11 shows the outer support base and the enclosure shell. The internal insulation was designed to minimize module size and heat loss while keeping the shell outside temperature low. The insulation support pins were attached to the shell inside wall and the insulation panels were installed. The stainless steel liner was then installed over the insulation and secured. The fabricated unit was loaded on a double drop lowboy using a standard crane and shipped to FuelCell Energy facility. This showed that the module design is fabricable, compact and transportable within US with minimal permitting. The transportation and handling logistics were further checked out when the unit was moved from Torrington manufacturing facility to Danbury site for a simulated hot test (Figure 12). At Danbury, the outer support base was installed on steel grillage and a concrete pad. The internal gas distribution system was then installed on base and instrumented. The enclosure shell was installed over the above set up and gas piping connections were completed. The field handling and installation of the module enclosure were found to be acceptable. A heater was connected to the unit set up and the hot test (~650°C) was performed. The internal insulation was inspected for hot spots using infrared thermal mapping of outer shell. The thermal mapping showed no hot spots indicating that the internal insulation was installed properly and it performed as designed (Figure 13). The post-test disassembly/inspection did not reveal any thermo-mechanical issues. The internal gas flow distribution/collection design that was based on 1:10 scale model in lab was further verified on full-scale hardware. The stack-to-stack flow variation is projected to be within  $\pm 0.5\%$ . The 4-stack module was transported back to Torrington and is now ready for MW-class stack test.



**Figure 11. 4-STACK (MW-CLASS) MODULE:**  
Fabrication of Outer Support Base and Shell Completed





**Figure 12. 4-STACK MODULE TRANSPORTATION HANDLING LOGISTICS VERIFIED:**  
Loaded on a Double Drop Lowboy Using Standard Crane. Arrived at FCE Facility and Unloaded.

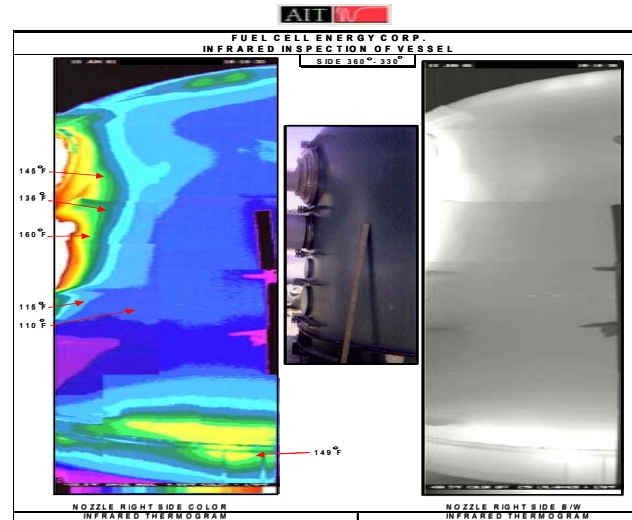
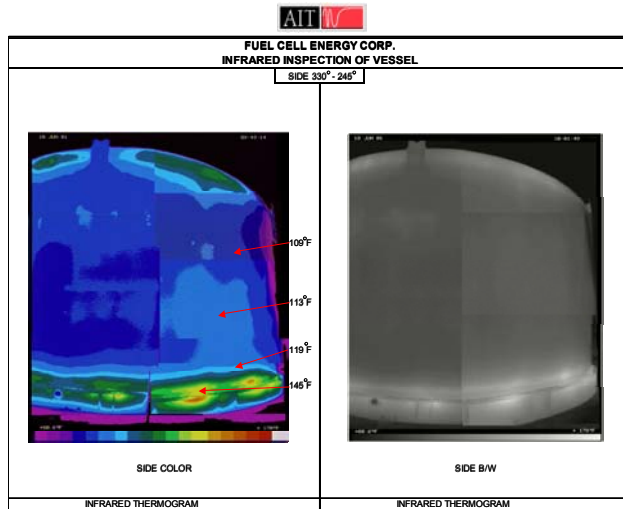
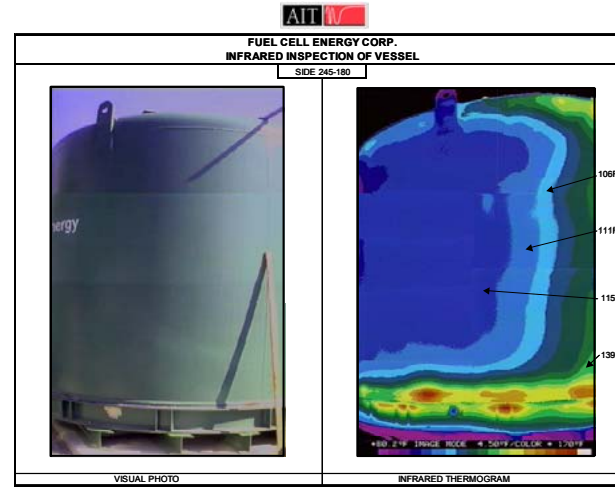
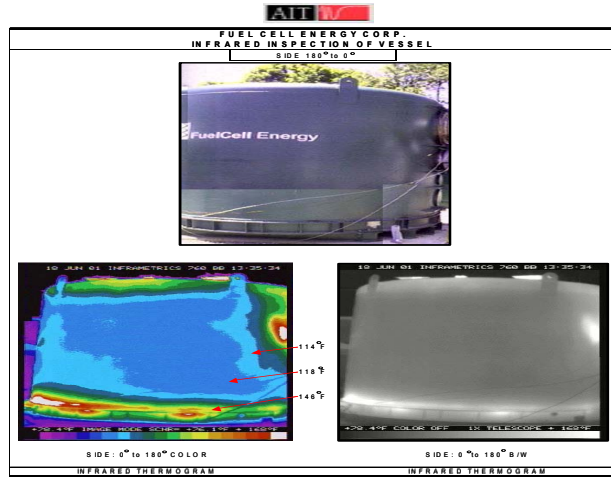


Figure 13. 4-STACK MODULE INFRARED THERMAL MAPPING:  
Vessel Wall Did Not Show Any Hot Sports

## **System Design, Analysis and Verification**

The final design of the 3 MW product has been completed. The detailed design of the 3 MW plant will evolve with component vendor feedback in the construction phase of the prototype. FuelCell Energy also has upgraded the sub-MW power plant design developed by technology partner MTU, for conformance with US codes and regulations.

FCE's participation in the development of fuel cell codes and standards was continued. Draft of IEEE P1547 standard for distributed resources interconnected into electric power systems was revised. Establishment of near and long-term strategic supplier relationships was also continued. Duke/Fluor Daniel and Jacobs Applied Technology have been FuelCell Energy partners for system engineering and packaging, respectively. Discussions are being held for selecting additional organizations for electrical and/or mechanical equipment supply.

## **Field Trials and Other Activities**

Several field trials were started including in US and Europe and are currently ongoing. In addition to the existing strategic alliance partners - Marubeni of Japan and PPL EnergyPlus LLC (PPL), a subsidiary of PPL Corporation - FuelCell Energy entered into market development agreements with CMS Viron Energy Services, Caterpillar Inc., and Chevron Energy Solutions L.P.