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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ABSTRACT

The program efforts are focused on technology and system optimization for cost reduction, commercial design development, and prototype system field trials. The program is designed to advance the carbonate fuel cell technology from full-size field test to the commercial design. FuelCell Energy, Inc. (FCE) is in the later stage of the multiyear program for development and verification of carbonate fuel cell based power plants supported by DOE/NETL with additional funding from DOD/DARPA and the FuelCell Energy team. FCE has scaled up the technology to full-size and developed DFC® stack and balance-of-plant (BOP) equipment technology to meet product requirements, and acquired high rate manufacturing capabilities to reduce cost. FCE has designed submegawatt (DFC300A) and megawatt (DFC1500 and DFC3000) class fuel cell products for commercialization of its DFC® technology. A significant progress was made during the reporting period. The reforming unit design was optimized using a three-dimensional stack simulation model. Thermal and flow uniformities of the oxidant-In flow in the stack module were improved using computational fluid dynamics based flow simulation model. The manufacturing capacity was increased. The submegawatt stack module overall cost was reduced by ~30% on a per kW basis. An integrated deoxidizer-prereformer design was tested successfully at submegawatt scale using fuels simulating digester gas, coal bed methane gas and peak shave (natural) gas.

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1.0 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 has designed submegawatt (DFC300A) and megawatt (DFC1500 and DFC3000) class fuel cell products for commercialization of its DFC® technology. These are standardized, packaged DFC® power plants operating on natural gas or other hydrocarbon-containing fuels. The power plant design also 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. Figure 1 shows key program elements (shaded) and their interrelationships.

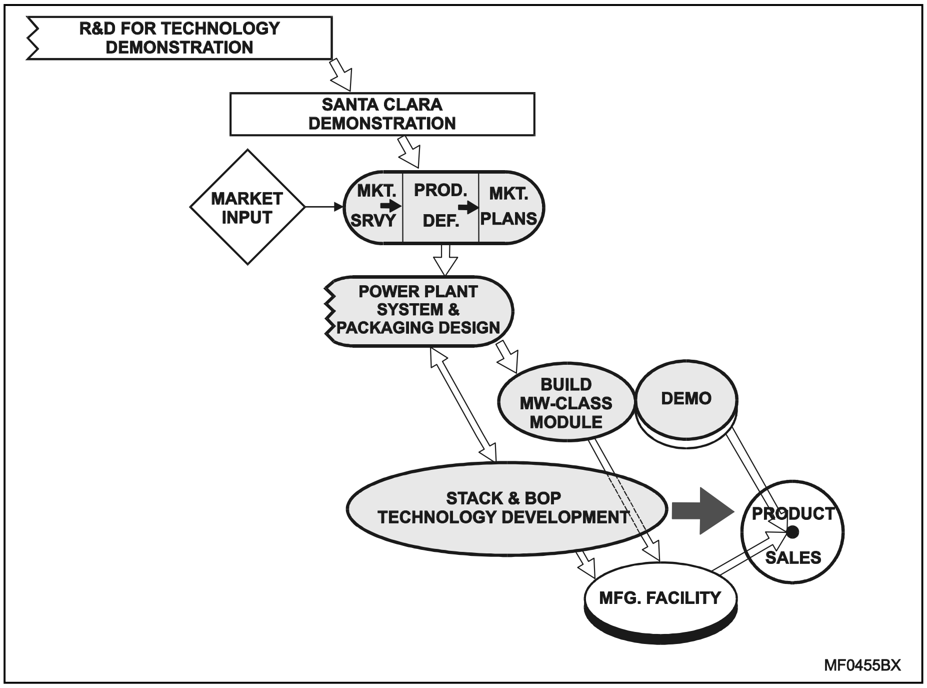


Figure 1. EFFORT AND INTERACTION OF KEY PROJECT ELEMENTS:
The Program Will Result in the Market Entry Commercial Product

2.0 EXECUTIVE SUMMARY

Under the cooperative agreement DE-FC21-95MC31184 with DOE/NET, 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, July through December 2002, as highlighted below.

- Cell and stack designs were refined to improve performance, reduce cost and further enhance performance and endurance capability.
  - The reforming unit (RU) design was optimized using a three-dimensional stack simulation model developed and validated in-house. The average cell voltage, RU methane reforming conversion, and fuel and oxidant utilizations were predicted by the model to within 2% of the measured values. The temperature uniformity of the stack has been improved and further design improvements are being evaluated in stack tests. The improved thermal management of the stack is expected to enable higher power density and/or higher efficiency operations of the power plant products.
  - Thermal and flow uniformities of the Oxidant-In flow in the stack module have been improved using Computational Fluid Dynamics (CFD) based flow simulation models. Location of the Oxidant Inlet piping nozzle was optimized for the full-height Stack FA-100-3 to improve temperature uniformity in the stacking direction. Stack module design modifications guided by the CFD model for the subMW-class product (A300) have shown the expected improvements in test results.
- The full-height Stack FA-100-2 test was voluntarily terminated after 6740h of operation. The stack performance decay over the test period met the expectations and the performance goal. The post-test analysis of the stack hardware and cell packages also confirmed the design life of the components. The next full-height Stack FA-100-3 (built with low-cost bipolar plate design) conditioning and load testing is planned to begin in early 2003.
- The submegawatt stack module overall cost has been reduced by ~30% on a per kW basis from 4th quarter of 2001 to 4th quarter of 2002. The major factors that contributed are the reduction of stack module enclosure cost, lower stack material costs, increase of manufacturing production volume/capacity and further improvements in component manufacturing yields.
- Progress in Balance-of-Plant (BOP) equipment technology improvements was also continued.

- For multi-fuel applications of DFC®, FCE developed an integrated deoxidizer-prereformer design that tested successfully in 400kW facility tests on fuels simulating digester gas, coal bed methane gas and peak shave (natural) gas.

- For liquid fuel applications of DFC®, operation of the integrated deoxidizer-prereformer in the 400kW facility tests was successfully tested using propane fuel.

- FCE evaluated inverters from four different vendors and qualified three vendors to supply inverters for DFC® products.

- Over the past year, FCE has achieved ~40% reduction in DFC300A BOP equipment costs.

3.0 EXPERIMENTAL

The program involves manufacturing process improvements, cell component development, stack design and BOP equipment development. Various tests such as simulated out-of-cell tests (OCT), property characterization tests, button cell, single cell, subscale stack and full-size stack tests were used to support these developments. FCE has five button cell and fourteen single cell test stands, three subscale stack and one full-size stack test facilities. The button cell and single cell test stands are used for active component development. The subscale stack test stations are used for cell design and endurance evaluation. The full-size stack facility is used for stack design, non-repeat hardware design and BOP equipment design. These test tools were used routinely throughout the execution of the program. Further experimental details are provided along with the relevant test results discussed under “Results and Discussions” section of the report.

4.0 RESULTS AND DISCUSSIONS

Progress continued in stack and balance-of-plant (BOP) equipment technology improvement and cost reduction (see Ref. 1 and 2 for previous progress reports). Key program accomplishments during the second half of year 2002 are discussed below.

Technology Improvement

FuelCell Energy Inc. (FCE) is developing fuel cell power plants based on company's Direct Fuel Cell (DFC®) technology. The current program is focused to get the technology ready for commercial products. The specific activities being pursued to achieve this goal include performance improvement, endurance improvement, product engineering and BOP equipment development. Progress achieved in these areas is discussed next.

Anode Performance Improvement: Efforts are underway to further improve the DFC® performance to realize higher power density and/or higher plant electrical 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 modifications to the baseline anode were initiated to increase wettability and surface area. Two modified anodes showed 10-15 mV cell performance improvement in 3 cm^2 labscale cell testing. Bench-scale single cell testing has been planned.

Cathode Performance Improvement: An important factor affecting the performance of the carbonate fuel cell is the oxygen reduction kinetics of the NiO cathode. Material additives to the baseline cathode to enhance the kinetics were evaluated. The selected materials were successfully synthesized. Preliminary tests of the coated cathodes in labscale cells (3 cm^2) showed lower cathode polarization loss (26 mV vs. 40-50 mV for the baseline cathode). Further labscale and bench-scale cell testing is planned to verify the performance benefit.

End Cell Design Improvement: FCE has designed an advanced end cell assembly, which minimizes contact loss and functions as an electrolyte reservoir for long-term operation. The benefits of the advanced end cell assembly, which correspond to 10-fold reduction of contact loss and two-times more retention of electrolyte, have been verified in stack Tests FA-20-7 and FA-15-1. The end cells of FA-15-1 mimic the applications to horizontal stacks (used in DFC300A product), while the end cells of FA-20-7 represent the applications to vertical stacks (used in DFC1500 and DFC3000 products). Figure 2 shows significantly reduced voltage loss of the advanced end cell assembly in recent stacks, compared to that in previous designs which was significantly higher even at the beginning of life (BOL). This advanced design has now been incorporated in submegawatt (DFC300A) and megawatt (DFC1500) stacks.

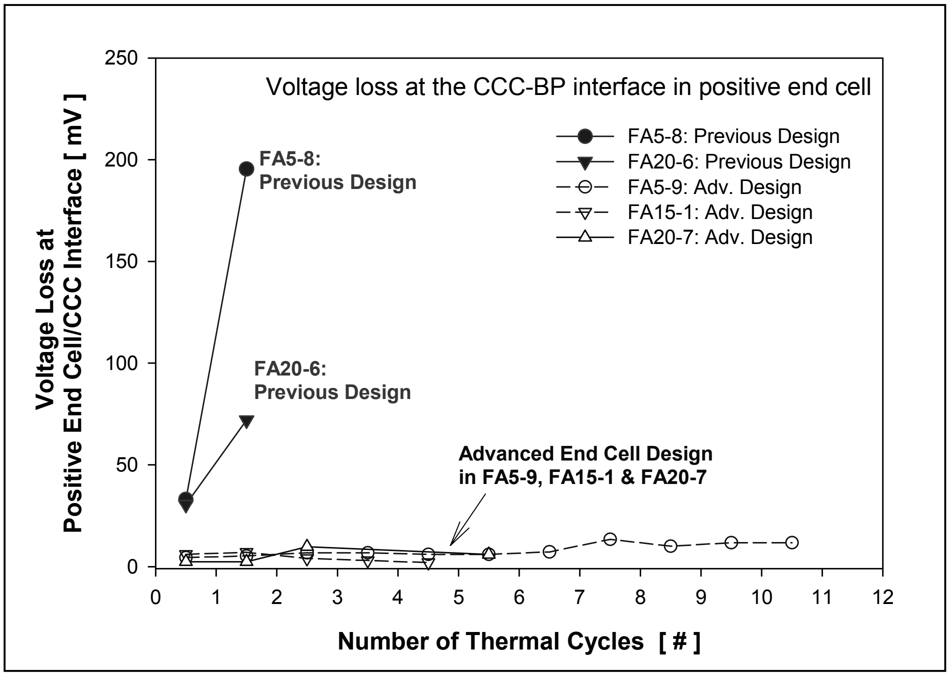


Figure 2. END-CELL VOLTAGE LOSS VS. THERMAL CYCLES:
Advanced End Cell is Very Stable

Temperature Uniformity Improvement by RU Design Optimization: FCE has developed a three-dimensional stack simulation model to improve cell temperature uniformity which is expected to contribute to higher performance and endurance (Ref. 3). The model captures all the essential physics in the fuel cell (fluid flow distribution, pressure drop, conservation of mass and species, conductive and convective heat transfer and chemical and electrochemical reactions). For given inputs of flow, temperature and composition of fuel and oxidant; and stack current (or current density), the model predicts the stack voltage and 3D distributions of temperature and current. The model predicts the temperature, flow and compositional variations of different gas streams (anode, cathode and reforming unit fluid flow) in the stack. Effect of certain design parameters of the reforming unit (RU) could be studied without any additional model changes. The model design and codes were made ready in the first half of 2002; the efforts in second half were focused on the following issues:

- Validation of the model with experimental data
- Simulation of thermal characteristics of different RU designs and optimization

Thermal model was validated using experimental data from subscale (30kW) Stacks FA-20-6 and FA-20-7 using two different RU designs (RU-14 and RU-15, respectively).

The in-plane temperature distribution predicted by the model (shown in Figure 3) closely matches the experimentally measured temperature distribution in the 30-cell full area Stack FA-20-6 (shown in Figure 4). All other variables calculated by the model also matched well with the subscale stack data. The RU-14 stack shows thermal gradients near the fuel inlet and higher methane conversion in the RU. The model was able to accurately predict both characteristics. The maximum and minimum temperatures were predicted within 10C of the experimental data. The locations of the maximum and minimum temperatures were also accurately predicted.

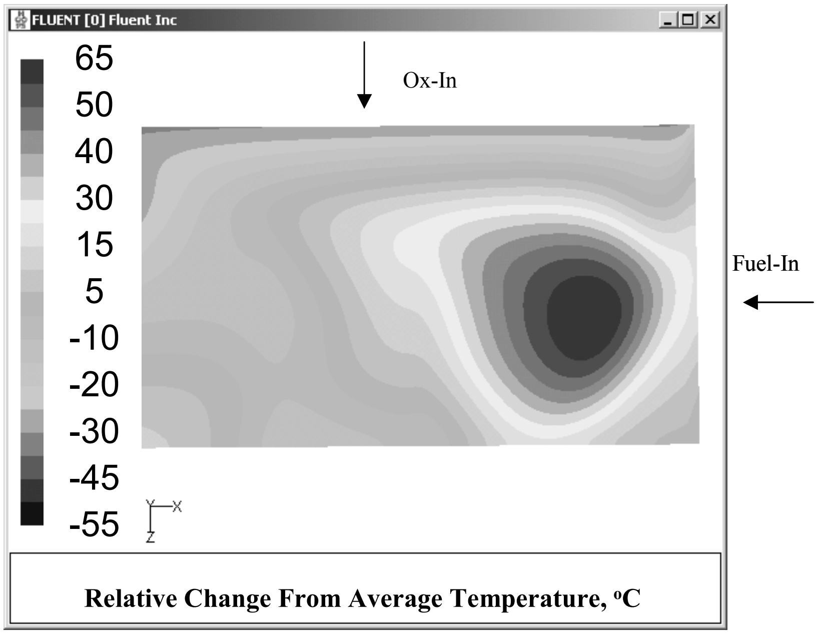


Figure 3. TEMPERATURE DISTRIBUTION PREDICTED BY THERMAL MODEL FOR STACK FA-20-6 (RU-14):
Hot Region Occupies a Small Area of the Cell

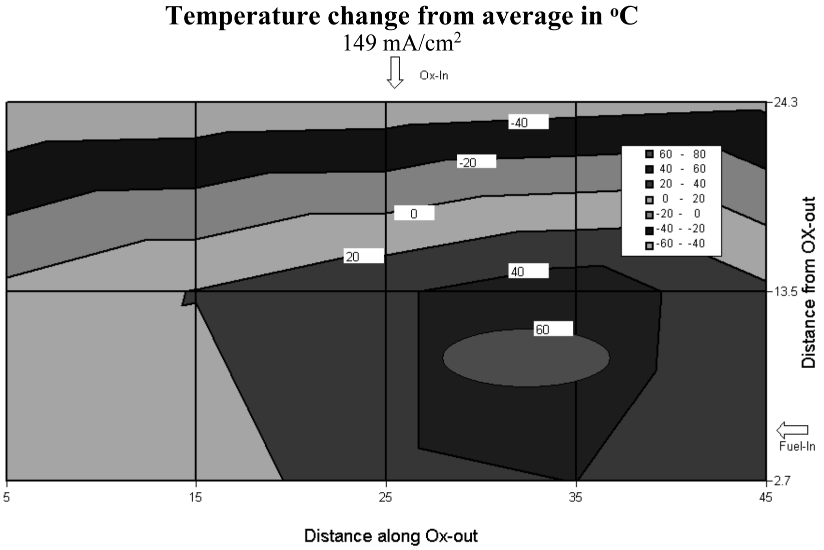


Figure 4. MEASURED TEMPERATURE DISTRIBUTION FOR STACK FA-20-6 (RU-14 DESIGN):
The RU-14 Experimental Thermal Profile Matches Model Prediction Shown in Figure 3.0

The thermal model was then used to predict the temperatures in FA-20-7 (30-cell stack), which had an improved design for the reforming unit (RU-15). The in-plane temperature distribution predicted by the model (shown in Figure 5) was in good agreement with the experimentally measured temperature distribution in Stack FA-20-7 (shown in Figure 6).

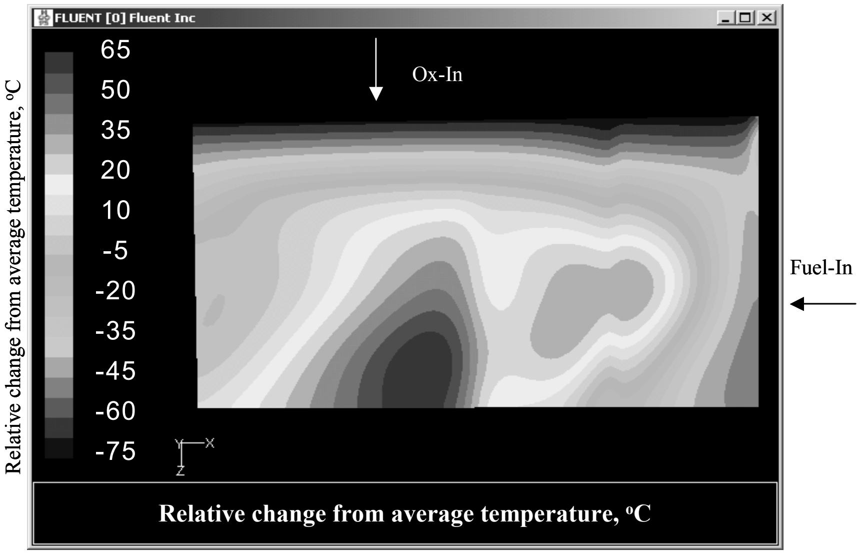


Figure 5. TEMPERATURE DISTRIBUTION PREDICTED BY THERMAL MODEL FOR STACK FA-20-7 (RU-15):
Model Predicts Improved Thermal Profile

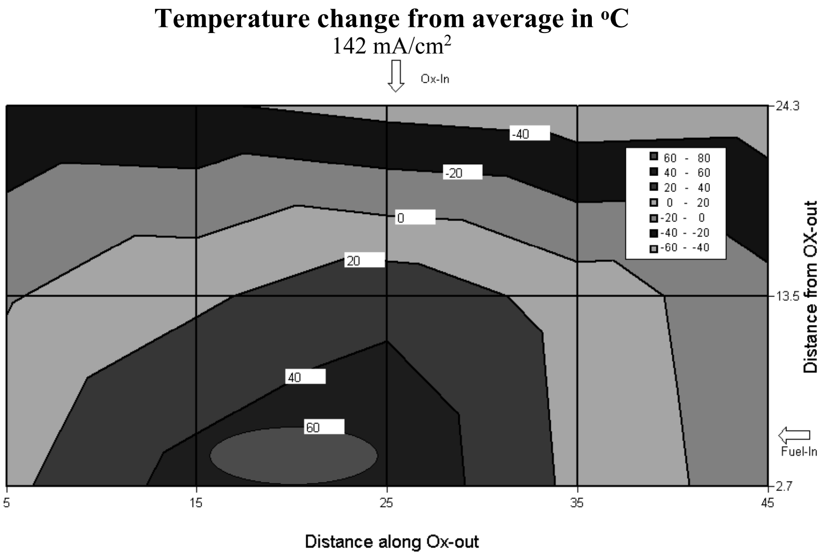


Figure 6. MEASURED TEMPERATURE DISTRIBUTION FOR STACK FA-20-7 (RU-15 DESIGN):
The RU-15 Experimental Results Also Match the Model

The thermal model was able to predict the maximum, minimum and the average stack temperatures within 10°C of the measured values in FA-20-7. Average voltage, conversion in the RU, fuel and oxidant utilizations were predicted within 2% of the measured values. The temperature gradients near the fuel inlet in FA-20-7 (RU-15 design) are smaller than those in FA-20-6 (RU-14 design). The temperature gradually increases from the fuel inlet to the fuel outlet and makes the current density distribution uniform. The thermal model was able to predict these changes with good accuracy.

Following validation of the comprehensive model, various RU design changes were evaluated by the model and the most promising RU-16 design was selected for experimental evaluation in the subscale Stack FA-20-8. The temperature distribution predicted by the thermal model for RU-16 is shown in Figure 7. The model predicts a gradual change in temperature from the fuel inlet to the fuel outlet region. The predicted maximum temperatures and the temperature gradients are also lower than those measured with the RU-15 design (Stack FA-20-7).

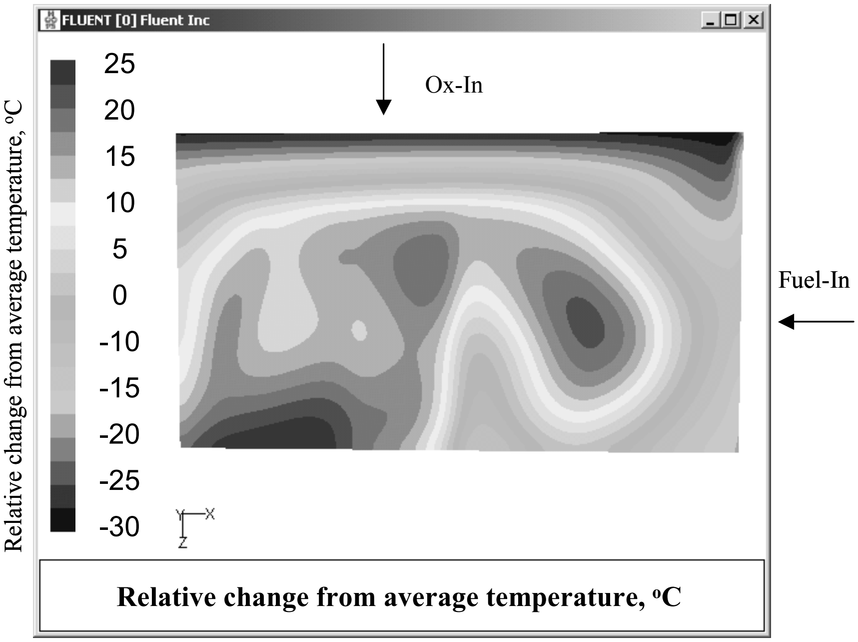


Figure 7. TEMPERATURE DISTRIBUTION PREDICTED BY THERMAL MODEL FOR THE RU-16 DESIGN:
Uniform Temperature Profile Predicted for RU-16

DFC® Design Improvement by Computational Fluid Dynamics Modeling: Analysis and modeling tools such as Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) have been used for fuel cell stack and system development (Ref. 3). Stack flow modeling activities were performed to guide the design improvement of the fuel cell component, module performance, and system operation. A few examples of design improvements identified by using the CFD tool are: 1) designed bipolar plate flow baffles to reduce oxidant gas flow bypassing (not utilized in cell electrochemical reaction) through cathode wet-seal area of cell; 2) optimum location of oxidant inlet piping nozzle for full-height Stack FA-100-3 to improve temperature uniformity in the stacking direction; 3) designed oxidant inlet nozzle configuration in MW-class fuel cell module design (M10) to reduce vertical temperature gradient inside the module.

Analysis of MW-class stack module oxidant gas flow and temperature distribution has been carried out using a CFD model. The model calculates the flow and thermal aspects of the current stack module design and investigates their impact on stack operation. The model predicted fairly uniform temperature profile inside the M10-1 module, and no major issue with the current design has been discovered by the model. The model simulated temperature field is shown in Figure 8.

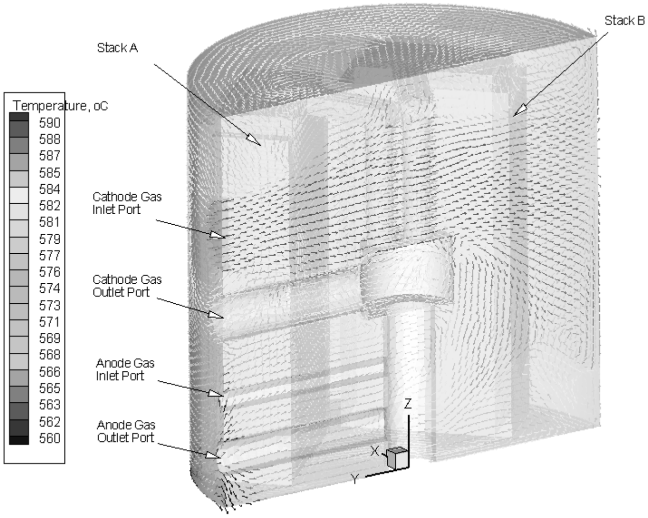


Figure 8. COMPUTATIONAL FLUID DYNAMICS SIMULATION OF THE MEGAWATT FUEL CELL STACK MODULE M10 (4-STACK):
Model Identifies the High Temperature Areas

The computations for M10-1 megawatt module have indicated that M10 Oxidant In nozzle configuration helps reduce vertical temperature gradient as oxidant gas enters near top section of the stack vessel, and prevents hot gas buildup in the top section of the vessel. The temperature gradient along the stack predicted by the CFD model was less than 10°C. The CFD model also predicted that the stack-to-stack variation of oxidant flow is small, and the results were confirmed by a cold test. Actual (hot) test results will be available in first quarter of 2003 for further verification.

CFD analysis of submegawatt stack module has been applied to simulate the oxidant flow distribution as shown in Figure 9. The study guided the design modifications. The initial A300 design showed relatively higher cathode inlet temperature gradient, and low negative end cell temperature and performance. The factors affecting the A300 flow and temperature distributions have been identified. Corrections have been implemented for improving the flow and heat transfer based on the CFD model results. Test results have confirmed the expected improvement.

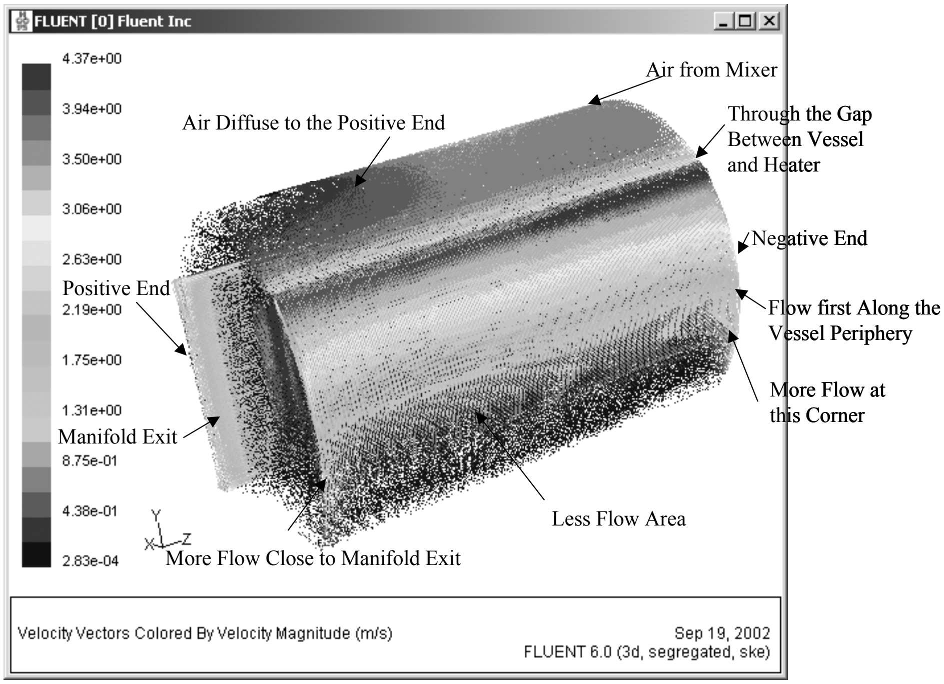


Figure 9. COMPUTATIONAL FLUID DYNAMICS SIMULATION OF THE SUBMEGAWATT STACK MODULE:
The CFD Model Identifies the High Flow Areas

Endurance Improvement

FCE is currently developing dense, conductive coatings for protection of the bipolar plate and cathode current collector from corrosion. It is known that internal cell resistance develops due to the oxide scale that forms on these stainless steel components during operation. The presence of these dense coatings inhibits oxide formation. Out-of-cell testing for coated components has shown that contact resistance can be decreased by 50% compared to the baseline uncoated material. An added benefit of the dense, conductive coating is a significant reduction in electrolyte creepage loss. "Creepage" is the absorption of electrolyte on the surface and within the oxide scale that forms during corrosion. This benefit has been documented with single cell post-test analyses. Figure 10 shows the reduction of total surface creepage for coated cathode current collector hardware. Such a dramatic reduction in electrolyte loss can increase the life expectancy of a stack by at least 2 years. One of the challenges is to develop a process for coating full size hardware. A labscale process has been developed. Full-size coated cathode current collectors were incorporated in Stack FA-20-8. Preliminary results are showing the cells with the coated hardware have the lowest internal resistance compared to the uncoated cells within the stack. Long-term evaluation of these coatings is planned. In addition coating optimization and process scale-up activities are in progress.

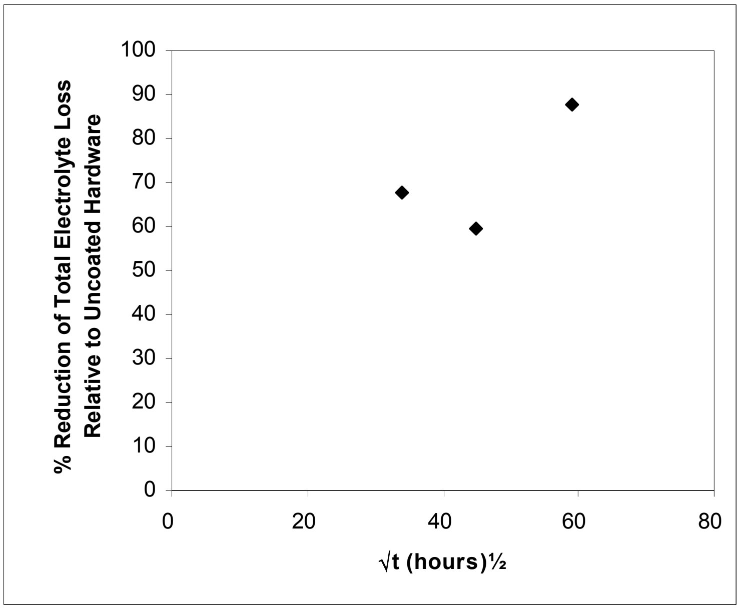


Figure 10. ELECTROLYTE SURFACE CREEPAGE:
Protected Cathode Current Collector Reduces Electrolyte Loss to Hardware by ~10 Times

Manufacturing Process Improvement

The manufacturing facility in Torrington continued to increase production volume through increased utilization of equipment, qualifying of new equipment, and training of new and existing employees. 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 is being commissioned 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 components. A matrix inspection station was received.

Electrolyte production system improvements were initiated. A grinder has been ordered that will eliminate the requirement for two separate grinding operations. The specifications for a new cathode sintering furnace capable of sintering at three times the current rate were prepared. Furnace vendor evaluation is nearly complete. 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. Cathode electrolyte filling process yield has been increased to ~90%.

Bipolar plate wet-seal attachment process development 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 system is in place and currently gathering data on defect characteristics to help automation. Alternate wet-seal attachment processes are currently under evaluation.

The cathode CCC accumulating conveyor passed functional pre-shipment acceptance test. Cathode-CCC cleaning equipment was identified and vendor quote was received. Degreasing of the die-cut bipolar plates has been successfully tested using an environment-friendly cleaning method, which will eliminate the need to ship the parts to a degreasing vendor.

All repeating component production teams continue to work on Kanban (simple production control strategy) implementation. Improved work instructions with defined operator competency levels are being created. A prototype reformer unit (RU) assembly assist workstation has been installed and is being tested for functional improvements.

An improved manifold compression fixture has been designed and ordered. Alignment tooling for A-300 style stack components (i.e. end plate, bellows, compression plate) has been designed. In 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 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 also ready. During the reporting period, the Torrington factory produced the full-size Stack FA-100-3, submegawatt-class stack modules and a MW-class stack module.

The MW-class stack conditioning facility was made fully operational. A photograph of the facility is shown in Figure 11. The MW-class stack module (M10-1) is also ready for conditioning which is expected to start in early 2003.

Figure 11. MEGAWATT TESTING AND CONDITONING FACILITY:
Fully Ready for Conditioning and Testing

Stack Test Activities

Stack test activities included completion of full-height Stack FA-100-2 test including the post-test examination, and several subscale stack tests.

Full-Height Stack Tests: Stack FA-100-2 test was voluntarily terminated for post-test examination after 6,740h of operation. 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. No measurable degradation of prereformer catalyst (with operation on H_2-free fuel feed) was observed. Post-test analysis of the stack hardware and cell packages also confirmed the design life of the components. The next full-height Stack FA-100-3 has been assembled with low-cost bipolar plates. A photograph of this stack is shown in Figure 12.

The 400 kW-class facility has been modified in preparation of Stack FA-100-3 test in conjunction with a microturbine. The modifications included incorporation of a new low temperature difference humihex and a new compact fuel superheater. These changes are expected to enable system for higher efficiency operation as more high temperature heat is recovered. The Foxboro Distributed Control System for the 400 kW facility was also upgraded. The new system is expected to offer many advantages over the previous system: 1) order of magnitude increase in speed of process control and data acquisition, 2) simplified access to data and analysis of data, 3) room to configure more automated control schemes, and 4) possibility of remote monitoring and operation of plant from home computer. Facility hot test has been completed. The stack conditioning procedure was modified and improved while performing the conditioning simulation. Stack FA-100-3 conditioning is expected to start in early 2003.

Figure 12. PHOTOGRAPH OF STACK FA-100-3:
Assembled with Low-Cost Bipolar Plates

Subscale Stack Tests: Three technology stacks were tested during the reporting period. The stacks and research objectives are summarized in Table 1. The major issues investigated were the improvement of manifold sealing efficiency and the optimization of thermal management. An innovative compliant manifold seal was evaluated in Stacks FA-20-7 and FA-15-1. The results showed about 60% improvement in seal efficiency. The improved manifold seal has also remained stable (6,000h so far). Optimization of RU design continued with Stacks FA-20-7, FA-15-1 and FA-20-8. Compared to the previous stacks, Stacks FA-20-7 and FA-15-1 with RU-15 design showed reduced thermal gradient and improved performance. New RU design (RU-16) is being tested in Stack FA-20-8. The results have been discussed earlier in the report.

Recent stacks also showed promising results of performance stability. The normalized performance decay of Stack FA-20-7 and FA-20-8 has been significantly reduced compared to previous stacks (Stack FA-20-5). The decay rate of these stacks is less than 0.2 mV/1,000 hrs. Longer term performance stability will be studied in Stack FA-20-7.

Table 1. SUMMARY OF MAJOR DESIGN FEATURES AND ACHIEVEMENTS OF SUBSCALE STACKS TESTED DURING 2nd HALF OF 2002:

Stack Type	Stack	Research Focus	Major Achievement
22-cell stack	FA-15-1	• Reduction of manifold and wet seal leakage • Improved thermal management • Reduced performance decay	• 45% improvement of seal efficiency • Reduction of performance decay (<0.2 mV/1000 hrs)
30-cell stack	FA-20-7	• Improved thermal management • Improved performance stability • Reduction of manifold and wet seal leakage • Improvement of long-term stability (Endurance)	• Improved thermal management • Reduction of performance decay (negligible performance decay for 5,000h)
30-cell stack	FA-20-8	• Reduction of manifold and wet seal leakage • Improved thermal managements • Improved performance stability with coated cathode current collector	• 60% improvement of seal efficiency • Low and stable internal resistance of cells with coated cathode current collector

BOP Equipment Development

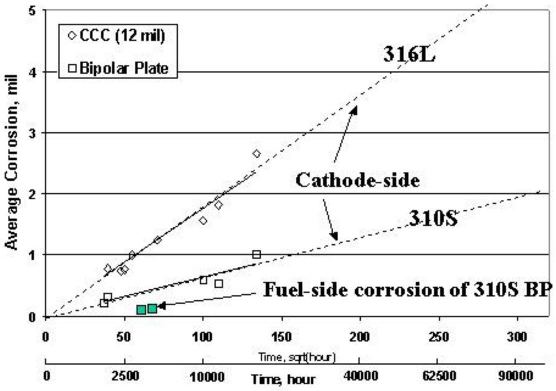
For multi-fuel applications of DFC®, FuelCell Energy has developed an integrated deoxidizer-prereformer design that can remove any oxygen present in fuels such as digester gas, coal bed methane gas, peak shave (natural) gas, etc. The integrated deoxidizer-prereformer unit design was tested during the 400 kW facility hot test using simulations of these fuels. Digester gas simulations contained 0.3-1.3% O_2, whereas peak shave gas simulations contained 1-5% O_2. The deoxidizer was found to remove oxygen from these fuel feeds at temperatures as low as ~300°C.

For liquid fuel applications of DFC®, propane reforming tests were also performed during the 400 kW facility hot test. Pure propane (for low propylene content) was fed through the integrated deoxidizer-prereformer to test effectiveness in converting propane to methane and hydrogen. It was found that even at low prereformer inlet temperature of about 300°C, the exiting gas had propane concentration of less than 0.4% and H_2 concentration in the acceptable range. Higher prereformer inlet temperatures lead to exit concentrations lower in propane and methane, and higher in hydrogen and carbon dioxide. The optimal prereformer inlet temperature was identified. An alternate inverter capable of grid-independent operation was evaluated in the 400 kW-class power plant. The inverter worked well in grid-connect mode. Tests to transfer the plant operation from grid-connected to grid-independent mode were successfully completed. Another inverter from a different vendor, designed for operation in grid-connect mode only, was also installed and operated successfully in grid-connect mode. 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.

FCE has identified a 3-way valve, for BOP applications, that offers advantages of low cost, better packaging, and better metering control for bypass lines. It is ideal for bypass lines where some leak-by is acceptable. This 3-way recuperator bypass valve has been received, bench tested and installed in the 400 kW facility for evaluation in conjunction with Stack FA-100-3 and DFC/T test.

Cost Reduction

Stack Material Cost Reduction: The DFC® stack baseline bipolar plate uses corrosion-protected stainless steel. The vendor specially manufactures this material. Because of the corrosion protection processing need, the cost of the bipolar plate is significantly higher than the material components cost. The corrosion protection material seems to also affect the stainless steel physical properties (density and coefficient of thermal expansion during operation). FCE has devised a cell design using an alternative material that can reduce the cost by >80% and also slow the process that causes the change in physical property by >5 times. The alternate design has been evaluated in numerous single cells and two subscale stacks for its impact on corrosion, contact resistance, DIR catalyst activity, and physical property changes. The corrosion resistance has been found similar to the baseline design (Figure 13). Each stack with this new bipolar plate material was operated for >6,000h, showing no effect on contact resistance. Also, no impact on DIR catalyst activity was observed. The new material has also shown favorable impact on stability of physical properties. Based on these test results, the low-cost alternate design has been incorporated in the full-size Stack FA-100-3 test and recommended for FCE's product stacks. The product stacks which will be produced in mid-2003 will incorporate this new material and the cost reduction brought in by this new design will be reflected in stack cost at that time.



Negligible corrosion of 310S BP in the absence of creeping electrolyte

Figure 13. ALTERNATE BIPOLAR PLATE HAS VERY LOW FUEL-SIDE CORROSION AND NORMAL CATHODE-SIDE CORROSION:

Stack Module Cost Reduction: The submegawatt stack module overall cost has been reduced by ~30% on a per kW basis from 4Q01 to 4Q02. This cost reduction has been achieved from parallel efforts in several fronts. The stack module enclosure cost has been reduced by 20% by developing an alternate domestic vendor. The stack cost has also been reduced by 30%. The stack cost reduction included: (1) material cost reduction, learning curve (direct labor reduction), and components yield increase. A modest 10% reduction of stack materials purchase price has been achieved. Learning experience has resulted in significant reduction in the labor component of stack manufacturing. The steepest learning curve benefits have been achieved in the stack final assembly area. In fact, the final stack assembly labor has been reduced to one-third from first to the twelfth unit. Cost reduction has also been achieved through increasing stack component manufacturing yields. Cathode manufacturing yield has been increased from 62% to 80% primarily by implementing a faster sinter process. Matrix yield has been improved 50 to 75% by optimizing the tape casting process parameters. Bipolar plate yield has been increased from 85% to 90% by improving the welding parameters. Efforts to improve the yields further by process parameters are continuing. FCE products use a common full-size stack. Therefore, the cost reductions achieved with the submegawatt stacks directly reflect into the megawatt-class power plant stack costs.

BOP Equipment Cost Reduction: FuelCell Energy, Inc. (FCE) has developed submegawatt (DFC300A) and megawatt size (DFC1000 and DFC1500) carbonate fuel cell power plants for distributed power generation based on its Direct Fuel Cell™ (DFC) technology. Power rating for market entry units is 250 kW for the DFC300A, 1 MW for DFC1000 and 2 MW for the DFC1500 models. The normalized BOP equipment costs ($/kW) of these units depend on the power ratings. A comparison of the current BOP equipment cost (4Q02) for these models is presented in Figure 14. As expected, the BOP equipment cost for the larger size plant is significantly lower on per kilowatt output basis. It is also apparent that over the past year FCE has achieved a ~40% cost reduction of DFC300A BOP equipment as a result of multi-pronged efforts. These cost reduction tasks in place are: (1) develop alternate vendors for key equipments, (2) directly purchase the key equipment and drop ship them to the packager eliminating the middleman's markup, (3) develop alternate power plant packagers, and (4) value engineer the baseline design for smaller size and cost.

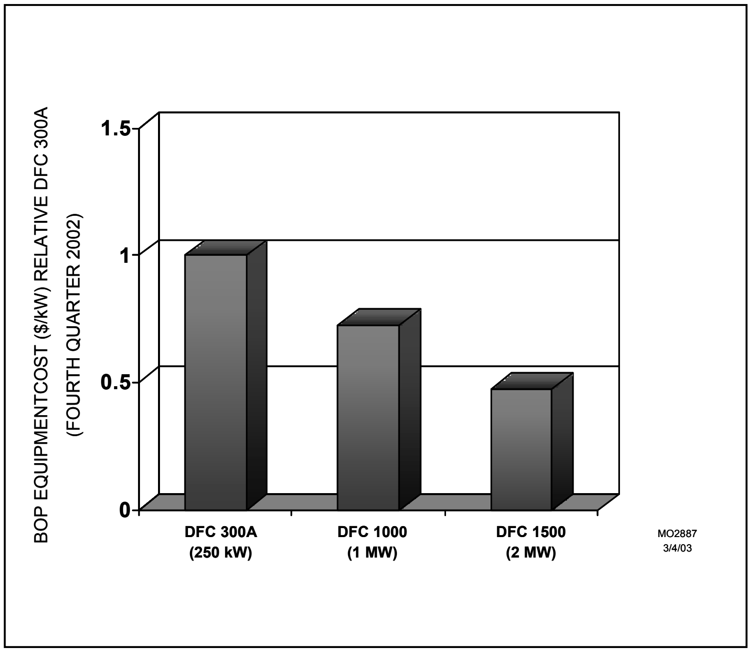


Figure 14. COST COMPARISON OF DIFFERENT SIZE PRODUCTS ($/kW):
MW-class BOP Cost is Significantly Lower on Per Kilowatt Basis

FCE has already evaluated and qualified three power-conditioning vendors for processing fuel cell DC power to grid quality AC power. FCE has received notice from the California Energy Commission (CEC) that its DFC300A Direct Fuel Cell® power plant has been certified for grid interconnection under California's "Rule 21" standard. The standard is a collaborative effort of CEC and California's three largest investor-owned utilities that specifies interconnection, operating and metering requirements for distributed electric power generators such as fuel cells.

FCE initially selected a packager in 2001 for fabrication and assembly of the initial batch of submegawatt power plants. The packager was also responsible for the purchase of the major equipment. The initial six units were purchased as per this approach. Using the lessons learned as well as by directly purchasing the major equipments such as the power-conditioning block, humidifying heat exchanger, air blower; FCE has been successful in reducing the BOP equipment cost by more than one-third (Figure 15).

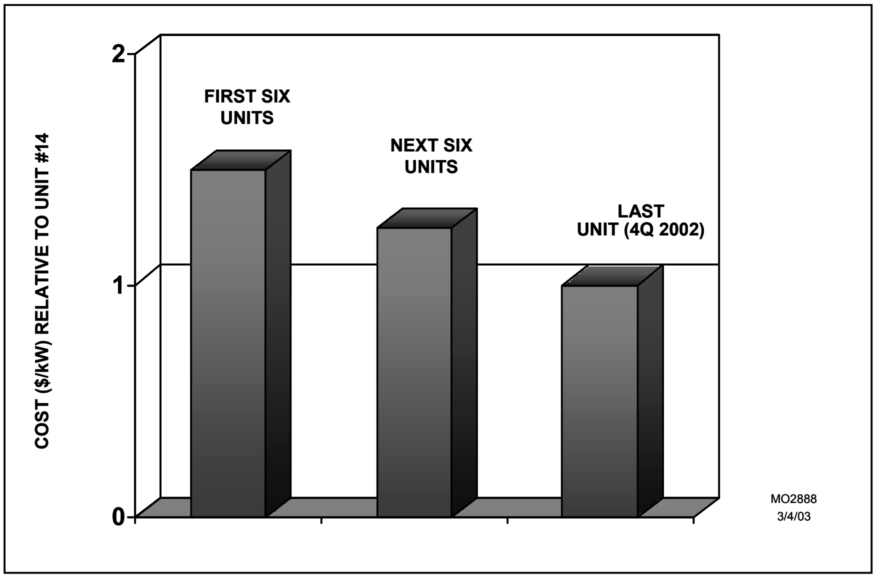


Figure 15. DFC300A COST REDUCTION ACHIEVED:
DFC300A Product Cost Has Been Reduced by ~40%

As means for further cost reductions, FCE has also selected two additional equipment packagers of the BOP equipment. Each alternate vendor has received a plant order from FCE for qualification of their fabrication skills. FCE believes, once the alternate fabricators are ready, the power plant production cost could be reduced further.

In the beginning of the year, FCE engaged a third party consultant and conducted a one-week workshop of design, engineering and operation teams to generate submegawatt product value engineering concepts. Also, as part of this effort an engineering company was contracted to implement the improvement concepts and develop the design for a smaller size and lower cost product. The final design has been completed and the prototype construction efforts have been initiated. FCE expects that this effort will lead to another one-third reduction of the BOP equipment costs in 2003.

5.0 CONCLUSION

The current program has met its planned major milestones to date. Under this program, FCE has scaled up the technology to full size and developed DFC® stack and balance of plant (BOP) equipment technology to meet product requirements, and acquired high rate manufacturing capabilities to reduce cost. FCE has designed submegawatt (DFC300A) and megawatt (DFC1500 and DFC3000) class fuel cell products and started several field trials of the submegawatt product design in Europe and the US. Accomplishments to date include over 70,000h of combined operational experience on 250 kW nominal rating plants, 47% electrical efficiency, and over 80% efficiency in cogeneration application. FCE has also developed 50 MW per year manufacturing capability to allow commercial product launch. Additional field trials of DFC products are planned in Europe, US, and Asia for 2003. Product cost reduction efforts have already results in ~30% reduction of stack module and another ~40% BOP equipment cost over the part twelve month period.

Major activities remaining to be completed include: (1) further reduction of manufacturing cost by performance improvement and materials cost reduction, (2) BOP equipment cost reduction, and (3) incorporation of improvements/changes in next set of units based on field trial results.

6.0 REFERENCES

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