MOLTEN CARBONATE FUEL CELL PRODUCT DESIGN IMPROVEMENT

**TECHNICAL PROGRESS REPORT FOR BUDGET PERIOD
DECEMBER 21, 1997 TO DECEMBER 20, 1998**

Report No. 4

**CONTRACT NO.
DE-FC21-95MC31184
(Includes funds provided under DOE/DARPA Agreement)**

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ACKNOWLEDGMENT

The activities reported here were sponsored by DOE/METC and DOD/DARPA and cost-shared by the Energy Research Corporation (ERC) team. The key ERC team members include: ERC's Advanced Technology Group and Fuel Cell Group, Fluor-Daniel, Jacobs Applied Technology, and Fuel Cell Commercialization Group. Numerous employees of ERC and these organizations have contributed to this project. The role of each of the organizations and its principal project leader are: **ERC Advanced Technology Group** - R&D arm coordinating the effort under all program areas, **ERC Fuel Cell Group**, Danbury, CT - for product definition oversight and overall plant construction management and customer service, **ERC Fuel Cell Group**, Torrington, CT - responsible for manufacturing process development and stack module fabrication (C. Bentley), **Fluor Daniel, Inc. (FDI)**, Irvine, CA - assisting ERC Fuel Cell Group, Danbury in power plant design (B. Fugard), **Jacobs Applied Technology (JAT)**, Orangeburg, SC - consulting in assembly and packaging of fuel cell stack and balance-of-plant (BOP) modules (H. Rast).

Energy Research Corporation, 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 P. Voyentzie, T. Leo, A. Kush, L. Christner, G. Carlson, and C. Yuh. Numerous ERC engineers contributed to this report.

Interactions and guidance of DOE/METC Technical Representative Thomas George and R. Rosenfeld of DOD/DARPA are acknowledged.

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ABSTRACT

Drawing on the manufacture, field test, and post-test experience of the sixteen Santa Clara Demonstration Project (SCDP) stacks, ERC is finalizing the next generation commercial entry product design. The second generation cells are 50% larger in area, 40% lighter on equal geometric area basis, and 30% thinner than the earlier design. These improvements have resulted in doubling of the full-height stack power. A low-cost and high-strength matrix has also been developed for improving product ruggedness. The low-cost advanced cell design incorporating these improvements has been refined through six short stack tests. Power production per cell of two times the SCDP maximum power operation, over ten thermal cycles, and overall operating flexibility with respect to load and thermal changes have been demonstrated in these short stack tests. An internally insulated stack enclosure has been designed and fabricated to eliminate the need for an inert gas environment during operation.

ERC has acquired the capability for testing 400kW full-height direct fuel cell (DFC) stack and balance-of-plant equipment. With the readiness of the power plant test facility, the cell package design, and the stack module, full-height stack testing has begun. The first full-height stack incorporating the post-SCDP second generation design was completed. The stack reached a power level of 253 kW, setting a world record for the highest power production from the advanced fuel cell system. Excellent performance uniformity at this power level affirmed manufacturing reproducibility of the components at the factory. This unoptimized small size test has achieved pipeline natural gas to DC electricity conversion efficiency of 47% (based on lower heating value - LHV) including the parasitic power consumed by the BOP equipment; that should translate to more than 50% efficiency in commercial operation, before employing cogeneration. The power plant system also operated smoothly. With the success of this test confirming the full-height stack basic design and with the completion of SCDP stacks post-test feedback, manufacture of the full-height stack representing the commercial prototype design has been completed and system demonstration is planned to start in the first quarter of 1999.

These developments as well as manufacturing advances are discussed in this report.

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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. ERC has been engaged in the development of this unique technology, focusing on the development of the Direct Fuel Cell [1 to 6]. 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, ERC has selected the Indirect Internal Reforming (IIR) - Direct Internal Reforming (DIR) combination as its baseline design. The IIR-DIR combination allows reforming control (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.

ERC plans to offer commercial DFC power plants in various sizes, focusing on the submegawatt as well as the MW-scale units. The plan is to offer standardized, packaged submegawatt as well as MW-class DFC power plants operating on natural gas or other hydrocarbon-containing fuels for commercial sale by the year 2001. The power plant design will include a diesel fuel processing option to allow dual 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. After gaining experience from the early power plants and as the technology matures, ERC expects to introduce mature commercial power plants operating on natural gas and/or other fuels (including biogas) in the early part of the 21st century.

ERC 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, ERC 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.

OBJECTIVES AND APPROACH

The ERC PDI program is designed to advance the carbonate fuel cell technology from the current full-size 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 multifuel, 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 issues, and design, build and field test a modular prototype power plant to demonstrate readiness for commercial entry.

A seven-task program dedicated to attaining the objectives in the areas noted above, was initiated in December 1994. Program accomplishments of the past year are highlighted in this report.

PROJECT DESCRIPTION

ERC is currently in the third budget period of the multiyear program for development and demonstration of a MW-class power plant supported by DOE/FETC with additional funding from DOD/DARPA and the ERC Team. Figure 1 shows key program elements (shaded) and their interrelationships. The product definition and specification have been derived with input from potential users, including the Fuel Cell Commercialization Group (FCCG). 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 planned. Based on the experience and data generated in the current program, ERC also plans to acquire manufacturing capability for market-entry products through expansion of the existing Torrington production facility.

RESULTS/ACCOMPLISHMENTS

In the past year, the ERC team has made steady progress in resolving technology issues, enhancing manufacturing capabilities and preparing for system design, analysis and system verification. Major accomplishments in each of these areas are discussed below:

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Figure 1. EFFORT AND INTERACTION OF KEY PROJECT ELEMENTS:
The program will result in the market entry, commercial product design.

Technology Improvement

Post-test examination of the sixteen first generation full-height stacks tested at the 1.8 MW Santa Clara power plant was completed. The stack design improvement opportunities identified from these analyses are: 1) uniformly compliant cell, 2) higher mechanical strength matrix, 3) dielectric isolation robustness, and 4) corrosion resistance of some of the stack hardware materials. Commercial cell and stack designs have been defined implementing this invaluable field experience. The new generation cells are uniformly compliant and use one-piece cell components. The cell weight is ~40% lighter than the first generation design on equal geometric area basis. A five-fold increase in the matrix mechanical strength has been achieved. Performance of this new matrix has been verified in accelerated thermal cycle tests. A lab-scale cell has been thermal cycled one hundred times indicating no effects of thermal cycling on performance (Figure 2). The pipe and manifold dielectric isolation designs have been refined to improve robustness. Furthermore, a ten-fold improvement in the electrical isolation strength has been achieved by a material change.

With these accomplishments, the design goals for the commercial entry product were attained. A verification test in a 10-cell stack has been initiated. The cells used in the stack represent the first ten cells built as per the commercial entry product design. The stack test has completed over 5,500 hours at the time of writing this report and has an excellent performance decay of only <0.25% per 1000h (Figure 3) meeting the mature commercial product goal.

In parallel with the cell design, the building block full-size stack design for the commercial entry product has been finalized. This stack is comprised of 340 commercial design cells, the advanced matrices discussed earlier and thirty-four reformer plates. The corrosion strength of the key stack materials are reported in Figure 4. Stack materials are designed to last for five years.

Figure 2. EFFECT OF THERMAL CYCLING ON CELL VOLTAGE:
Excellent stability even after one hundred thermal cycles.

Figure 3. STACK FA-5-6 LIFEGRAPH:
Achieved performance stability in subscale stack consistent with commercial stability goal.

Figure 4. STACK MATERIALS STABILITY WITH RESPECT TO GOAL:
Present design meets five-year life goal.

The full-size stack representing the commercial entry product design is currently in final assembly and the test start in early 1999 is planned. However, to get early design feedback, a full-size stack incorporating almost 90% of the entry product design features was assembled and tested comprehensively for 3,000 hours. Figure 5 shows the stack being truck-transported from the Torrington manufacturing facility to ERC for testing. The stack design features and test objectives are described in Table 1. This stack test began on March 16, 1998 at Danbury and produced clean, quiet and efficient electric power for over five months. The stack reached a power level of 253 kW, setting a world record for the highest power production from the advanced fuel cell system. An excellent performance uniformity at this power level (Figure 6) affirmed manufacturing reproducibility of the components at the factory (located in Torrington, CT). On-load cell performance variation of less than $\pm 1.5\%$ from the stack average and the stack open circuit voltage variation of $\pm 0.2\%$ were observed. The test was conducted in ERC's simplified system mode. This unoptimized small size test has achieved a pipeline natural gas to DC electricity conversion efficiency of 47% (LHV) including the parasitic power consumed by the BOP equipment; that should translate to more than 50% in commercial operation, before employing cogeneration. This level of efficiency is well above all conventional means of producing electricity, and well above that of low temperature fuel cells.

Table 1. FIRST FULL-HEIGHT STACK (FA-100-HS) FEATURES:
Intended for early design feedback for 1999 building block stack test.

■ 326 Cells, 9000 cm² Cell Area (nominal); One Reformer per Ten Cells■ Cell and Stack Incorporated ~90% of the Entry Product Design Features■ Used Internally Insulated Round Container■ Purpose: - Power Plant Test Facility Verification- Tall Stack Thermal/Mechanical Characteristics- Assembly Procedures- Provide Input for Commercial Entry Product Building Block Test

Figure 5. FULL-HEIGHT STACK BEING TRUCK-TRANSPORTED:
Commercial design stack in an internally insulated container.

Figure 6. STACK FA-100-HS PERFORMANCE:

Performance uniformity within $\pm 1.5\%$ of average was achieved at 253 kW operation.

As planned, Stack FA-100-HS full-size test was terminated on July 24, 1998 for post-test analysis after completing more than 3,000 hours of operation including 2,000 hours at greater than the rated 200 kW load. The unit produced >470 MWh of electricity from pipeline natural gas. The stack has met all, in fact, in most cases exceeded the goals for the test. The test sequence included thermal cycles, many planned and unplanned plant trips, very fast load ramps, other normal operating events as well as simulated stress conditions such as an uncontrolled thermal cycle, an oxidizer trip and an emergency plant trip with no deliberate action taken for five hours. In one test, the rated full load was achieved from the standby operation in twelve minutes. This fast load response attribute is expected to qualify the DFC product for use as a power peaker by the utility industry. In another test, an emergency fuel loss was simulated verifying that the DFC stack can be maintained in the field very cost-effectively in the event of fuel supply or power grid failures without deleterious effects on the performance. The full-size stack indicated excellent robustness to the test events showing <0.4% decay per 1000 h over the entire test period (Figure 7). This successful test validated the basic direct fuel cell commercial design for the prototype product test to follow.

Building on the validation of the basic full-size stack design in the FA-100-HS test, another full-size stack-design-confirmatory test (FA-100-1) has been planned. The FA-100-HS test identified a few opportunities for further improvements and these have been incorporated in the Stack FA-100-1. These improved features include: 1) automated DIR catalyst loading for fuel flow uniformity and cost reduction, 2) lower stack compression pressure for reduction of height shrinkage, 3) lower cost matrix, and 4) specially designed manifolds for improved performance and manufacturing simplicity. Stack FA-100-1 has been assembled and compressed and manifolding is in progress. A six-month system demonstration is planned to start in the first quarter of 1999.

An end plate was developed to integrate the functions of the stack compression hardware, stack end plate, and oxidant side pipe dielectric. This specially engineered component significantly simplified the packaging of four stacks within the truck-transportable circular

Figure 7. STACK FA-100-HS VOLTAGE HISTORY PLOT:
Total performance decay was only ~1% after 3,000 hours of comprehensive testing.

module enclosure. The SCDP stacks post-test results also catalyzed a unique manifold dielectric isolation design to improve electrical isolation robustness.

The 10 kW-class stack test facility has been used almost continuously over the past year for testing three 10-cell short stacks. The availability of the test facility has been one hundred percent. A 30 kW-class stack test facility was made available for the first 30-cell stack test. Stack FA-20-2 containing 30 cells and three reforming units was tested for 750 hours before cooling it down for post-test analysis.

The 400 kW-class power plant test facility for verification of full-size stack and BOP equipment design in subscale test was made fully operational. In addition to system operation, this facility is capable of stack conditioning. Its performance was verified during operation of the full-size stack test discussed earlier. A photograph of the stack on test at the facility is shown in Figure 8. All facility equipment operated as per design, only a fuel flow control valve required some troubleshooting during initial operation. The simplified low-cost stack conditioning procedure implemented in this facility was executed flawlessly. This facility incorporated an advanced anode tail gas oxidizer design which met all design requirements at transient, steady state, and trip conditions. Following this successful test, the oxidizer design will be scaled up for the MW-class power plant use.

Manufacturing Capabilities

ERC plans to expand the existing stack manufacturing facility capability to 50 MW/yr in steps over a multiyear period to meet the growing demand for initial commercial sales. The plant layout for this production capacity has been identified and activities for facility expansion are in progress. The present equipment capacity for one shift operation is >5 MW/yr. All the processes and tooling required for the manufacture and assembly of the commercial design DFC stack, the building block of ERC's power plant, have been established. A semiautomatic stack assembly facility has been commissioned to assemble the full-height stack from cell packages, matrices, and end plates. A robotic arm is used for lifting and placement of cell packages and matrices. A photograph of the robotic arm

Figure 8. FULL-SIZE (326-CELL) STACK ON TEST:
World's largest advanced fuel cell stack on test.

of the stack assembly facility is shown in Figure 9. The first full-size (9000 cm²) 326-cell stack has been manufactured and assembled to verify the manufacturing readiness for building block stacks. A photograph of the first full-size stack during assembly on the semiautomatic facility is shown in Figure 10.

In parallel with manufacturing capacity enhancement, the components manufacturing processes were improved and streamlined. The bipolar plate high rate manufacture tooling was developed and accepted. Bipolar plates are being routinely produced by this tool for stack use. The cell component manufacturing lines have been further refined to reduce components thickness and size variations as well as to improve yields. These improved processes are being routinely utilized to manufacture cell components. Figure 11 compares the thickness variations and yields achieved for some key cell components with respect to the goals for commercial entry product. The commercial entry product tolerance and yield goals have essentially been attained in the manufacture of the first prototype full-size stack components. The direct internal reforming catalyst loading process has been automated to improve cell-to-cell fuel flow reproducibility and to lower cell manufacturing cost.

The stack module in the commercial design is an internally-insulated cylindrical container having four stacks, as compared to the rectangular base with four individually insulated stacks used at SCDP. This design has significantly increased the cell packaging density. The final design of the stack module is being developed through detailed analysis and iterative subscale testing. The stack module assembly and transportation issues have been identified and resolved. Stack module assembly and handling equipment has been commissioned at the stack manufacturing facility (a photograph of the module assembly facility is shown in Figure 12). Operational logistics of this facility have been verified using a full-size stack enclosure. The baseline stack module design has been finalized. The lowest-cost module transporter design has been defined and the design drawings have been prepared.

Figure 9. SEMIAUTOMATIC FULL-HEIGHT STACK ASSEMBLY:
A robotic arm is used for picking and placement of cell packages.

Figure 10. FULL-SIZE STACK ASSEMBLY IN PROGRESS:
Operation of the semiautomatic stack assembly facility verified by stacking this first full-size stack.

Figure 11. CURRENT STATUS OF KEY CELL COMPONENTS TOLERANCE AND YIELD:
Commercial entry product goals for tolerance and yield have essentially been achieved.

**Figure 12. MODULE ASSEMBLY AND HANDLING EQUIPMENT
COMMISSIONED AT STACK MANUFACTURING FACILITY:**
Operation of the facility is checked out using a full-height single-stack enclosure.

In the ERC product philosophy, each stack module will be factory preconditioned and quality checked before being truck transported to the field site. A preconditioning facility design has also been completed. Engineering drawings are ready for equipment purchase and start of construction. This check-out facility will precondition one stack module at a time and is capable of operating the module up to 1 MW.

System Design, Analysis and Demonstration

The standard power plant will contain two stack modules, providing a net 3 MW AC. The 3 MW power plant design is based on factory-constructed truck-transportable modules having a total plot area of <420 square meters, which is approximately one-tenth the footprint of the 1.8 MW SCDP proof-of-concept DFC plant. The height of the commercial plant will not exceed 7.6 meters and thus can be sited in virtually any US location. The design effort has factored in the SCDP operating experience and resulted in improvements to the anode exhaust oxidizer, inverter electrical configuration, and an optimized plant layout from heat loss and maintenance considerations. The plant is designed to have an availability of 95%.

A cost estimate based on budgetary quotes from vendors indicated that the capital cost of \$1,130/kW (1998 dollars) is achievable. An analysis based on the Monte Carlo Simulation showed that there is a 78% probability that power plant cost will be <\$1,145/kW.

An ERC-sponsored market study has shown that a substantial market can be captured with a higher cost, smaller one-module (nominal 1MW size) DFC power plant. Based on these results and the current power generation market conditions, ERC believes that this simpler one-module plant appears to be attractive for the market entry. The current ERC efforts are being focused on the translation of the two-module design to a single-module (four 250 kW stacks) product design. This work will lead to the design of the prototype power plant.

ERC has taken a major step toward developing a world wide market for the direct fuel cell by completing a cross-licensing agreement with MTU, a Diamler Benz affiliate. MTU is a developer of the innovatively packaged 300 kW cogen plant based on ERC's direct carbonate fuel cells. This agreement will allow both ERC and MTU to manufacture and sell each other's stationary power fuel cell products in their respective regions.

Significant effort has been made to gather market intelligence and to organize precommercial demonstrations in addition to the prototype field trial noted above. A Demonstration Project Team (DPT) has been established to provide a high priority focus on the activities leading up to a successful prototype product demonstration.

Summary

The objective of the program is to develop a cost-effective, market-responsive DFC power plant design and demonstrate it in an operating prototype unit. Significant progress has been achieved during the past year.

- Manufacturing process development continues at the Torrington, CT facility with the preparations for the full-size stacks. Present manufacturing capability is over 5 MW/year and is planned to be upgraded to 50 MW/year with additional investment.
- Incorporating Santa Clara proof-of-concept test experience, the cell and stack designs have been refined to provide improved stability, reliability and thermal cycling capability consistent with commercial goals and to achieve a power rating of approximately 1 kW/cell and a performance decay rate of <0.25% per 1000h.
- The previous 100 kW power plant test facility has been upgraded to 400 kW size.
- A "hot box" concept has been developed for better stack packaging and to reduce piping requirements and was verified in conjunction with a full-height stack (~250

kW capacity) test. This test has achieved up to 253 kW, which is a world record for a single advanced fuel cell stack.

- A Demonstration Project Team (DPT) has been established to provide a high priority focus on the activities leading up to a successful prototype product field trial(s). Significant effort has been mounted to gather market intelligence and to obtain market entry orders.

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