Santa Clara Direct Carbonate Fuel Cell Demonstration

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Introduction

Fuel Cell Engineering Corporation (FCE) has been involved in a DOE Cooperative Agreement Program (private-sector cost-shared) aimed at the demonstration of direct carbonate fuel cell (DFC) technology at full scale. FCE is a wholly owned subsidiary of Energy Research Corporation (ERC), which has been pursuing the development of the DFC for commercialization near the end of this decade. The project involves the design, construction, and testing of a 2MW carbonate fuel cell demonstration power plant in the city of Santa Clara, California. Construction of the plant - including the installation of the fuel cell stack modules - was complete in March 1996. Testing was begun in April 1996 and the test program was completed in this reporting period, in March 1997.

Objectives and Approach

Potential users of the commercial DFC power plant under development at ERC will require that the technology be demonstrated at or near the full scale of the commercial products. The objective of the Santa Clara Demonstration Project (SCDP) was to provide the first such demonstration of the technology. The approach ERC has taken in the commercialization of the DFC is described in detail elsewhere [1]. An aggressive core technology development program is in place which is focused by ongoing contact with customers and vendors to optimize the design of the commercial power plant. ERC has selected a 2.4 MW power plant unit for initial market entry. Two ERC subsidiaries are supporting the commercialization effort: The Fuel Cell Manufacturing Corporation (FCMC) and the Fuel Cell Engineering Corporation (FCE).

FCMC manufactures DFC stacks and multi-stack modules, currently from its manufacturing facility in Torrington, CT. FCE is responsible for power plant design, integration of all subsystems, sales/marketing, and client services. The commercial product specifications have been developed by working closely with the Fuel Cell Commercialization Group (FCCG). FCCG members include municipal utilities, rural electric co-ops, and investor-owned utilities who have expressed interest in being the initial purchasers of the first commercial DFC power plants. The utility participants in the SCDP have been drawn from the membership of FCCG.

FCE was the prime contractor for the design, construction, and testing of the SCDP Plant, and FCMC manufactured the multi-stack submodules used in the DC power section of the plant. Fluor Daniel Inc. (FDI) served as the architect-engineer for the design and construction of the plant, and also provided support to the design of the multi-stack submodules. FDI is also assisting the ERC companies in commercial power plant design.

Project Description

The project involved the design, construction, and testing of megawatt-scale DFC demonstration power plant in the city of Santa Clara, California. The rated output of the nominally 2MW SCDP plant was 1.8 MW. The plant is located at 1255 Space Park Drive in Santa Clara. The site is owned by the City's Electric Department and is adjacent to a 115/60kV switching station on the City electrical system. A photograph of the power plant is shown in Figure 1.

The natural gas fueled power plant consists of the fuel cell power section (16 electrochemical fuel cell stacks, configured into four 4-stack submodules) and the balance of plant (BOP) equipment. The BOP is comprised of the process, mechanical, and electrical equipment which provides the required gas flows to the stacks and converts the stacks' DC power to AC power at the required grid voltage. The design of the power plant is based on ERC's proprietary DFC "Simplified Design," which is also the basis for ERC's initial commercial offering. The Simplified Design includes provision for startup, fuel cleanup, recirculation of carbon dioxide to the cathode side and exhaust of spent gases through a Heat Recovery Unit (HRU) which provides the required fuel pre-heat and steam generation. ERC has also investigated other process design options which provide higher efficiency operation, but at the expense of increased system complexity and higher capital cost

Figure 1
Santa Clara Demonstration Project Power Plant

The design and fabrication of the fuel cell stack modules was done with the support of the U.S. Department of Energy through FETC, under Cooperative Agreement DE-FC21-92MC29237. The period of performance for the Cooperative Agreement is October 1, 1992 through September 30, 1997.

The design and procurement of the balance of plant and the construction and testing of the complete system was supported by the Santa Clara Demonstration Participants. The participants in the SCDP are as follows: City of Santa Clara, City of Los Angeles Department of Water and Power, City of Vernon, Electric Power Research Institute, National Rural Electric Cooperative Association, Sacramento Municipal Utility District, and Southern California Edison Company. Salt River Project and the Northern California Power Agency (NCPA) also supplied some project funding through a consortium agreement with the City of Santa Clara. In addition, the California Energy Commission has provided funding to the City of Santa Clara to partially support the balance of plant pre-test activities. ERC also contributed to the project, at about the level of an SCDP share.

Results

As reported last year, the plant startup was begun in April 1996. After the initial heatup, power generation operations began with a period of gradual power level increases during Power Conversion Unit tuning operations. The plant output was increased beyond the 1.8 MW rated capacity to 1.93 MW, during which time the fuel cell stacks exhibited extremely uniform performance (+/- 1% variation in stack voltage) at levels in excess of the plant design projections. The voltage uniformity at 1.93 MW net AC is shown in Figure 2, and the voltage performance of the stacks over the load range is shown in Figure 3. In the first run of operation at rated power, the plant was operated in a conservative mode, since the stability of the PCU system had not yet been confirmed and the response of the system to grid disturbances had not yet been demonstrated. This involved running the two auxiliary natural gas burners in the plant (one in the anode exhaust line and one in the HRU) in order to enhance system stability in the event of a plant trip. These burners would normally be off, and would be started in the event of a trip to standby, so keeping them running would provide a “soft landing” plant trip.

With the auxiliary burners firing, the system efficiency did not meet the target 49% (LHV) level, but an efficiency of 44% (LHV) was achieved, a record for a simple cycle natural gas power plant at this size level. The performance of the stacks and the system operating parameters indicated that once the auxiliary firing was curtailed, the 49% target could easily be met.

During operation at rated power, transients were observed in some of the stack voltages and the system was shut down for inspection. The cause was determined to be parasitic electrical circuits, caused by a breach of the electrical isolation between the fuel cell stacks and the gas distribution piping. The source of these circuits was traced to a glue used to install the thermal insulation around the feed and exit process lines to the fuel cell stacks. At elevated temperatures glue became electrically conductive, diminishing the effectiveness of dielectrics used to isolate fuel and air metal pipes from the fuel cells. Since differential potentials can reach 1000 VDC in the power plant, it became possible for stray parasitic currents to flow through the tainted dielectrics.

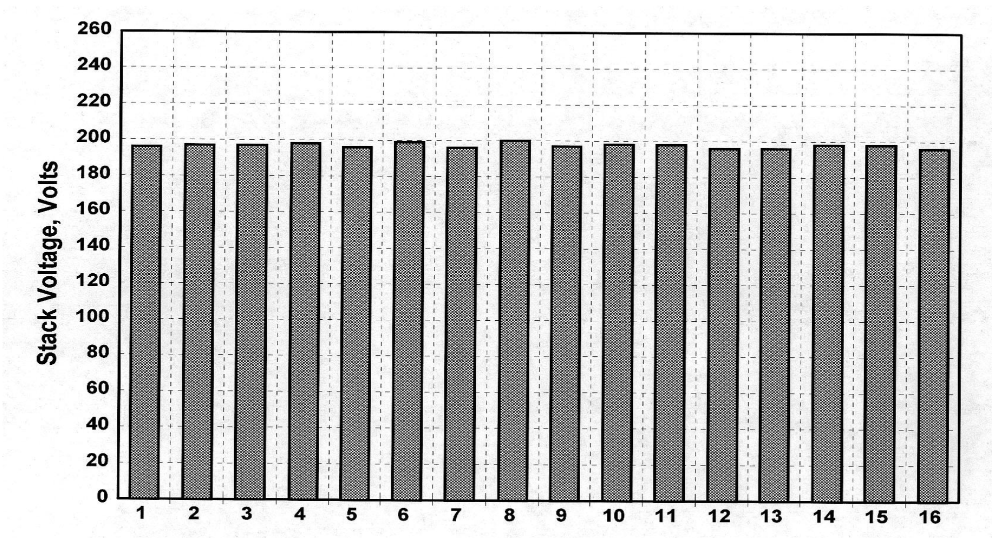

Figure 2

Voltage Performance of 16 SCDP Stacks on Load at 1.93 MW net AC Power

The Stack Voltages Were Uniform to Within +/- 1%

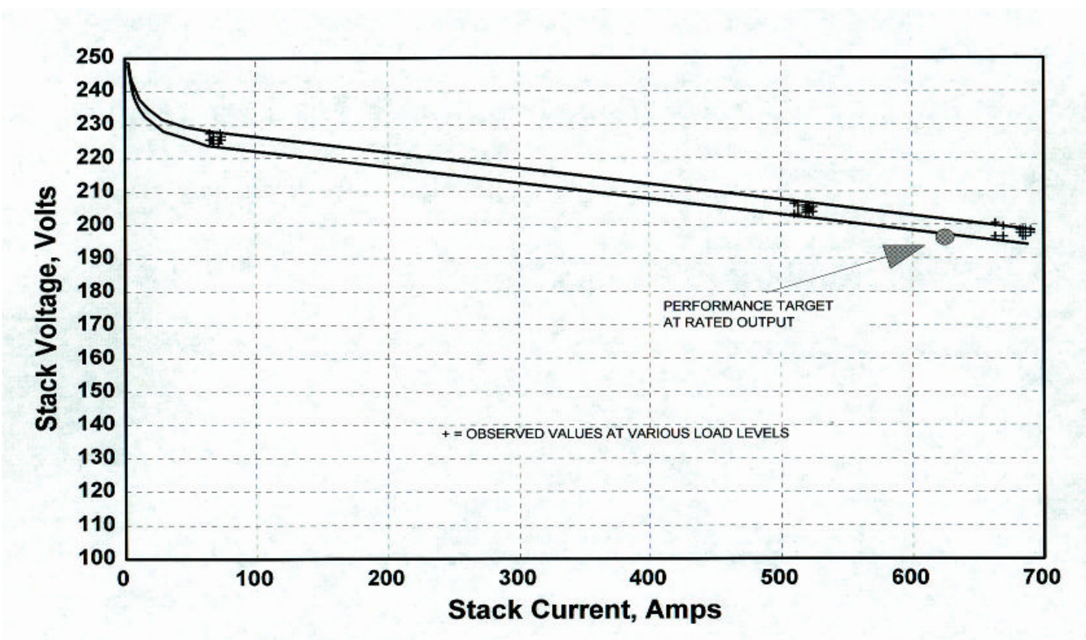

Figure 3

Voltage Performance of SCDP Stacks Over Full Range of Power Output

The Stacks Performed Slightly Above the Target Design Basis Level

Power plant operations were resumed once the compromised dielectric components were repaired or replaced. During this second operating period, power output was ramped to 1.2 MW gross DC (1.0 MW net AC) before the performance of some of the stacks precluded further ramping. It was observed that all of the stacks operating below design levels shared a common position in the electrical circuit. It appears that during the pipe dielectric shorting which forced the first plant shutdown, the voltages of the shorted pipe and stack hardware in some portions of the circuit were driven to levels which triggered secondary electrical damage at the stacks. This left residual damage which became progressively worse during the second operational run. The eight stacks in the unaffected portion of the circuit did not incur this problem, and all eight were observed to operate well.

As a result, operations were continued using the unaffected eight stacks in a reconfigured 1MW operating mode. Isolation of the desired stacks was done by installing blinds midway down the run of the flow headers, as shown in Figure 4. This eliminated the eight stacks at the four ends of the piping system, preserving a symmetrical flow configuration which is important in maintaining a uniform pressure profile throughout the stacks. The mechanical reconfiguration was done in a 10 hour operation, during which time the stacks were not delivered any gas flows.

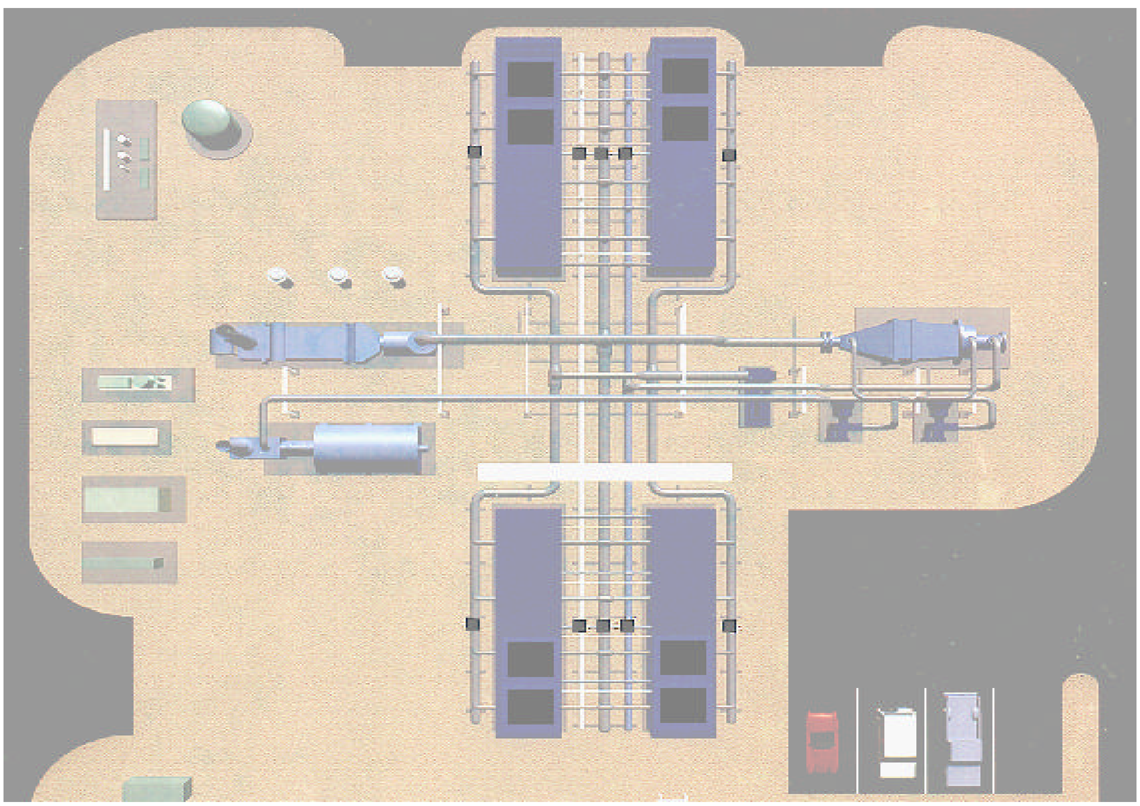

Figure 4
Stack Isolation Approach Used For Plant Reconfiguration
The Isolation Preserved a Symmetrical Flow Configuration to the Eight Operating Stacks

Following the mechanical reconfiguration, the plant was left in hot standby awaiting the delivery and installation of an additional transformer between the inverter and the grid, which was needed to allow the lower voltage output of the reconfigured power plant to interface with the City's electrical system. Once the transformer was installed the third operating period was begun. The planned curtailment of auxiliary fuel firing could not be done in the third operating period, since the heat output from the eight stacks was not sufficient to support the HRU pre-heat and steam generation functions, without the use of auxiliary firing.

The initial power ramp in the third operating period brought the plant to a power level of 950 kW gross DC, 95% of the Gross DC target level for the 8-stack system. Figure 5 compares the average performance of the operating eight stacks during this load ramp to the performance of the eight stacks during the load ramps in the first and second operating periods. It can be seen that the performance of the stacks in the load ramp in the second period was very similar to the ramp at the beginning of the first operating period.

The load curve for the third period is similar in terms of polarization slope, but the average stack voltage was slightly less than that seen in the previous two operating periods. The slightly lower voltage was due to the lower operating temperatures of the stacks. As the 8-stack process gases were circulated through the 16-stack piping system, the normal plant heat losses resulted in twice the cooling effect due to the reduced mass flow. As a result, the inlet temperatures to the stacks were significantly cooler than in earlier operating periods and the exit temperatures were slightly cooler than in previous runs. The lower voltage of the stacks was consistent with model predictions of the temperature effect. The temperature differential across the stacks - the difference between the coolest inlet and the warmest outlet process gas - was 30 to 40 percent higher than in earlier power generation periods at comparable power output levels.

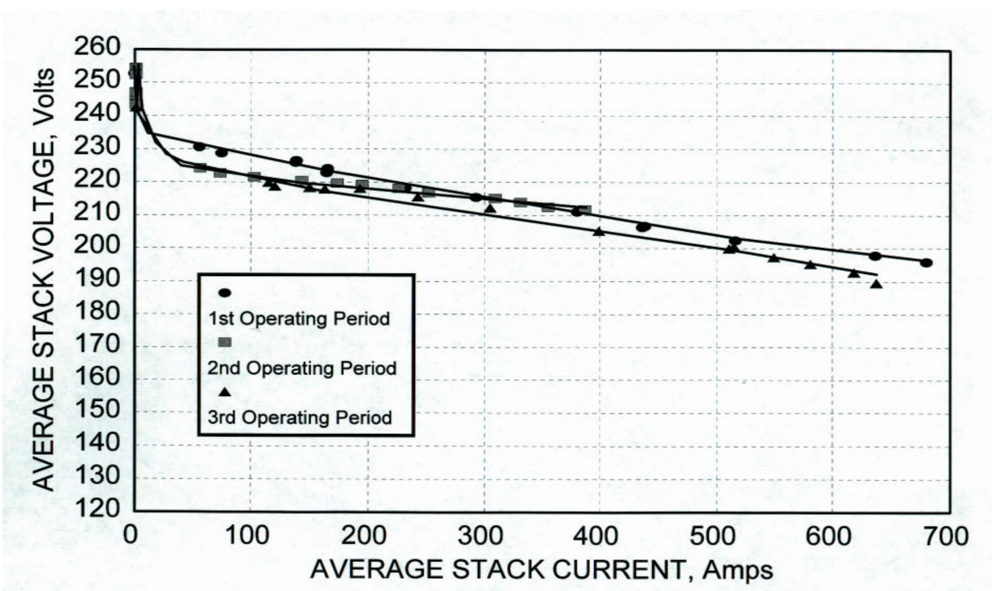

Figure 5
Comparison of Initial Power Ramps in Three Operating Periods Performance Variations Were Limited To Effects Of Temperature And Gas Composition

While operating at the 95% DC power level, the performance of two of the stacks began to decline. The possibility that the wide thermal gradients were causing localized contact problems was considered, and the plant was put on standby for about 150 hours to allow the stacks to thermally equilibrate on standby. On resumption of power generation, one of the two weak stacks recovered performance and the other stabilized, indicating that the thermal gradients had played a role in their performance loss. In this and subsequent operations the thermal gradient across the stack was minimized by running with a higher than normal steam content in the fuel to the stacks. This increased the heat capacity of the fuel inlet, lessening the heat loss impact on the system.

The stacks used in the SCDP plant represent a 1993 design, and incorporate cell hardware which is less tolerant of extreme thermal gradients than the hardware currently being used at ERC. The advanced hardware which is currently being tested in full area short-stacks is designed to tolerate thermal gradients significantly beyond those seen during the off-design operating periods in the SCDP plant. Testing to date on the new hardware has verified this capability, which was a major objective of the new design.

Once the process adjustment was made to limit the thermal gradient across the stacks, the balance of the third operating period was characterized by stable operation at 50% to 75% power for extended time periods. There were three short BOP-related shutdowns in this period. One was caused by a short circuit in a power cord in the control room and two were caused by the buildup of debris in the HRU. The HRU includes a catalyst block for oxidation of VOCs during the initial power plant heatup (this initial conditioning of the fuel cell stacks was done in the field at Santa Clara but is expected to be a factory operation in commercial stack production). This catalyst block began to collect deposits related to the use of unclean pipeline natural gas in the startup burner firing into the system exhaust. Changes in the commercial BOP configuration and stack designs will preclude this from recurring. These three outages were the *only* BOP related outages in the entire test program since the initial startup.

The few outages that did occur in the third operating period provided the opportunity to evaluate one of the SCDP's key performance criteria, ramp rate. The criteria to be demonstrated was a ramp rate of standby to full power in 30 minutes, a rate of 3.3% per minute. Seven automatically controlled power ramps were performed in the third operating period, the fastest of which was at a rate of 4.8% power per minute. The stable operations observed in the third operating period also provided the opportunity to evaluate other design criteria, such as noise level, power quality, and emissions. The testing of the reconfigured power plant was continued through March 3, 1997, when the testing operations were concluded. The plant was operated in grid-connected mode for a total of 4000 hours. Following the completion of the test program, the fuel cell stack submodules were shipped back to FCMC's Torrington, CT facility for post-test analysis, which is now ongoing.

In addition to meeting and exceeding its rated power criteria and ramping criteria, the power plant operations met many other key project objectives. Specific project criteria which were successfully demonstrated included rated output, peak operation, voltage harmonic power quality, low NOx and SOx emissions, and operation within noise limits. A summary of the power plant performance against key project criteria is shown in Table 1. The SCDP balance of plant proved to be exceptionally reliable. The system rode through minor grid disturbances and responded to major grid problems exactly as intended. The overall availability of the balance of plant during the test program was 99%, and the entire test program (including the BOP pre-test) was carried out with an excellent safety record, with no lost-time accidents. These would be excellent results for any plant, but are particularly impressive in this first-of-a kind demonstration plant.

Table 1
SCDP Power Plant Performance vs Key Project Criteria
Almost All of the Key Project Criteria Were Met in the Demonstration Program

Power Output	1.8 MW Rated Power Target Exceeded with Power Output up to 1.93 MW.
Heat Rate	Stack Performance Level Necessary for Target Heat Rate Achieved. < 7000 Btu/kWh (48.7% Efficiency) Target Not Achieved due to Conservative Approach To Operating the Plant in the Early Phase Of Testing, and Process Impacts in Reconfigured Plant. Minimum Heat Rate of 7820 Btu/kWh (43.6% Efficiency) Achieved.
Power Quality	Voltage Harmonics Less Than Half of IEEE 519 5% Distortion Level. Overall Current Harmonics Below IEEE 519 Level, With Four Individual Harmonics Above Level. Correctable With Additional PCU Tuning.
Ramp Rate	3.3% Power per Minute Target Rate Exceeded Maximum Ramp Rate Tested was 4.8% per Minute
Emissions	SOx Emissions Level Undetectable NOx Emissions Level Undetectable Upstream of Startup Burner, only 2ppm at System Exhaust Downstream of Burner
Noise	Met SCDP and City of Santa Clara Requirements <60 dB(A) 100 feet from Equipment and <70 dB(A) at Property Line

Beyond its success at demonstrating many of the key project criteria, the test program was also invaluable as a learning process for the DFC development team. The project represents the first time that global power plant type issues (e.g. heat loss, system control, grid interface, multi-stack operation, etc.) have been dealt with for carbonate fuel cells in the field and at the megawatt scale. The advantages of the simplified BOP design utilized in ERC's DFC concept were clearly demonstrated by such results as the excellent BOP reliability. The limitations of the design (e.g. the impact of heat loss on the stack temperature gradient in early operations of the 8-stack system) were successfully faced and resolved (e.g. by increasing steam content to minimize heat loss impacts). In terms of both capabilities demonstrated and lessons learned, the test program has been an important advancement toward the commercialization of the Direct Fuel Cell. The accomplishments of this project were recognized through an APPA Energy Innovator Award and an EPRI Technical Achievement Award. A summary of the overall program accomplishments is shown in Table 2.

Table 2
Key SCDP Accomplishments

Permitting/Construction	Ease of Permitting for Direct Fuel Cell (DFC) Powerplant Demonstrated Demonstrated DFC Construction Approach BOP Configured with Vendor Supplied Skid Mounted Modules and Shop Fabricated Piping Spools DC Power Block with Multi-Stack Submodules Truck Shipped Across U.S. Engineering, Procurement and Construction Completed Within 0.1% of 1993 Budget Forecast.
Power Plant Start-Up	Start-Up of Multiple-Stack System in the Field Demonstrated Automatic Control of Start-Up Parameters Demonstrated
Stack Operation	Uniform Performance of DFC Stacks Above Target Performance Level Achieved
Power Output	Power Output at and Above 1.8 MW Rated Power Level, up to 1.93 MW Net AC 1710 MWh Delivered to City of Santa Clara Grid Largest Fuel Cell Powerplant Operated in Western Hemisphere Largest DFC Powerplant Operated in the World
Power Quality	Voltage Harmonics Less Than Half IEEE 519 5% Distortion Limit Overall Current Harmonics Below IEEE 519 Level, with Four Individual Harmonics Above Level. Correctable with PCU Retuning .
BOP Operation	Automatic Control of BOP Equipment and Power Level Demonstrated 99% BOP Availability Plant Staffed by Locally Hired Power Plant Operators No Nuisance Trips. Plant rode through minor grid disturbances and responded to major grid disturbances exactly as intended
DC Power Module	Fuel Cell Stacks Exhibited Uniform Performance, in Excess of Design Projections Design and Electrical Configuration Issues Continue to be Addressed in Ongoing Development Program, along with Thermal Cycle and Durability Issues
Learning	Operation of Multiple Stacks in Common Flow System and Electrical Circuit Provided Insight into Multiple Stack Power Plant Design Issues Experience Gained in DFC Power Plant Operation Dynamic Response of Stacks and BOP Equipment During Transients and Load Ramps Provided Insight Into Design of Commercial Power Plant.

Future Activities

As noted above, the fuel cell stacks have been returned to FCMC's facility in Torrington, Connecticut, where a process of post test analysis is now ongoing. ERC, FCMC, and FCE personnel are participating in the post test program, which will be complete later this year, and reported on at the next conference.

Acknowledgments

The guidance and support of the FETC Contracting Officer's Representative, Mr. Thomas J. George, has been greatly appreciated.

References

[1] H. Maru, et al.; "ERC Program Overview". Proceedings of the Fuel Cells '97 Review Meeting. August 1997

[2] Skok, A.J et. al.; "Startup, Testing, and Operation of the Santa Clara 2MW Direct Carbonate Fuel Cell Demonstration Plant"; Proceedings of the 1996 Fuel Cell Seminar, November 1996

[3] Skok, A.J et. al.; "Power Conversion and Quality of the Santa Clara 2MW Direct Carbonate Fuel Cell Demonstration Plant"; Proceedings of the 1996 Fuel Cell Seminar, November 1996

[4] "Santa Clara 2MW Fuel Cell Demonstration Power Plant, Interim Acceptance Test Report"; EPRI Report TR-107076; November 1996

[5] Leo, A.J., Kush, A.K., Farooque, M.; "Development and Demonstration of Direct Carbonate Fuel Cell Systems at Energy Research Corporation"; Proceedings of the 31st IECEC Conference; August 1996

[6] Leo, A.J, Skok, A.J., O'Shea, T.P; "Santa Clara Demonstration Status"; Proceedings of Fuel Cells '96 Review Meeting, U.S. Department of Energy Federal Energy Technology Center, August 1996

[7] "Santa Clara 2MW Fuel Cell Demonstration Design, Construction, and Permitting Report"; EPRI Report TR-106155; July 1996