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Simulated Coal-Gas Fueled Carbonate Fuel Cell Power Plant System Verification

**Final Report
September 1990 - June 1995**

March 1995

Work Performed Under Contract No.: DE-AC21-90MC27168

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Energy Research Corporation
Danbury, Connecticut

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**By
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March 1995

ACKNOWLEDGEMENT

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ABSTRACT

This report summarizes work performed under U.S. Department of Energy, Morgantown Energy Technology Center (DOE/METC) Contract DE-AC-90MC27168 for September 1990 through March 1995. Energy Research Corporation (ERC), with support from DOE, EPRI, and utilities, has been developing a carbonate fuel cell technology. ERC's design is a unique direct fuel cell (DFC) which does not need an external fuel reformer. An alliance was formed with a representative group of utilities and, with their input, a commercial entry product was chosen. The first 2 MW demonstration unit was planned and construction begun at Santa Clara, CA. A conceptual design of a 100MW-Class dual fuel power plant was developed; economics of natural gas versus coal gas use were analyzed. A facility was set up to manufacture 2 MW/yr of carbonate fuel cell stacks.

A 100kW-Class subscale power plant was built and several stacks were tested. This power plant has achieved an efficiency of ~50% (LHV) from pipeline natural gas to direct current electricity conversion. Over 6,000 hours of operation including 5,000 cumulative hours of stack operation were demonstrated. One stack was operated on natural gas at 130 kW, which is the highest carbonate fuel cell power produced to date, at 74% fuel utilization, with excellent performance distribution across the stack. In parallel, carbonate fuel cell performance has been improved, component materials have been proven stable with lifetimes projected to 40,000 hours. Matrix strength, electrolyte distribution, and cell decay rate have been improved. Major progress has been achieved in lowering stack cost.

EXECUTIVE SUMMARY

This final report summarizes the work performed under the U.S. Department of Energy, Morgantown Energy Technology Center (DOE/METC) Contract DE-AC21-90MC27168 for the September 1990 through March 1995 period. Energy Research Corporation (ERC), with support from DOE, EPRI and utilities, has been developing a carbonate fuel cell technology for efficient and clean power generation. ERC's approach involves a unique direct fuel cell (DFC) which does not require the external fuel reformer utilized in conventional carbonate or other types of fuel cells. ERC is currently focusing on a MW-Class product which is designed to operate at atmospheric pressure to permit reliable, unattended operation. Activities under this contract were focused to bring the direct carbonate fuel cell technology from the research stage to the demonstration stage. The specific plans to attain the overall program goal are:

- Obtain market input to choose the early commercial entry product. Form an alliance and carry out dialogue with utility customers and define the first full-size demonstration project.
- Define the final design of a full-size MW-Class demonstration power plant. Develop the conceptual design of a 100MW-Class dual fuel power plant and analyze economics of the dual fuel power plant based on natural gas versus coal. Develop a full-size stack design for the power plants.
- Set up a facility to manufacture 2MW/yr of carbonate fuel cell stacks for design and development evaluation at ERC, for the full-size demonstration power plant, and for gaining experience for scaleup to the commercial level.
- Design and build a 100kW-Class subscale power plant to support development testing of full-height carbonate stacks and balance-of-plant (BOP) equipment.
- Improve carbonate fuel cell performance, demonstrate system operation and attainment of life goal, and reduce costs of expensive components, thus permitting a versatile stack design for power plant use.
- Define cell resistance contributing factors and devise approaches for cell resistance reduction and stability improvements.

A six-task program, where each task is dedicated for attaining one specific topical objective discussed above, was planned. All the objectives in each of the topical areas were successfully achieved, culminating in testing of full-height fuel cell stacks under system operating conditions in a subscale power plant. This report is organized according to the above-mentioned topical areas. The achievements in each of the tasks are summarized below.

COMMERCIALIZATION

To facilitate commercialization, ERC joined with an assemblage of near-term customers made up of utilities interested in fuel cells, called the Fuel Cell Commercialization Group (FCCG). This group has over thirty members. Based on the interest in the utilities community, and using the FCCG inputs, ERC has defined a 2MW power plant design specification. Working interactively with FCCG, ERC has defined the full-size power plant demonstration project; the project has been initiated. Testing, led by ERC's subsidiary, Fuel Cell Engineering Corporation (FCE), is planned for the 1995-1996 time frame. In parallel, ERC, with assistance from Fluor Daniel, Inc., surveyed a significant segment of the utility market, representing ~37% of U.S. and Canadian generating capacity. This survey revealed that natural gas was the fuel of choice for the near-term (up to 2010) and that early users of carbonate fuel cells prefer power plants in the 2 to 50 MW size range.

POWER PLANT DEVELOPMENT

ERC is developing a standardized, packaged MW-Class carbonate fuel cell power plant operating on natural gas or bio-derived fuels for distributed power generation applications as a near-term product. As a first step towards a commercial MW-Class product, ERC developed a full-size demonstration power plant design projecting an overall operating efficiency of 50% (LHV). This power plant will be demonstrated in the city of Santa Clara, CA. The plant is now under construction (a computer generated rendition of the power plant is shown in Figure S-1), and is scheduled to operate during 1995-1996.

Figure S-1 MW-CLASS CARBONATE FUEL CELL POWER PLANT:
World's First and Largest Carbonate Fuel Cell Power Plant is
Being Demonstrated Using Technology Developed Under This Program

As experience on this early product is gained and technology matures, ERC plans to introduce larger dual fuel plants for operation on natural gas and/or coal gas for on-site and central power generation applications. The technical and economic characteristics of stand-alone natural gas and dual fuel (natural and coal gas) plants were evaluated using a common design basis. The stand-alone natural gas power plant has a 12% efficiency (HHV basis) advantage. Furthermore, the plant cost is approximately half of the coal gasification power plant. However, considering a cost of electricity analysis based on DOE/EIA energy cost forecasts and the higher availability for a dual fuel power plant (91% vs. 85% for stand-alone plant), it was judged that: 1) a natural gas fueled system to operate for 30 years would be most attractive, if the plant is put into operation by the year 2000; 2) for a plant begun after the year 2006, natural gas with coal gas phased in would be most attractive. The precise date of switchover to coal gas would, of course, depend on the fuel price.

In the DFC power plant design, the carbonate fuel cell stacks will be arranged in truck shippable modules, where each module will contain a number of identical carbonate fuel cell stacks. The stacks in the 2MW demonstration power plant will consist of 258 cells of ~6,000 cm² cell area, with a nominal rating of 125 kW. The demonstration stack design has been finalized showing attainment of manufacturability, truck transportability, performance goal, cell conversion efficiency, performance uniformity (Figure S-2), thermal uniformity, and system operations. The stack test has produced 130 kW power operating on pipeline gas, with stack conversion efficiency of 55% (LHV) from natural gas to electricity, which is the highest carbonate fuel cell power produced anywhere in the world to date.

Figure S-2 PERFORMANCE AT 130kW OPERATION IN A SUBSCALE POWER PLANT (Natural Gas; 74% Fuel Utilization):
Excellent Performance Distribution

MANUFACTURING FACILITY DEVELOPMENT

ERC has set up a wholly-owned subsidiary, Fuel Cell Manufacturing Corporation (FCMC), to produce stacks for power plants. FCMC has established a carbonate fuel cell manufacturing facility occupying 5,800 m² area having a production capacity of 10MW/yr on a three-shift basis. This is possibly the largest carbonate fuel cell manufacturing facility in the world. The facility is fully operational. Three stacks have been manufactured and tested at ERC. Figure S-3 shows one of the stacks being assembled on the stack assembly platform. Construction of stacks for the first demonstration project is proceeding.

Figure S-3 STACK ASSEMBLY WORK STATION AT FCMC:
Precision Alignment of Cell Packages During Stacking
of Full-Height Stacks is Ensured by the Equipment

TESTING FACILITY DEVELOPMENT

A versatile subscale power plant has been designed and built for evaluation of full-height carbonate stacks and BOP equipment. This power plant can simulate ERC's MW-Class power plant operation with natural gas and can also simulate the 100MW-Class coal/biogas plant operation. Over 6,000 hours of flawless operation including 5,000 cumulative hours of stack

operation of the power plant has been demonstrated. This test experience has resulted in improved stack and BOP equipment design as well as fuel cell operator training. A photograph of a stack on test in this power plant producing 130 kW power is shown in Figure S-4. This power plant has achieved greater than a 50% overall efficiency level (LHV) of natural gas to direct electric power conversion. This reflects the highest electrical generation efficiency ever achieved with natural gas in a single-cycle machine.

Figure S-4 130kW STACK ON TEST IN A SUBSCALE POWER PLANT AT ERC:
The World's Highest Carbonate Fuel Cell Power of 130 kW was Produced in This Test

STACK RESEARCH

The heart of the carbonate fuel cell power plant is the DC power block which is made up of many DFC stacks. In this effort, extensive vendor engineering, out-of-cell tests, ~180 single cells, three lab-scale stacks, and seventeen short stack tests were performed to improve ERC's DFC stack technology and advance the design from the laboratory test vehicle to that of the demonstration power plant power block stack. Over 50,000 total stack test hours were accumulated with large area short stacks. Virtually all of the testing was performed at system conditions, providing operating experience at high reactant utilizations. Four of these stacks exceeded 6,000 hours each. The longest test was for 10,000 hours under a parallel EPRI cost-share program. Each of the stacks tested in the program were post-tested for endurance information and design feedback. The major accomplishments in stack research include:

- A 5% improvement in the cell electrochemical conversion efficiency has been demonstrated in large area stack tests. Additional improvement potentials have been identified in single cell tests.

- Anode, cathode, and cell hardware materials appear stable and project life in excess of 40,000 hours.
- Matrix strength has been significantly improved and significant enhancement in cell thermal cycleability has been demonstrated in stack tests. Additional improvement potential has been verified in single cell tests.
- Electrolyte redistribution has been mitigated by modifying hardware design, including gaskets, end plates, and current collector material and geometry. With these improvements, attainment of 40,000 hours with the beginning-of-life electrolyte charge can be projected.
- Endurance stack tests have shown that the cell decay rate has been improved from the 7mV/1000 hour at the beginning of the program to 3mV/1000 hour at the end.
- In pursuit of lowering stack costs, major progress has been achieved. As an example, the anode cost has been lowered by approximately a factor of 10. In another example, material use in the end plate has been reduced by about a factor of five. Manufacture of this component by a mass producible technique has been demonstrated.
- Stack auxiliary hardware design has been developed for tall stack use.

UNDERSTANDING CARBONATE FUEL CELL RESISTANCE ISSUES

An effort was devoted to increase fundamental understanding of factors limiting cell performance. It was determined that the electrolyte matrix is the major resistance contributor, followed by the cathode-side hardware. The anode-side resistance is negligible. Cell resistance can be further reduced by increasing matrix porosity. Cell resistance stability can be achieved by insuring adequate contact between components and oxide-free cathode current collectors at assembly.

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GLOSSARY

100-MW Class	100-400 MW Size Dual Fuel - Natural Gas and/or Coal-gas Power Plants
AB-X-Y	ERC's Stack Identification Convention
AF-X-Y	A = Atmospheric, F = Full Size, S = Subscale, B = Bench-Scale
AS-X-Y	X = kW Rating, Y = Serial Number
AFBC	Atmospheric Fluidized Bed Combustor
BFW	Boiler Feed Water
BOL	Beginning-of-Life
BOP	Balance-of-Plant
BP	Bipolar Plate
CCC	Corrugated Current Collector
CFCPP	Carbonate Fuel Cell Power Plant
CGCPP	Coal Gas Carbonate Power Plant
COE	Cost-of-Electricity
DC	Direct Current
DCS	Distributed Control System
DESTEC	Dow Chemical Power Plant Group
DFC	Direct Fuel Cell
DIR	Direct Internal Reformer
DOE	Department of Energy
EOL	End-of-Life
EPRI	Electric Power Research Institute
EPU	Early Production Unit
ERC	Energy Research Corporation
FCCG	Fuel Cell Commercialization Group
FCE	Fuel Cell Engineering Corporation (ERC's engineering subsidiary)
FCMC	Fuel Cell Manufacturing Corporation (ERC's manufacturing subsidiary)
HHV	Higher Heating Value
HRSG	Heat Recovery Steam Generator
HTI	Haldor Topsoe International (Houston, TX)
IGCC	Integrated Gasification Combined Cycle
IIR	Indirect Internal Reformer
KRW	Kellog Rust Westinghouse
LHV	Lower Heating Value
MW-Class	2-10 MW Size Natural Gas/CFC Power Plant
NG	Natural Gas
NGCPP	Natural Gas Carbonate Power Plant
OSHA	Occupational Safety and Health Administration
PC	Pulverized Coal
PG&E	Pacific Gas & Electric Company (San Francisco, CA)
ppmv	Parts Per Million, Volume Basis
RU	Reforming Unit
SCDP	Santa Clara Demonstration Project
SRNG	Simulated Reformed Natural Gas
TAG	Technical Assessment Guide (EPRI Special Report)

1.0 COMMERCIALIZATION

To facilitate commercialization of the direct carbonate fuel cell power plant, ERC joined with an assemblage of near-term customers made up of utilities interested in fuel cells, called the Fuel Cell Commercialization Group (FCCG). This group has over thirty members and is representative of the utility industry. Based on the interest in the utility community, and using the FCCG inputs, ERC has defined a 2 MW power plant design specification. Demonstration of this 2MW natural gas fueled power plant in the field has been planned for the 1995-1996 time frame; the project has been initiated. In parallel, ERC reached out to a large portion of the utility market, representing ~37% of U.S. and Canadian generating capacity, in a survey which revealed that natural gas seems to be the fuel of choice for the near term (up to 2010), and that early users of carbonate fuel cells prefer power plants in the 2-50 MW size range.

1.1 INTRODUCTION

Energy Research Corporation's current research activity is dedicated to the commercial introduction of a Direct Fuel Cell power plant for grid or non-grid connected, dispersed power generation by the turn of the century. Direct fuel cell (DFC) power plants will provide ultra-clean, highly efficient power using abundant U.S. supplies of fossil fuels and renewable fuels such as landfill gas and ethanol.

To foster accurate and timely commercialization goals, ERC helped to form, and then enlisted the aid of the Fuel Cell Commercialization Group. This group of over thirty utilities and prospective near-term customers, distributed throughout the U.S. and Canada, serves as a valued alliance to encourage dialogue with the utility community. With their input and advice, ERC is developing production requirements and specifications for its fuel cell products.

In parallel, to identify market attractive features for the DFC power plants, ERC, working with Fluor Daniel Corporation, developed and conducted a market survey among a group of utilities representing ~37% of North American generating capacity. Input obtained from this market survey aided ERC in predicting some of the dominant factors for fuel cell use for the next several decades. These factors included the level of interest in fuel cell power plants, and the significant fuel cell features which are attractive to the industry. Two results of this survey were the near-term choice of natural gas fuel, and the smaller size power plant for the early commercial entry.

1.2 MW-CLASS POWER PLANT COMMERCIALIZATION

The overall objective of this activity was to support the commercialization aspects of ERC's MW-Class power plant design in close consultation with the users. In 1990, the Fuel Cell Commercialization Group (FCCG) was formed by a group of municipal and investor-owned utilities. It presently has over thirty members distributed throughout North America, as shown on the map in Figure 1.2-1. The membership of the FCCG represents a broad gamut of utility types, locations and sizes which is highly representative of the utility industry.

This not-for-profit group, under the Chairmanship of Robert Claussen of the Alabama Municipal Electric authority, has met four times each year over the last four years. They have been working closely and interactively with the ERC team on many aspects of commercialization including marketing, sales, power plant design, contractual relationships, and power plant demonstration plans. This has served to review and critique the fuel cell power plant design and the overall approach to commercialization.

Figure 1.2-1 FCCG MEMBERS:
Members are Well Distributed Geographically and by Type

Five formal committees have been formed under the FCCG to work with ERC. These are the Design Engineering, EPU (Early Production Unit) Model Contract, Permitting and Licensing Systems/Planning Evaluation, and Information Transfer & Promotion committees. Interfacing with these utility committees and their utility representatives has enabled ERC to exchange information relative to their interests, requirements, and product needs, while at the same time allowing ERC to present to the utilities the status of its fuel cell developments and anticipated power plant characteristics.

Derivative from FCCG is the Santa Clara Demonstration Project (SCDP) under the Chairmanship of Paul Eichenberger of the City of Santa Clara, CA. The specific objective of the SCDP is to have a 2 MW natural gas power plant design specification defined and in operation by 1995. Six members of the FCCG are participants in the SCDP. They include: The City of Santa Clara, The Los Angeles Department of Water and Power, Southern California Edison Company, Sacramento Municipal Utility District, the City of Vernon, California and the National Rural Electric Cooperative Association. EPRI and the Department of Energy are also providing substantial support to the project. The Santa Clara participants have come together to advance fuel cell technology toward utility-scale application.

Supported by this aggressive program, ERC is now moving toward the demonstration of a simplified 2MW natural gas Carbonate Fuel Cell Power Plant (CFCPP) at the City of Santa Clara, CA in the 1995-1996 time frame. The objective of this test is to demonstrate the logistics

of stack transportation, site installation, start-up, operation, and shutdown of the carbonate fuel cell stacks in an operational field setting. Verification of such characteristics as heat rate, part-load performance, availability and other operating characteristics will also be accomplished by this test. Specific advantages of the carbonate fuel cell power plant, such as high efficiency, low emissions, reactive power capability, and high reliability will also be demonstrated. Detailed design of the power plant has been completed (Section 2.2), and groundbreaking occurred on April 7, 1994.

1.3 UTILITY INDUSTRY SURVEY

ERC, working with Fluor Daniel Corporation, in 1991 conducted a market-survey to assess utility acceptance of the carbonate fuel cell power plant technology and to define the long-term fuel cell power plant development strategy. The survey was also intended to identify user preference for power plant size, fuel type, and other design and economic factors which would influence fuel cell commercialization.

The results of this market survey were presented elsewhere (1-1, 1-2, 1-3)*. Thirty-one utilities from different sizes and geographical locations, representing ~37% of the U.S. and Canadian generating capacities, were surveyed. The system analysis results of carbonate power plants, as well as its comparison with current and emerging competing systems, were provided to the utilities surveyed. Utility opinion was sought in the areas of future energy sources, carbonate fuel cell design feature, and future capacity needs. The insight gained from the survey, as discussed next, has provided valuable input for developing commercialization strategy.

Price level and stability were identified to be important factors impacting the choice for fuel. Because of ample natural gas supplies, low prices and the economic effects of environmental policies, most utilities expected natural gas to be the fuel of choice in near term. Natural gas is expected to be available for power generation capacity additions until the year 2010. Therefore, natural gas was the choice of fuel for earlier potential users of carbonate fuel cells. Coal-based capacity additions were expected by the responding utilities to decline currently until about the year 2010, at which time, because of pricing advantages, they expected an increase at the expense of natural gas. The use of alternate fuels such as hydroelectric, nuclear, fuel oil and liquified natural gas for capacity additions was expected to decline rapidly. The renewables, such as solar and wind, were expected to be available, but, less than 40% of the utilities surveyed expected to incorporate this technology in their mix of power generation systems in the future.

Almost all utilities indicated that they dispatch electricity based on marginal cost of production (Figure 1.3-1). However, 26% of the utilities indicated that, in addition to the cost-of-electricity, they dispatch based on the factors which favor fuel cells such as heat rate, environmental emissions, transmission restriction and reliability. Although environmental factors currently play only a small role in dispatching at existing plants, they were viewed as becoming very important in considering the carbonate fuel cell technology. Figure 1.3-2 shows the expected importance of SO_x and NO_x and CO_2 during the 2000-2029 time frame. All were regarded as about equal in importance, with a small increase in importance in the future years.

* References are listed in Section 7.

Figure 1.3-1 BASIS FOR DISPATCHING PLANTS:
Most Utilities Use Cost-of-Electricity as a Basis for Dispatching Plants

Figure 1.3-2 IMPORTANCE OF EMISSIONS:
Environmental Factors Expected to be Very Important in the Next Century

The fuel cell power plant was rated very favorably by the responding utilities, 45% rating very attractive vs. 55% rating attractive. More than 25% of the survey respondents indicated that under proper conditions they would be interested to be among the first to add a carbonate fuel cell power plant to their system. The survey indicated that interest in being among the first to add a full-scale carbonate fuel cell power plant was independent of utility size and load growth characteristics.

Utilities indicated significant interest in power plant sizes of 2-50 MW, with a sizeable group showing interest in sizes above 50 MW. The importance of fuel cell characteristics to responding utilities is shown in Figure 1.3-3. Interest in fuel cell power plants is focused on cost, environmental performance and efficiency attributes. Natural gas fueled combined cycle was viewed as the most important competing technology. Beyond the year 2010, the price of natural gas relative to coal was expected to increase, and at that time, Integrated Gasification-Combined Cycle (IGCC) would become an important competitor. No long-term market projection was made because only a few utilities chose to respond about their plans for capacity additions beyond year 2010.

WM9617

Figure 1.3-3 IMPORTANCE OF FUEL CELL CHARACTERISTICS:
Interest in Fuel Cell Power Plants is Focused on Cost,
Environmental Performance and Efficiency Attributes

As per the survey insight, carbonate fuel cell power plant development should initially concentrate on sizes in the 2-50 MW range using natural gas as fuel. The emphasis can be switched to larger sizes using coal gasification in the out-years as the price of coal becomes cheaper relative to the price of natural gas.

1.4 CONCLUSION

ERC has defined the parameters of most interest for near-term carbonate fuel cell power plants based on the interest in the utilities community. Following these guidelines, in association with the Fuel Cell Commercialization Group, a group of near-term customers from utilities interested in fuel cells, the first full size power plant demonstration project has been defined. A 2MW natural gas fueled power plant has been planned for demonstration in the 1995-1996 time frame, and the plant construction has been initiated.

2.0 POWER PLANT DEVELOPMENT

ERC is developing a standardized packaged MW-Class power plant as a near-term commercial product. As a first step towards commercialization, a full-size 2MW demonstration power plant design projecting an overall efficiency of 50% (LHV) has been defined.

As the experience is gained on the early MW-Class product and the technology matures, ERC plans to introduce 100MW-Class dual fuel power plants for operation on natural gas and/or coal gas. The technical and economic characteristics of stand-alone natural gas and dual fuel "phased" in coal gas power plants were analyzed revealing that, although the natural gas power plant has an efficiency advantage of 12% (HHV) and an ~50% cost advantage (over coal operation), the dual fuel power plants will have a lower cost-of-electricity after the year 2006 due to lower fuel cost.

In ERC's DFC power plants, the carbonate fuel cell stacks will be arranged in truck shippable modules. The DFC stack design for the demonstration power plant was finalized, manufacturability verified and performance demonstrated in integrated system tests.

2.1 INTRODUCTION

This section describes the design status of the MW-Class and the 100MW-Class large power plants. Readiness of the carbonate fuel cell stack for the power plant use is also described.

2.2 MW-CLASS POWER PLANT DESIGN

ERC is developing the MW-Class power plants for dispersed stand-alone or grid-connected power generation. These power plants use ERC's direct fuel cell. Natural gas and liquid hydrocarbon fuels can be used directly without requiring fuel conversion to hydrogen in an intermediate reforming step.

Two types of power plant designs have been considered: a "Simplified" design and an "Integrated" design. Briefly, the integrated design is more complex, self-sufficient in water requirements, and would operate at a higher efficiency. The simplified design requires an external water supply and operates at a somewhat lower efficiency, but requires a much less complex balance of plant. In contrast with the integrated design, it eliminates water recovery, a hydrogen transfer device, cathode recycle and several heat exchangers and their associated equipment. The overall power plant efficiency for early commercial units is expected to be 55% (LHV), which is quite high compared with other generators, 2MW size power plants in particular. The efficiency is expected to be higher for matured commercial units.

For initial market entry, ERC is focusing on the simplified system, as mentioned above. This selection is an outgrowth of ongoing collaboration between the Fuel Cell Commercialization Group (FCCG) and ERC to commercialize fuel cell technology in the late 1990's. The FCCG, as described in Section 1.2, is a group of utilities who are potential buyers of the pre-commercial Early Production Unit (EPU) power plants. A commercialization path has been identified which includes the demonstration of the technology in a full-scale 2MW power plant prior to EPU

phase. The Santa Clara, CA plant will be the first of these demonstrations, and the project participants in the Santa Clara Demonstration Project (SCDP) are also members of the FCCG. The power plant design approach incorporates modularization techniques such as assembly of the stack modules with factory setup of piping, electrical and instrumentation connections to minimize field installation labor. Design and status of this SCDP plant is discussed next.

A preliminary design was submitted to the SCDP in August 1991. Optimization was carried out over a one year period and final engineering was completed in March 1993. Plant construction is proceeding at this time. Operation is anticipated in the 1995-1996 time frame.

2.2.1 2MW DEMONSTRATION POWER PLANT DESCRIPTION

The Santa Clara Demonstration Project is being funded by a group of utilities (participants were listed in Section 1.2), DOE and ERC. The Fuel Cell Engineering Corporation (FCE), a fully-owned subsidiary of ERC, is providing the overall management of the project. ERC has developed the stack design under this DOE/private sector cost-shared program. The fuel cell stacks and multi-stack modules will be fabricated by FCMC under a cooperative program with DOE. Fluor Daniel, Inc. provided engineering support. An organization chart for the project is shown in Figure 2.2-1.

Figure 2.2-1 2MW CARBONATE FUEL CELL DEMONSTRATION PROGRAM ORGANIZATION:

Organizational Structure Allowed Efficient Implementation of the Project

The site of the plant is located in the city of Santa Clara, CA, immediately adjacent to the Scott Receiving Station, a 115/60kV switching station of the city's electrical system. The power plant design specifications are presented in Table 2.2-1. The operating efficiency of this plant is projected to be 50% (LHV).

Table 2.2-1 POWER PLANT DESIGN OBJECTIVES:
The 2MW Power Plant Efficiency is Quite High Compared to Conventional Generators

Nominal Capacity (MW)	2
Power Plant Rating (MW) Net AC	1.8
Heat Rate (LHV) @ Power Plant Rating (Btu/kWh)	6850
Maximum Emissions @ Plate Rating (lb/MWh)	
SO _x	0.003
NO _x	0.0004
CO ₂	~845
Noise (db(A) @ 100 ft)	60
Power Quality	IEEE Std 519
Nominal Output Voltage	12 kV AC 3 Phase, 60Hz
Frequency/Power Drop	5%
Reliability	
Designed to Meet Utility Standards	
Availability Factor	90%
Reactive Power Capability	±1.67 MVAR

A simplified power plant process flow diagram is shown in Figure 2.2-2. The system represents ERC's Simplified Design, with provisions for start-up, fuel cleanup, recirculation of carbon dioxide to the cathode side and exhaust of spent gases. Incoming natural gas is preheated using the system exhaust gases and treated to remove odorants and impurities before being mixed with steam for use in the fuel cells. The fuel is internally reformed to hydrogen in the fuel cell stacks, and 75% of the hydrogen is consumed in the power generation reactions of the fuel cell anodes, producing water and CO₂. The anode exit stream consists of steam, CO₂, carbon monoxide from the shift reactions and the residual hydrogen. The exit stream is fed to the anode exhaust oxidizer where the residual hydrogen and carbon monoxide react with excess air. The oxidizer produces no measurable NO_x.

Figure 2.2-2 PROCESS FLOW DIAGRAM FOR 2MW DEMONSTRATION POWER PLANT:

Overall Power Plant Efficiency is 50% (LHV) and Uses a Simple Balance-of-Plant Layout

The oxidized exhaust stream is quenched with fresh air to provide the desired temperature. This stream contains the oxygen and CO_2 required by the fuel cell cathodes, and is sent back to the fuel cell as the cathode feed stream. After the cathode reactions consume some of the oxygen and CO_2 , the cathode exit gases are sent to the heat recovery system. The exit gases provide heat to the fuel treatment system, the fuel/steam heater, water boiler/superheater and the fuel preheater. These heat exchangers are configured into a packaged heat recovery unit, which also contains the start-up heater, the steam generator deaerator and the system exhaust stack.

In addition to the systems described above, other subsystems in the plant include the water treatment system, instrument air compressor and backup power generator. The layout of the plant is shown in Figure 2.2-3. The plot plan shows the location of the major equipment depicted in the process flow diagram, plus additional facilities such as the control room and visitors center. As can be seen, the DC power section of the plant will consist of two multi-stack 1MW modules. The 1MW fuel cell stack module will be divided into two submodules, which are the truck shippable units enclosing the fuel cell stacks. Each submodule will consist of four stacks and associated piping, instrumentation, and electrical components in a sealed enclosure.

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Figure 2.2-3 2MW SANTA CLARA CARBONATE FUEL CELL POWER PLANT PLOT PLAN:

The Plot Plan Shows the Location of Major Equipment and Other Facilities

The structural enclosure for the stack submodules will be shop fabricated and shipped to the FCMC facility in Torrington, CT., where all piping, electrical, and instrumentation work within the enclosure will be completed. All piping connections will terminate at the enclosure sides with weld connections which will be sealed during shipment to the site. The penetrations of the pipe connections through the enclosure have been designed to limit heat loss from the hot pipes to the cool enclosure structure, and to withstand mechanical stresses caused by thermal expansion as the process pipes are heated from ambient to operating temperature.

All electrical and instrument connections will be brought to terminal boxes on the outside of the enclosure, which will minimize field installation labor. A sketch of the module arrangement is shown in Figure 2.2-4. Each module will consist of two submodules with associated gas distribution piping, instrumentation connections and electrical connections. The design of the gas distribution piping is critical to the power plant since significant variations in flow between stacks could lead to reactant utilizations in excess of the design range. A flow modeling effort was conducted during the module design work to ensure that the gas distribution system could meet the flow variation specification. To further ensure the attainment of good flow uniformity, flow trimming valves have been incorporated in the cathode feed lines. These will be set during Balance-of-Plant (BOP) pretest before the stacks are installed using spool pieces which simulate the pressure drop characteristics of the stacks.

Figure 2.2-4 1MW CARBONATE FUEL CELL MODULE:
Module Design Minimizes Field Installation Labor

The power plant is now under construction. A computer rendition of the plant is shown in Figure 2.2-5. The plant is scheduled to operate in the 1995-1996 time frame.

Figure 2.2-5 SCDP POWER PLANT:
Construction of this World's Largest Carbonate Power Plant is Underway

2.3 100MW-CLASS POWER PLANT DESIGN

After gaining experience from the early MW-Class small size power plants, and with maturing of stack and BOP integration experience, ERC expects to introduce the 100MW-Class (100 to 400 MW) baseload central power plants operating on natural gas and/or coal gas.

In an earlier study (2-1, 2-4), ERC, in collaboration with Fluor Daniel, conducted a detailed EPRI Technical Assessment Guide Level 2 plant design, performance and cost analysis of four complete coal gas fueled carbonate fuel cell systems (CGCPP). This study has since been published (2-2). All four CGCPP systems, consisting of three different gasifier types (entrained bed, fluidized bed, and moving bed) and two different oxygen sources, indicated very high efficiency (45 to 47% on coal (HHV) and very close ranking in terms of cost-of-electricity (COE). The performance, cost, and COE of these cases indicated that attractive CGCPP systems can be configured with most of the available gasifiers. Limited parametric variations conducted in this earlier study showed that further improvements in CGCPP efficiency and COE is achievable through optimization. Parametric studies on plant size and location were also conducted and showed that these variables had significant impact on the cost-of-electricity. This highlights the necessity of comparing any power plant design on a consistent basis.

As part of that same study (2-4), ERC has also identified that 100 MW-Class systems can be configured with methane-producing gasifiers projecting system efficiencies approaching 54% on coal (HHV). Although methane-producing gasifiers are not in active development, a successful development of this process may provide a very attractive option for producing high efficiency energy conversion with low COE.

Also, three conventional coal technologies representing the presently used pulverized coal (PC), Atmospheric Fluidized Bed (AFBC) and advanced IGCC systems were analyzed to the same level of detail as the carbonate fuel cell systems using the same design and economic basis. The results indicated that CGCPP systems are significantly superior to the present day technologies such as PC and AFBC, and economically competitive with the advanced IGCC. The CGCPP systems indicated an efficiency advantage of 10 to 14% over the IGCC systems, with significant reductions in acid rain precursor (SO_x and NO_x), CO_2 emissions, and water requirements.

Using these prior results as the basis in the present study, the relative economics of natural gas versus coal gasification/fuel cell power plant systems were analyzed and compared at different energy price scenarios. Two 100MW-Class power plant designs were selected for economic evaluation. These designs, natural gas and "phased" coal gas, were analyzed on a common basis of consistent design and cost assumptions. The "phased" concept evaluated in this study involves constructing a plant to operate on natural gas initially and then adding a gasification block at a later date based on relative fuel costs. The results of cost and performance analysis of phased construction of 100MW-Class plants are discussed next.

2.3.1 RELATIVE ECONOMICS OF NATURAL GAS VERSUS COAL GASIFICATION FOR 100MW-CLASS POWER PLANTS

The relative economics of the natural gas versus coal gasification based power plant is strongly dependant on the energy price scenario. Natural gas price is expected to remain cheaper in the near term. The utility perception is that in the long-term, coal will be a cheaper source of energy. Since there will be a gradual transition, and furthermore since there may not exist a clear cut breakeven point of transition, ERC studied the option of introducing the phased construction of a 100MW-Class carbonate fuel cell power plant (results also presented elsewhere [2-3, 2-5]). The phased construction concept involves the construction of the plant for initial operation on natural gas with subsequent switching to coal gas as the economics become attractive.

This section describes the capital cost, performance characteristics and design considerations associated with the phased construction of the carbonate fuel cell power plant.

A 220MW carbonate fuel cell power plant was the basis of this study. The power block for the Phase-1 natural gas fueled facility consists of 18 clusters of carbonate fuel cell clusters of 10 MW each and a steam bottoming cycle. Each cluster consists of four 2.5MW modules, and each 2.5MW module is comprised of 12 fuel cell stacks of 300 cells. The balance of the plant process systems for the natural gas phase (Phase-1) includes a fuel gas treating system with a conventional reformer to produce hydrogen for hydrosulfurization, while the coal phase (Phase-2) includes a coal gasification system. The coal gasification plant is based on the Kellogg Rust Westinghouse (KRW) fluidized bed gasification system with a hot gas cleanup sulfur removal system. A fuel gas expander will also be added for additional power generation during the coal phase. This gasification plant design was analyzed to TAG 2 level in an earlier study (2-4).

The Phase-1 natural gas system is depicted in Figure 2.3-1. Natural gas is heated in the reformer/fired heater, mixed with hydrogen and then fed to the desulfurization beds. The hot desulfurized fuel gas is mixed with steam to avoid Boudouard carbon deposition, then heated to 565°C using anode exit gas prior to entry into the internally reforming carbonate fuel cell. The hydrogen necessary to drive the fuel cell anode half-cell reaction is produced by internal reforming and shift reactions in the fuel cell.

Approximately 85% of the heating value of the fuel gas is converted to electricity in the anode. The anode exit gas steam is then cooled by preheating the anode feed gas and by superheating steam. The cooled gas is mixed with preheated excess air and reacted in a catalytic combustor. The catalytically combusted cathode feed gas at 600°C provides the required carbon dioxide and oxygen to carry out the cathode side electrochemical half-cell reaction. Twelve fuel cell stacks are joined electrically in a combination of series and parallel circuits to achieve approximately 1000 VDC on each 2.5MW module.

The process gas exits the cathode at a temperature of 677°C. This gas is then routed to the Heat Recovery Steam Generator (HRSG) where 953 psia, 565°C superheated steam and 55 psia saturated steam is produced with the waste heat before the cooled flue gas is vented to the atmosphere.

Figure 2.3-1 PRELIMINARY PROCESS FLOW DIAGRAM OF THE 100MW-CLASS NATURAL GAS FUEL CELL POWER PLANT:

The Design Configuration Considers Anticipated Switch-over to Coal Gasification at a Later Date

Figure 2.3-2 is a block flow diagram of the completed Phase-2 CGCPP plant. The gasification unit is fed by 1084 short tons per day (st/d) of 95 mole percent oxygen and 1800 st/d of as-received Illinois #6 coal as well as limestone and steam. In-bed bulk sulfur removal using limestone absorbent is used to remove most of the sulfur compounds in the raw syngas. The 1010°C raw syngas from the gasifier is then quenched and cooled to 515°C before entering the zinc ferrite hot gas cleanup sulfur removal beds. Trace sulfur compound removal is accomplished with zinc oxide. The clean fuel gas at 422 psia is then expanded through a two-stage expander with interstage reheat to 15.5 psia. This provides additional power and the pressure necessary to route the feed gas to the carbonate fuel cells. Coal fines, spent limestone, and ash are conveyed to the sulfation boiler where 90% of the calcium sulfide in the gasifier ash is converted to the more stable calcium sulfate and the residual carbon is combusted. The performance characteristics of the Phase-1 natural gas and Phase-2 coal gasification plants are compared in Table 2.3-1. The natural gas power plant operates with an efficiency of 55% (HHV). It has 12% efficiency and a 50% cost advantage over the coal power plant.

Table 2.3-1 COMPARISON OF 100MW-CLASS POWER PLANT CHARACTERISTICS:
100MW-Class Carbonate Power Plant has Attractive Performance
and Cost Characteristics for Natural Gas as Well as Coal Gas Fuels

	Stand-Alone Natural Gas Fueled Carbonate Fuel Cell Power Plant	Phased Construction ⁽¹⁾ Natural Gas/Coal Gasification Carbonate Fuel Cell Power Plant - KRW/O ₂ /HGC
Net Power Production (MW)	220	220
Fuel	Natural Gas	High Sulfur Bituminous Gas
Heat Rate (Btu/kWh)		
(HHV)	6040	6860 ⁽¹⁾
(LHV)	5440	
Capital Cost Relative \$/kW	1.0	2.11
CO ₂ emitted (lbs/MWh)	697	1514
SO _x emitted (lbs/MWh)	0.00025	0.0061
NO _x emitted (lbs/MWh)	0.0097	0.092
Water Usage (lbs/MWh)	2093	3315
Solid Waste (lbs/MWh)	-	268

(1) Coal operation only - Phase-II

Figure 2.3-2 BLOCK FLOW DIAGRAM FOR KRW FLUIDIZED BED GASIFICATION SYSTEM WITH HOT GAS CLEANUP:
A Higher Availability Results from the Flexibility of Switch-over to Coal Gas

2.3.2 DESIGN CONSIDERATIONS FOR PHASED CONSTRUCTION

Determination of the Phase-1 and Phase-2 process configurations and preinvestment trade-offs depends on the time delay between the start-up of the natural gas fueled Phase-I plant and the start-up of the coal fired Phase-2 plant. For this study, it was assumed that the natural gas fueled Phase-1 would operate for the first five years, with the coal fueled Phase-II plant in operation for the remaining twenty-five years. The base design configuration was chosen to optimize the operation of the coal fueled Phase-2 plant, with the resultant operational efficiency of the natural gas fueled Phase-I being highly dependent upon the surface areas and capabilities of Phase-2 equipment.

The fundamental process difference in the fuel cell power block between Phase-1 and Phase-2 operation is the reduction in the amount of methane reforming that occurs in the anode side of the fuel cell. This methane reforming helps to achieve a heat balance within the fuel cell unit when the plant is operating on natural gas during Phase-1. The reforming of methane, which is an endothermic reaction, acts as a heat sink and provides approximately two-thirds of the cooling required during Phase-1. The concentration of methane in the feed gas routed to the fuel cell anode decreases from 95 mole percent in Phase-1 to 1.9 mole percent in Phase-2, thereby decreasing the amount of methane reforming occurring in the fuel cell. The heat balance in the fuel cell unit during Phase-2 is maintained by the addition of a cathode recycle loop consisting of a cathode blower which allows additional air flow through the cathode, and the cathode heat recovery unit which removes additional heat by superheating high-pressure steam.

An additional major process difference in the fuel cell power block involves the larger steam flows in Phase-2. The steam and boiler feed water (BFW) systems are designed for the larger steam flows of Phase-2 and use a floating header pressure configuration. A floating header pressure system allows a constant volumetric steam flow to the inlet of the steam turbine, thereby optimizing its performance. The design high-pressure steam condition at full design flow during Phase-2 is 1465 psia at 565°C; the comparable steam condition at full-rated flow during Phase-1 is 953 psia at 564°C. To accommodate the larger steam system required for Phase-2, additional BFW pumps and cooling tower cells are added during the construction of this phase.

Major equipment differences in the fuel cell power block between the component sizing of Phases-1 and -2 are as follows:

- The power conditioner was designed to handle the larger amount of DC power produced by the natural gas fueled plant in Phase-1.
- The cathode air blower was designed to handle the larger air flow required for the natural gas fueled plant in Phase-1.
- The anode and cathode inlet ducts were designed to handle the larger anode and cathode inlet gas flows required for the coal gasification Carbonate Fuel Cell power plant in Phase-2.

In order to improve the availability of the overall plant during the operation on coal, the natural gas feed system from Phase-1 was retained and utilized as a backup fuel source during Phase-2. It was assumed for this study that the overall plant availability in Phase-2 increased from 85 to 91% as a result of this natural gas backup fuel.

2.3.3 ECONOMIC BREAK-EVEN ANALYSIS

An energy forecast was made to the year 2040 by using a natural gas and coal price forecast based upon a High Oil Price Scenario forecast consistent with the 1991 DOE Energy Information Agency High Oil Price Scenario (2-6). These energy prices and the construction schedules shown in Figure 2.3-3 were used as a basis for Cost-of-Electricity (COE) calculations to determine a phase-in point for the coal based phase. As shown in Figure 2.3-3, the phased construction and operation schedule is based upon natural gas operation for five years, then switching to a coal based operation for an additional 25 years. Two different plant startup dates, 2000 and 2010, were used for the break-even analysis.

As can be seen in Figure 2.3-4 for the year 2000 start-up date, operation of either the Stand-Alone Natural Gas plant or the Phase-1 plant fueled by natural gas for 30 years is the preferred option since this mode of operation results in the lowest COE for the power plant operation. The Stand-Alone natural gas plant is a carbonate fuel cell power plant that has no preinvestment for a Phase-2 coal refueling option. For the year 2010 start-up date, phasing of natural gas to coal after five years gives the lowest COE. This can be seen by the change in position of the coal versus natural gas fueled power plant COE values. This change in the relative COE positions of the natural gas versus phased coal refueling option results in an economic break-even crossover point as shown in Figure 2.3-4. By utilizing the assumptions in this simplified analysis, the phase-in break-even point would lie approximately between the years 2004 to 2006.

2.3.4 COMPARISON WITH COMPETING TECHNOLOGY

Table 2.3-2 compares the systems of this study to the present day as well as emerging alternate coal based technologies. These alternate technologies were studied in a previous study (2-4). Emissions for the carbonate fuel cell power plants are extremely low, water usage is also low, and overall thermal efficiencies are higher when compared to competing technologies. The CGCPP has about 15% efficiency advantage over the nearest competition, the IGCC system. Although the capital cost is somewhat higher, the COE of CGCPP is lower than the PC and AFBC systems and quite comparable to the IGCC.

NOTES:

- = ENGINEERING AND CONSTRUCTION ACTIVITIES
- = FULL EPC RELEASE, ENVIRONMENTAL PERMITS HAVE BEEN ISSUED
- = START-UP OF FACILITY

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Figure 2.3-3 PHASED CONSTRUCTION SCHEDULE SUMMARY AND KEY MILESTONES:

Two Different Plant Start-up Dates, 2000 and 2010, Were Analyzed

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Figure 2.3-4 COST-OF-ELECTRICITY BREAK-EVEN ANALYSIS:
For Plants Starting in Year 2005 Time Frame, Phase Construction Appears Attractive

Table 2.3-2 COMPARISON OF 100MW-CLASS POWER PLANT CHARACTERISTICS:
100 MW-Class Carbonate Power Plant Project Attractive Performance
and Cost Characteristics for Natural Gas as Well as Coal Gas Fuels

CARBONATE FUEL CELL POWER PLANTS			CONVENTIONAL POWER PLANTS		
	Stand-Alone Natural Gas Fueled Carbonate Fuel Cell Power Plant	Phased Construction ⁽¹⁾ Natural Gas/Coal Gasification Carbonate Fuel Cell Power Plant - KRW/O ₂ /HGC	PC (2-4) - Air-Blown - Coal Cleanup - Denox & Wet FGD	AFBC (2-4) - Air-Blown - Coal Cleanup - In-bed Desulfurization	Advanced Gasification Combined Cycle Plant (2-4) - KRW/O ₂ /HGC (In-bed Desulfurized, External Zinc Ferrite)
Net Power Production (MW)	220	220	195.2	195.0	233.6
Fuel	Natural Gas	High Sulfur Bituminous Coal	High Sulfur Bituminous Coal	High Sulfur Bituminous Coa	High Sulfur Bituminous Coal
Heat Rate (Btu/kWh)					
(HHV)	6040	6860 ⁽¹⁾	10,571	10,780	8420
(BHV)	5440				
Capital Cost Relative \$/kW	1.0	2.11	2.05	1.94	1.78
CO ₂ emitted (lbs/MWh)	697	1514	2070	2170	1600
SO _x emitted (lbs/MWh)	0.00025	0.0061	1.6	3.2	0.16
NO _x emitted (lbs/MWh)	0.0097	0.092	1.00	0.81	1.00
Water Usage (lbs/MWh)	2093	3315	6000	5000	4800
Solid Waste (lbs/MWh)	-	268	NA	370	320

(1) Coal operation only - Phase-1

2.4 ENGINEERING OF FULL-HEIGHT STACK

In the DFC power plant design, the carbonate fuel cell stacks will be arranged in truck shippable modules, where each module will contain a number of identical carbonate fuel cell stacks. An example of such a module was shown in Section 2.2. The 2MW demonstration project stack submodule will be 11.3m x 2.6m x 3.7m and contain four full-height stacks. These stacks will consist of 258 cells of approximately 6,000 cm² cell area, with a nominal rating of 125 kW. The program efforts at ERC were dedicated to getting the full-height stack ready for field demonstration. The design has been finalized, manufacturability verified, and performance demonstrated in integrated system tests; details are discussed in this section. The engineering study has been published elsewhere (2-7).

2.4.1 FULL-HEIGHT STACK DESIGN DEVELOPMENT

Main features of ERC's stack include: 1) external manifolding, 2) cross-flow configuration, and 3) internal reforming. The important design considerations for the full-height stack are: transportability using a common carrier, manufacturing to controlled tolerances to maintain uniformity of mechanical contact, and uniformity of reactant flows in order to achieve performance uniformity.

ERC assembled a tall stack simulator and tested four tall stacks to resolve/verify design and manufacturing issues, including the manifold system, stack compression system, and the internal reformer design. A summary road-map of the improvements and their verification is presented in Table 2.4-1. The latest stack test, AF-100-4, verified the design incorporated in the SCDP stacks.

Table 2.4-1 STACK DESIGN ISSUES AND VERIFICATIONS:
Demonstration Stack Design Basis was Derived
from a Simulator and Tall Stack Tests

ISSUE	DESIGN ITERATION/VERIFICATION				
	Simulator Stack	AF-100-1 (70 kW)	AF-100-3 (125 kW)	AF-100-2 (125 kW)	AF-100-4 (125 kW) Demonstration Power Plant Stacks
STACK ASSEMBLY	X	X	*		
LIGHTWEIGHT MANIFOLD SYSTEM		X	X	*	
FLOW DISTRIBUTOR	X	X		X	*
STACK COMPRESSION SYSTEM		X		*	
STACK ENCLOSURE			*		
INTERNAL REFORMER		X		X	*
TRANSPORTATION		X	*		

X Denotes Design Verification/Iteration

** Denotes Design Selected for SCDP Stacks

Design Development

The number of cells in the stack has been selected based on truck transportation considerations. The demonstration stack is approximately 3.5 meter tall, incorporating 258 cells. A photograph of a tall stack having the same cell area as the demonstration power plant stack is shown in Figure 2.4-1. Full-height stack transportation design, maintaining shock and vibrations below a 2G force, and the logistics for handling, lifting and rigging were originally resolved using a factory-conditioned 234-cell stack which was successfully transported from Connecticut in a 2.1m x 2.1m x 3.4m rectangular container to a west coast utility test site. Smaller stacks have been transported by air and truck to other U.S. and European sites. A photograph of the full-height stack being transported on a highway is shown in Figure 2.4-2. The stack uses an enclosure which, in addition to providing protection during shipping, allows control of the environment around the stack during operation. The demonstration power plant stacks will be transported in four-stack submodules to test site. Using these tall stack transportation experiences, the design and the logistics for the submodule shipping have been defined.

Figure 2.4-1 PHOTOGRAPH OF A TALL DFC STACK:
This is Approximately 3.5 Meters Tall and Easily Transported Using a Common Carrier

Figure 2.4-2 PHOTOGRAPH OF THE STACK IN TRANSPORT:
Full-Height Stack Being Trucked from the Manufacturing Facility for Testing at ERC

The stack manifolds are used for receiving reactants from the system piping, distributing them uniformly through the cells, and collecting them for further processing. The ERC stack uses simple, cost-effective lightweight sheet metal manifolds. A dielectric separator is used in between the manifold and the stack for electrical separation. A lightweight manifold compression system operating at the stack temperature is used. Selective strengthening of the manifold is required for managing thermal distortion during operation. The basic design of the manifold body and compression system have been developed through detailed thermomechanical analyses, and further refined through stack test experiences. The design selected for the 2MW demonstration stacks have been verified in a 258-cell stack test. The stack was tested 1,800 hours with two planned thermal cycles. The requirements for gas sealing efficiency and electrical isolation have been met. Figure 2.4-3 shows that a gas sealing efficiency of five times higher than the demonstration stack goal has been demonstrated in a tall stack test.

The carbonate fuel cell is designed to operate with a high utilization of the anode and cathode side reactants to achieve a high heat rate. This dictates a requirement for uniform flow distribution between the cells in a stack. The factors which contribute to the nonuniformity are variations in skin friction loss, momentum loss and hydrostatic head pressure along the height of the stack. The manifold in the ERC stack incorporates a flow distributor design to compensate for flow biasing towards the bottom of the stack and to achieve the desired cell-to-cell flow uniformity. A full-height stack simulator incorporating the flow fields and flow resistances of a carbonate stack was used to evaluate different flow distributors. Both the oxidant and fuel side distributors were developed during the stack simulator tests.

Figure 2.4-3 MANIFOLD SEAL EFFICIENCY OF FULL-HEIGHT STACK AF-100-4:
Manifold Seals Achieved Five Times Better Efficiency than the Demonstration Goal

Improvement achieved in the fuel side flow distribution through the use of flow distributor is shown in Figure 2.4-4 as an example. Without a flow correction, a 5% variation in fuel flow from cell-to-cell is expected. A 70kW stack tested with this design indicated top-to-bottom voltage and thermal gradients which were traceable to the fuel flow variations along stack height. The first generation flow distributor design improved fuel flow variation to within 2%. This design showed a slight voltage variation when evaluated in the Stack AF-100-2, which was also consistent with the predicted flow pattern. The distributor design was further refined for the 2MW demonstration power plant stack predicting a fuel flow variation of less than 1% (Figure 2.4-4). A higher flow variation can be tolerated on the cathode and a <4% flow variation is predicted for flow distributor design incorporated in the cathode manifolds.

Maintenance of constant stack compression pressure throughout the stack life is very important for performance as well as transportation considerations. Simplicity and compactness are also required for packaging and cost-effectiveness. The old design used in the first tall stack test occupied too large a space and, most importantly, resulted in over 1.9 kg/cm² stack compression variation in the 234-cell stack test. A compact system providing only <0.2 kg/cm² compression pressure variation over the useful life was designed. This improved design was verified in a 246-cell stack test, AF-100-2 (Figure 2.4-5).

Figure 2.4-4 IMPROVEMENT IN FUEL SIDE FLOW DISTRIBUTION
USING FLOW DISTRIBUTOR:
Less Than 1% Fuel-Side Cell-to-Cell Flow Variation is Expected

Figure 2.4-5 FULL-HEIGHT STACK COMPRESSION PRESSURE LIFEGRAPH:
Stack Compression Pressure within 0.2 kg/cm² was Maintained with the Current Design

The full-height stack design incorporates both the Indirect Internal Reformer (IIR) and Direct Internal Reformer (DIR) concepts. Tall stack tests showed that the Fuel-Turn/Oxidant-Out corner of the stack appeared to operate warmer than other parts of the stack primarily because of local higher current density and minimal local cooling. This part of the stack was designed intentionally to operate the warmest to maximize methane conversion in the indirect internal reforming section. The indirect reformer design was modified to achieve uniform heat removal. This modified internal reformer design was verified in 2kW and 20kW stack tests, and then incorporated into the tall stack design.

Stack Manufacturing and Test Experience

ERC has completed four full-height stack tests for design verification improvements to date. A 70kW stack containing 234 cells of 4,000-cm² nominal cell area was tested in 1991-92. The stack was pretested at ERC, thermally cycled twice, and operated at full power. The stack was then crated and truck transported out to PG&E's 100kW pilot plant in San Ramon, California. The stack was then operated in an integrated system mode using pipeline natural gas and output power provided to the utility grid. The stack performance characteristics at ERC were essentially reproduced, verifying ERC's stack thermal cycling as well as stack transportation procedures. System integrated operation at PG&E was conducted for approximately 1,400 hours, to give a total of 2,000 hours of testing for the stack. The majority of the testing was at approximately 65% load, and 70kW full-power output was also briefly demonstrated. A total of 33MWh of electricity was generated and supplied to the utility grid. This test provided operating experience of stack as well as BOP which was later utilized to develop a stack enclosure for environment control and build a robust stack test facility at ERC.

When the FCMC manufacturing facility began operation in 1992, a 246-cell stack of 6000-cm² cell area using an improved design was built at the facility. The first product from FCMC was tested at a newly built 100kW-Class subscale power plant at ERC's Danbury site. The test facility matches power plant configuration and allows operation and evaluation of 100kW-Class stacks and balance-of-plant equipment in power plant integrated operation. A photograph of the stack on test at this facility is shown in Figure 2.4-6.

The first stack was tested for 250 hours (Figure 2.4-7), of which 100 hours was at 123 kW. This test provided an evaluation of the environment controlled stack enclosure which was introduced for the first time in this test. The stack performance at different load levels is shown in Figure 2.4-8. The stack produced an average cell voltage of 0.8 V/cell at the rated power which is consistent with the BOL (beginning-of-life) performance goal of the 2MW power plant demonstration. The group-wise performance variation was only $\pm 2.5\%$. At the 123 kW operating point, the plant achieved greater than 50% overall efficiency level (LHV) of natural gas energy conversion to direct-current electricity. This probably represents the highest electric generation efficiency ever achieved using natural gas in a single-cycle machine.

Figure 2.4-6 STACK ON TEST AT ERC:
World's Highest Carbonate Power was Produced in this Facility

Figure 2.4-7 STACK AF-100-3 LIFEGRAPH:
The Stack was Initially Tested for 250 Hours of Which 100 Hours was at 123 kW

Figure 2.4-8 120kW STACK PERFORMANCE (Natural Gas; 65% Fuel Utilization):
The Stack Produced 800 mV/cell at 125 mA/cm² Consistent with Goal for 2MW Power Plant

Following the first stack test, improvement in stack external hardware design was identified and implemented in a second 120kW test (third full-height stack test). This stack, (AF-100-2) with improved hardware, was tested during the fourth quarter of 1993 for 1,800 hours and included: 870 hours at 125 mA/cm² operation, two thermal cycles and diagnostic testing (stack lifegraph shown in Figure 2.4-9). This test produced ~134MWh electricity from the pipeline natural gas. The compositions of the natural gas used in the test is shown in Table 2.4-2. The heating value of the gas varied ~1% during the course of the test.

The stack characteristics were checked after each thermal cycle and 140 mA/cm² operation was conducted at 1,632 hours. The performance of the stack at different test stages are reported in Figure 2.4-10. Less than 3% change in heat rate was observed during the entire testing.

Cell performance, as measured by the group voltages, was very uniform ($\pm 1.5\%$) except for Group 2 which evaluated a non-standard cell design. This improvement in performance uniformity, from over $\pm 2.5\%$ for the first two full-height stack tests, appears to have resulted from better fuel flow distribution and improved stack components tolerance achieved for Stack AF-100-2. This stack test was used to confirm the stack compression system and manifold system design. Nonetheless, a slight voltage variation along the vertical height of the stack was consistent with the predicted flow pattern. Subsequently, the distributor design was further refined, predicting fuel flow variation of less than 1%. This improved design was incorporated into the next stack test.

Figure 2.4-9 120kW STACK OPERATING HISTORY:
Stack AF-100-2 Produced 134MWh Electricity from Pipeline Natural Gas

Table 2.4-2 NATURAL GAS COMPOSITION FOR THE ERC TEST:
A Small Change in Natural Gas Heating Value was Encountered

COMPONENT %	~600h	~1600h
CH ₄	95.6	95.6
C ₂ H ₆	2.3	1.7
C ₂ +	0.5	0.2
N ₂	0.5	1.5
CO ₂	1.0	1.0
HEATING VALUE Btu/Ft ³ (LHV)	925	915

The last stack test, AF-100-4 (258-cell; 6000-cm²), reflected an optimized design attained through earlier tests. This stack is identical to the demonstration stack design. Improvements in flow distributor and internal reformer design were incorporated. These accomplishments are reflected in uniformity and stable stack performance with high fuel utilization. Stack AF-100-4 completed 1,200 hours of testing, including one planned thermal cycle. The stack open circuit voltage distribution in 6-cell groups, shown in Figure 2.4-11, indicated only 0.2% variation. This demonstrates excellent manufacturing reproducibility. This stack produced 130 kW of power operating on pipeline gas (at 74% fuel utilization), with stack conversion efficiency of 55% (LHV) from natural gas to electricity. We believe this is the highest carbonate fuel cell power produced to date. The stack voltage variation at the 130 kW operation for each of the 6-cell groups is shown in Figure 2.4-12. Excellent performance distribution was observed; ~95% of the groups were within $\pm 1\%$ of the stack average performance.

Figure 2.4-10 120kW STACK PERFORMANCE (Pipeline Natural Gas):
Less Than 3% Change in Heat Rate was Observed

Figure 2.4-11 OPEN CIRCUIT UNIFORMITY:
Excellent Manufacturing Reproducibility

Figure 2.4-12 PERFORMANCE AT 130kW OPERATION
(Natural Gas; 74% Fuel Utilization):
Excellent Performance Distribution

The stack was thermally cycled and the stack performance, as well as group-to-group performance, remained essentially unchanged. Thermal profile of the Stack AF-100-4, reported in 2.4-13, shows that significant improvement in thermal uniformity was achieved by the modified internal reformer design. The oxidant gas is used for heat removal from the stack. Oxidant exhaust temperature approached the warmest cell temperature to within 20°C, as opposed to 100°C observed in earlier non-optimized designs. The NO_x and SO_x emissions from the test were measured. The emission levels were found to be negligible (Table 2.4-3). This represents a clean power production unmatched by any other fossil fuel based power conversion technology.

Table 2.4-3 VERIFICATION OF ENVIRONMENTAL CHARACTERISTICS:
Low Levels of NO_x, SO_x and Noise Verified

System Test	NO _x ppm	SO _x ppm	Sound db
125 kW ERC Test	0.04	<0.01	~60* at 10m

* Excludes electric load

a. Thermal profile using baseline IIR, Stack AF-100-2 at 140 mA/cm² (MW-Class System; 62.5%/65% fuel/oxidant utilization)

b. Thermal profile using Modified IIR, Stack AF-100-4 at 140 mA/cm² (MW-Class System; 74%/74% fuel/oxidant utilization)

Figure 2.4-13 IMPROVEMENT IN THERMAL UNIFORMITY:
Improvement in Thermal Uniformity Achieved by Modifying the IIR Design

The Stack AF-100-4 test was conducted in an enclosed area. The sound noise level of the mechanical and flow system of the test was measured. The data showed that the noise level is low, comparable to average street level noise, and normal conversation could be carried out around the test area. Additional tests have shown that the noise drops to 60 db at 10 meters when the "open space" condition is achieved.

2.5 CONCLUSION

As a first step towards commercialization, the demonstration 2MW power plant design has been defined; power plant construction initiated; operation is expected to start in the third quarter of 1995.

System analysis of next generation 100MW-Class power plants has revealed that in the design of the power plant with respect to choice of fuel may be dependent on the operation time period. Plants starting in the early part of 2000 may be designed for natural gas, and plants starting after year 2006 may be designed for dual fuel, optimized for coal gas operation.

The DFC stack design for the demonstration power plant was finalized, manufacturability verified and attainment of performance demonstrated in integrated system tests.

3.0 MANUFACTURING FACILITY DEVELOPMENT

FCMC, ERC's wholly-owned subsidiary for the manufacture of carbonate fuel cell stacks, established a manufacturing facility with private investment to produce stacks for the full-size power plant demonstration project(s) and gain necessary experience for the commercial manufacturing facility design. Possibly the largest carbonate fuel cell manufacturing facility in the world, occupying 5,800 square meter area, and having a production capacity of 10 MW/yr on a three-shift basis, was made operational and the manufacture of stacks for the first full-size demonstration project was initiated.

3.1 INTRODUCTION

The Fuel Cell Manufacturing Corporation (FCMC), a wholly-owned subsidiary of ERC, was established in 1989 to provide manufacturing support for ERC's commercialization effort. The primary objectives of FCMC are:

- To provide a manufacturing facility with the capability of manufacturing at least two megawatts of fuel cell stacks per year in support of technology demonstration projects.
- To provide experience and planning for manufacturing capacity scale-up to commercial facilities capable of up to 400 MW of annual fuel cell stack production.
- To design, build, and operate the commercial-scale facilities.

Attainment of the first objective was the focus of the current task.

3.2 STATUS

FCMC, located in Torrington, CT, occupies a 5,800 square meter facility strategically located within one mile of a major highway for easy truck accessibility. The building is fully air-conditioned and humidity controlled where necessary. Carbonate fuel cell manufacturing processes developed at ERC were scaled-up and transferred to FCMC. This facility is fully equipped and features technologically advanced manufacturing equipment for powder blending, slurry preparation and tape casting. Anodes and matrices for stacks are tape cast on FCMC's state-of-the-art casting machine shown in Figure 3.2-1. This machine was custom designed for these operations with input from ERC's R&D experience, and is capable of casting approximately 10 MW worth of components (anodes and matrices) annually based upon a single shift operation. A state-of-the-art catalytic incinerator has been installed to dispose of all organic vapors generated by the various processes. Numerically controlled computerized presses are in place and used for pressing, sheet metal forming and sizing operations. Large capacity batch retort, rotary kiln and continuous belt furnaces have been installed for the various heat treatment operations required for active component manufacturing. The equipment in place is capable of 10 MW/yr production on a three-shift operation.

Figure 3.2-1 TAPE CASTING MACHINE:
FCMC Tape Casting Machine Capable of Casting up to 10 MW of Active Components Annually Based Upon a Single Shift Operation

The plant layout is designed to facilitate smooth and efficient material flow from incoming raw materials through the various processing operations, to the active component subassembly and stack assembly areas, and finally to the stack shipping area where the finished stacks are loaded onto a truck for customer delivery. Figure 3.2-2 is a photograph showing a section of FCMC's subassembly area where the various components for the repeating cell packages are brought for assembly.

Figure 3.2-2 REPEATING COMPONENT SUBASSEMBLY AREA:
Various Components for Repeating Cell Packages are Brought for Subassembly

Quality assurance is emphasized during all manufacturing processes and procedures at FCMC. Quality assurance work stations are located throughout the factory to ensure immediate feedback of in-process data to the operators. Figure 3.2-3 shows a state-of-the-art coordinate measurement machine (CMM) located in the subassembly area for complete active component quality inspection. This CMM is capable of providing total dimensional analysis of the components. This equipment represents an improvement in measurement precision and repeatability with a reduction in labor associated with QA/QC of the repeating components.

Figure 3.2-3 COORDINATE MEASUREMENT MACHINE (CMM):
CMM Provides a Measurement Precision and Repeatability with a Reduction in Labor

Once the active component packages are subassembled, they are transferred to the final assembly area for stacking. A unique stack assembly work station has been designed and installed which ensures precision alignment of cell packages during stacking of full-height stacks. A photograph showing final stack assembly at this station is shown in Figure 3.2-4. Once the repeating cell components are stacked, the stack is manifolded and insulated. A final step, as shown in Figure 3.2-5, is to place the stack in an enclosure and make it ready for shipping. This enclosure allows control of the external stack environment during shipping and fuel cell operation. Finally, as shown in Figure 3.2-6, the fuel cell stack is loaded on a truck to be shipped to the customer site for operation.

FCMC is currently fully staffed for 2 MW annual production. The staff is organized into quality assurance, process engineering, shop operations, facilities engineering and materials processing groups. Manufacturing work units consisting of small groups of employees working independently are utilized to improve quality and productivity. Each group consists of process operators working with a team leader who has received training in team organization to supplement his specialized functional skills. FCMC's work concept emphasizes total employee involvement in product improvement and quality control decisions.

Figure 3.2-4 FINAL STACK ASSEMBLY WORK STATION:
Ensures Precision Alignment of Cell Packages During
Stacking of Full-Height Stacks

Material and processing cost reduction has been an on-going objective for FCMC. Cost reduction has been realized by working closely with vendors on material specifications, alternative manufacturing methods and substitute materials. Identifying and qualifying new vendors for multiple vendor sourcing has resulted in lower cost and improved product quality. Make-buy decisions are considered and evaluated for selected materials.

The facility is fully operational. On-going process parameter optimization and the continuing efforts in process control have resulted in significant improvements in manufacturing yields throughout the plant. Direct yield comparisons are complex because specifications are continually being tightened for improved performance. For example, electrode tape casting yields have improved by 89% (comparing 1994 and 1992) while the thickness tolerance has been reduced by 33%. Overall manufacturing yields for matrix assemblies have remained constant while variations of thickness, porosity, density and visual inspection have been tightened.

Figure 3.2-5 STACK ENCLOSURE ASSEMBLY:
Stack is Enclosed in Protective Enclosure for Protection During Shipping
and Control of Stack External Environment During Operation

For this program, three full-height stacks of 6,000 cm² area cells have been manufactured for testing at ERC for design and manufacturing facility qualifications. Construction of stacks for the full-scale demonstration power plant is going at this time. This experience will provide the basis for further manufacturing simplification for cost reduction and design of a large commercial manufacturing plant.

3.3 CONCLUSION

A stack manufacturing facility capable of production of fuel cell stacks to support demonstration projects is fully operational, and construction of stacks for the first demonstration project is in progress at this time.

Figure 3.2-6 STACK READY FOR SHIPMENT:
Stack is Loaded on a Truck Inside FCMC's Facility

4.0 TESTING FACILITY DEVELOPMENT

ERC has designed and built a versatile subscale power plant for evaluation of full-height carbonate stacks and balance-of-plant (BOP) equipment. This power plant can simulate ERC's MW-Class power plant operation with natural gas, and can also simulate the 100 MW-Class coal/biogas plants. Over 6,000 hours of operation of the power plant has been demonstrated. This test experience has resulted in improved stack and BOP equipment design, and has trained fuel cell power plant operators.

ERC has also participated in the design and construction of a flexible 20 to 100kW facility at a gasifier plant site for testing of a stack on a coal gasifier slip stream. A 20kW stack test has been conducted for 4,000 hours on this facility.

4.1 INTRODUCTION

ERC has developed a flexible 100kW-Class power plant for evaluation of candidate power plant designs and their operations. This system can simulate the MW-Class as well as 100MW-Class systems. Features of this testing facility include distributed control, operation on pipeline natural gas, a natural gas cold cleanup gas system, a catalytic anode tail gas converter and a cathode gas heat exchanger (HRSG) which integrates generation of the steam needed for the fuel cell process. This facility also features cost-effective simulation of coal/bio-derived fuel compositions blended from natural gas, CO₂ and H₂O feeds. A hot gas recirculation blower is also included to provide for higher heat removal during coal/biogas operations.

Another facility, built in conjunction with DESTEC, Haldor Topsoe International (HTI) and Electric Power Research Institute (EPRI), is capable of testing a 20kW stack using a slipstream from a coal gasifier facility as a fuel and simulating operation of the 100MW-Class power plant.

The details of the design and operation of the 100kW-Class power plant are described below.

4.2 100kW-CLASS POWER PLANT

This power plant was designed to evaluate carbonate fuel cell stacks and BOP equipment in system integrated operations, therefore, features were included to allow simulation of both the MW-Class and 100MW-Class power plant operations. A simplified flow diagram of the power plant, shown in Figure 4.2-1, shows the major mechanical system components and their interconnections. The plant normally operates on natural gas, but can also simulate coal/bio-derived fuel gases cost-effectively from natural gas, additional carbon dioxide, and steam. The steam is produced in a heat recovery steam generator (HRSG) which integrates recovery of heat from the cathode process gas stream and steam generation needed for the anode gas stream.

Figure 4.2-1 100kW-CLASS POWER PLANT PROCESS FLOW DIAGRAM:
Provides Evaluation of 100kW-Class Stacks and BOP
Equipment in Power Plant Operation

Sulfur-containing odorant compounds are removed from the natural gas fuel feed by a cold gas cleanup system, shown in the photograph of Figure 4.2-2. A high temperature cleanup system is available and will be evaluated in the SCDP plant. The cold temperature system is being evaluated as an alternative because it offers significant opportunities for power plant design simplification. The cleanup unit in the 100kW system offers full flexibility of choice between types of cold cleanup absorbents with change-out when needed. The operating experience will be used to develop a standard cleanup design for the modular power plant.

The cleaned fuel and water are introduced to the system through the HRSG where they are heated by the cathode off-gas. The water is converted to steam inside the HRSG before being mixed with the fuel. The fuel-steam mixture is further heated in a heat-exchanger using heat from the anode exhaust stream before being introduced to the carbonate fuel cell stack, where a percentage of the fuel is converted to electricity.

Figure 4.2-2 NATURAL GAS COLD CLEANUP SYSTEM:
Will Provide Simplification of Power Plant Design

The anode exhaust from the fuel cell stack then enters a converter. The converter recovers heat from unused fuel and prepares a CO_2/O_2 containing cathode feed stream. This tail gas converter utilizes exhaust gases which have a wide range of heating values. Earlier tests with a 70kW stack found that the typical combustion-type of design is not suitable for fuel cell use because of flame instability with low Btu fuel cell exhaust and high NO_x production. The catalytic converter design used in the 100kW power plant, shown in the photograph in Figure 4.2-3, offered the opportunity for resolving these issues and at the same time simplifying the fuel cell power plant design. The anode tail gas is combusted in the converter with fresh air from the blower, and the converter gas stream, now with sufficient CO_2 and O_2 , then enters the oxidant manifold of the stack.

A portion of the cathode exhaust may be recycled by the hot recycle blower as needed for heat balance, particularly for coal gas operation. The cathode gas then exits the facility through the cathode HRSG where some of the sensible heat is used to produce steam and preheat the fuel gases.

The facility has been constructed as a compact, skid-mounted unit. A photograph of this plant is shown in Figure 4.2-4. Another feature of the power plant is that the operation is controlled by a distributed control system which allows precise and largely automatic operation of the system. Operation, monitoring and control are executed by computerized software from a central control room. A photograph of this control room is shown in Figure 4.2-5.

Figure 4.2-3 CATALYTIC ANODE TAIL GAS CONVERTER:
Operated Stably; Opportunities for Further Improvements Identified

Figure 4.2-4 100kW-CLASS POWER PLANT PHOTOGRAPH:
6,000 Hours of Operation Achieved

Figure 4.2-5 PHOTOGRAPH OF THE FACILITY CONTROL ROOM:
Allowed Smooth Operation using Commercial Distributed Control System

4.3 POWER PLANT OPERATING EXPERIENCE

The 100kW power plant accumulated over 6,000 hours of flawless operation. This included several hot-tests to qualify and evaluate BOP designs, and also included three stack tests. Two of these stack tests approached 2000 hours each. In all of the operations there were no BOP related shutdowns. This power plant has achieved greater than a 50% overall efficiency level (LHV) of natural gas to direct electric power conversion. This reflects the highest electrical generation efficiency ever achieved using natural gas in a single-cycle machine.

The catalytic combustor converts unused fuel to CO_2 for feed to the cathode. It was used both in start-up mode and during steady state operation under full system integration. Experience with the combustor found it to be quite stable under integrated mode. There were occasional hot areas in the catalyst bed, probably due to non-uniformity of the fuel gas distribution. Possible design and operational changes to mitigate this have been identified. During start-up mode, when an auxiliary fuel was being fed, there were occasions when the fuel ignited in the space above the catalyst bed. The ignition was probably catalyzed by oxide coatings on the walls of the chamber, and resulted in a stable flame front. While the burner operation was stable in this configuration, there was a tendency for the surface of the catalyst to overheat. Also, the production of NO_x tended to increase, as would be expected from a flame producing burner. The flame could usually be extinguished by adjustment of gas flows. Once the system was fully integrated with the anode tail gas, the system operated smoothly at steady state. Opportunities for improvement of the burner operation include adjustment of flow patterns to minimize the temperature imbalance in the catalyst bed. The addition of a properly designed baffle plate at the entrance of the tail gases, and adjustment of the auxiliary fuel flows through a choice of two entry ports have already improved the bed temperatures uniformity.

4.4 CONCLUSIONS

ERC has developed a versatile subscale power plant. Reliable operation on this power plant has been demonstrated. Both stack and BOP equipment designs have been developed through integrated system tests in this power plant. This is the first time that carbonate fuel cell stacks have been tested in a full fledged power plant mode.

5.0 STACK RESEARCH

To advance the DFC technology to the level of demonstration stack design, extensive design, engineering and testing effort was undertaken. Out-of-cell experiments, as well as 180 single-cells, 3 labscale (250 cm²) stacks, and 17 short large-area stacks were tested. Over 50,000 hours of stack test duration, virtually all of it at system conditions, have been accumulated, with individual stacks tested for up to 10,000 hours. Major milestones on performance improvement and cost reduction have also been attained. The test results show that a decay rate of only 2mV/1,000h and attainment of 40,000 hour life for cell hardware may be projected.

5.1 INTRODUCTION

Field demonstration of multi-MW size carbonate fuel cell power plant will be initiated in 1995-1996 (5-1), a step toward commercialization in the late nineties. The heart of the carbonate fuel cell power plant is the DC power block which is made up of DFC stacks. In this task, extensive vendor engineering, out-of-cell, ~180 single-cell, 3 labscale stacks (250 cm²), and 17 short large-area stacks (eleven 2kW, three 8kW, and three 20kW) tests were performed to improve ERC's DFC stack technology. The goal was to advance stack design from the level of laboratory test vehicle to that of demonstration power plant power block. The specific areas addressed included: 1) performance improvement, 2) resolution of endurance issues, 3) cost reduction, 4) operating issues, and 5) hardware design improvements.

Vendor engineering primarily focused on cost reduction and auxiliary hardware manufacturing. Single-cell tests were used mostly to evaluate active components design as well as manufacturing improvements. Distribution of single-cell tests with respect to different issues addressed are shown in Figure 5.1-1. About 50% of the cell tests were dedicated to evaluation of active components: anode, cathode, and matrix. A significant portion of the tests, 18%, were used to address operating issues such as start-up, shutdown, standby, and off-design operations. Designs and procedures qualified through single-cell tests were next verified in stack tests. The stack tests were also utilized for hardware design evaluations and resolution of stacking issues, as well as endurance verifications.

ERC used four types of stack test vehicles in this program: labscale, 2kW, 8kW, and 20kW size stacks. Three labscale stacks (250 cm²) were tested to evaluate endurance issues such as thermal cycleability and electrolyte redistribution. Eleven 2kW stack tests were performed to address cell area scaleup, operating issues, and designs of internal reformer, active components and end cell. Two 8kW size stacks were tested to study thermal management and system integration issues. One of the 8kW stacks was tested at a utility site on pipeline natural gas in fully automated, system integrated mode for 6,500 hours, producing electricity during 95% of the time. ERC also conducted three 20kW stack tests primarily to resolve issues related to tall stack assembly, thermal management, and stack auxiliary hardware designs (manifold geometry, manifold dielectric, manifold compression system, manifold gasket, stack compression system, stack container vessel, stack assembly fixture and thermal insulation). One of the 20kW stacks was tested on coal gasifier slip stream.

Figure 5.1-1 DISTRIBUTION OF SINGLE-CELL TESTS FOR DIFFERENT ISSUES:
 About 180 Single-Cell Tests Were Performed Primarily
 Focusing on Active Components Design Evaluation

The large area stack tests conducted in the program, major objectives and the test hours for each of the tests are reported in Table 5.1-1. As shown, virtually all of the testing conducted at ERC was performed at system conditions, providing useful operating experience at high reactant utilizations. Note that five stacks tested in the early part of the program used 4,000 cm² cell area, and this was increased to 6,000 cm² for latter stacks. Over 50,000 total stack test hours were accumulated in the program. Four of these tests exceeded 6,000 hours each. Each of the stacks tested in the program was post-tested in detail for design feedback leading to further improvements. The technology accomplishments attained in the program are discussed next.

5.2 PERFORMANCE IMPROVEMENT

Cell electrochemical performance improvement is needed to increase power density leading to stack cost reduction. Areas targeted for performance improvement included matrix ionic resistance, contact resistance, and electrode polarization. Out-of-cell, single cell, and stack tests were performed to evaluate various design options.

Matrix is the major resistance contributor, contributing to more than 70% of the total cell resistance. Therefore, its reduction will have a major impact on power plant efficiency. Increasing matrix porosity (without sacrificing strength or electrolyte holding capacity) may improve ionic resistance significantly. An innovative, high-porosity matrix has been evaluated in single-cell testing for resistance reduction, showing resistance improvement by about 15 mV under normal operating conditions. This improved design will be incorporated in stacks in the future.

Table 5.1-1 SUMMARY OF ERC'S PROGRAM SUBSCALE STACK TESTS:
Over 54,000 Hours of Stack Test Experience Accumulated at System Operating Conditions

STACK DESCRIPTION	MAJOR OBJECTIVE	LIFE, hr	OPERATING CONDITION**
2kW-Class			
- AF-2-9A *†	Transporting Issues	1,200	MW-Class Type-A
- AF-2-9B*†	Endurance	10,000	MW-Class Type-A
- AF-2-8†	Reforming Unit	700	MW-Class Type-A
- AF-2-11	Component Improvement	6,000	MW-Class Type-A
- AF-2-10	Area Scale-up	6,800	MW-Class Type-A
- AF-2-13	End Plate Design, Thin Anode	3,000	MW-Class Type-B
- AF-2-14	Evaluate Field Start-up	250	Mw-Class Type-B
- AF-2-15	RU Design	1,500	MW-Class Type-B
- AF-2-16	Design Improvements	900	MW-Class Type-B
- AF-2-18	Endurance	6,500	MW-Class Type-B
- AF-2-19	Bipolar Plate Design	1,300	MW-Class Type-B
8kW-Class			
- AF-8-2†	Height Scale-up	3,400	MW-Class Type-B
- AF-8-4	Power Plant Operation	6,500	MW-Class Type-B
20kW-Class			
- AF-20-1†	Tall Stack	1,300	MW-Class Type-A
- AF-20-4*	Coal Gas Operation	4,100	100MW-Class Coal
- AF-20-5	Thermal Management Verification	1,000	MW-Class Type-B

**SYSTEM DESIGNATION	CURRENT, mA/cm ²	FUEL COMPOSITION, %							OXIDANT, %				
		H ₂	CO ₂	CO	CH ₄	N ₂	H ₂ O	UTIL	O ₂	CO ₂	N ₂	H ₂ O	UTIL CO ₂
MW-Class Type-A	160mA/cm ²	32			27		41	75	9	13	73	5	50
MW-Class Type-B	140mA/cm ²				40		60	75	13	16	55	16	75
100MW-Class Coal	160mA/cm ²	50	35		5	1	9	85	13	12	63	12	25

* Represents cost share stacks (Test results discussed in Internal Reforming Molten Carbonate Fuel Cell Demonstation, Research Project RP3058-1 Report to EPRI).

† 4,000 cm² cell size; others 6,000 cm²

The oxide formed at the cathode-CCC (cathode current collector) interface has been found to contribute to about 10mV loss @ 160 mA/cm². This resistance increases with time due to the thickening of the oxide scale. Altering the structure and composition of the interfacial oxide to reduce oxide ohmic resistance has the potential of improving the oxide resistance. Several surface modification schemes have been evaluated under this program. One potential surface coating has shown improved resistance reduction in out-of-cell testing (Figure 5.2-1). However, for long-term effectiveness, the coating application method needs to be modified to obtain a uniform and consistent interfacial structure. This effort will continue in the future.

Figure 5.2-1 SURFACE MODIFIED CCC IMPROVES CCC-CATHODE CONTACT:
 Low and Stable Contact Resistance Using Surface
 Modification Demonstrated in Out-of-Cell Testing

At present, the performance of the baseline anode is adequate for commercialization. However, its improvement is still possible if its structure can become more porous. This approach has been verified in single cells with anodes of varying porosities (Figure 5.2-2). Based on this result, anode porosity of more than 50% is desirable. The present porous NiO cathode is projected to cause ~100 mV total polarization loss at 160mA/cm². Although this loss is acceptable, further reduction of this loss will enhance efficiency significantly. Incorporating additives to the baseline cathode has enhanced its performance (in-cell testing) by about 10 mV during single-cell testing. Further evaluation of the anode and cathode improvements in stack testing is planned.

Figure 5.2-2 CELL PERFORMANCE AS A FUNCTION OF ANODE POROSITY:
Anode Porosity Between 50-55% Appears Optimum

In the current program, improvements of the cathode-side collector and use of a compliant matrix in the stacks has resulted in a 35 mV performance enhancement, as qualified in Figure 5.2-3. Performance improvement of 35 mV corresponds to ~5% increase in power density maintaining the same heat rate. This performance exceeds the demonstration power plant stack performance goal quite comfortably (Figure 5.2-4).

5.3 ENDURANCE

To be economically competitive, a life goal of 40,000 hours is desired for a commercial carbonate fuel cell. Under this program, out-of-cell, single-cell and stack tests were performed to investigate stack endurance issues. Four of the stacks tested exceeded 6,000 hours; one attained 10,000 hours. Post-test observations and the results were thoroughly analyzed to gather information on endurance issues: a) anode, b) cathode, c) matrix, d) electrolyte management, e) bipolar current collector, and f) decay rate. These findings are discussed next.

Anode and Cathode

Nickel alloy anode has been developed at ERC to provide good electrochemical activity and strength against creep (5-2, 5-3). Under this program, the developed anode was further evaluated in long-term stack testing (7,000 to 10,000 hours). As shown in Figure 5.3-1, little changes of Ni-Al anode morphologies occurred after 10,000 hour stack operation. The creep strength was also found acceptable. Therefore, anode life of 40,000 hours can be projected. Furthermore, an advanced low-cost anode has been verified in cell and stack testing, without sacrificing performance and creep strength (discussed in Section 5.4).

Figure 5.2-3 STACK PERFORMANCE COMPARISON AT 160 mA/cm² (2MW-CLASS INTEGRATED SYSTEM CONDITIONS):
35 mV Performance Improvement Demonstrated in 2kW Stack Test

Figure 5.2-4 SHORT STACK PERFORMANCE EXCEEDED SCDP GOAL:
Subscale Stack Performance Exceeds Demonstration Stack Goal

**Figure 5.3-1 NO SIGNIFICANT CHANGE IN ANODE MORPHOLOGY
AFTER 10,000h OPERATION:**

Anode Life of 40,000 Hours can be Projected

In terms of the NiO cathode, its dissolution and deposition in matrix is one of the important issues in carbonate fuel cell research (5-4, 5-5). Cathode material loss and internal short circuiting could reduce cell long-term performance stability. ERC has found that a 750 μ m cathode may lose up to 40% of its total mass in Ni and still function within the desired performance limit (5-6). As Figure 5.3-2 shows, NiO surface morphology has not changed significantly in 10,000 hours. Therefore, life to short is an important life criterion. It has generally been agreed that the NiO cathode dissolves by acidic mechanism and an increase in melt basicity reduces solubility. Therefore, a CO₂ lean cathode gas and more basic melts can suppress Ni dissolution rate. The effect of Ni deposition on time to short has been studied extensively in cell tests (5-7). The time to short was found proportional to matrix thickness and inversely proportional to NiO solubility. A 40,000 hour life is achievable using a thick matrix operating under low CO₂ partial pressures (~0.1 atm) and at -100mV polarization with respect to a 33O₂/67CO₂ reference electrode. Using another reported correlation (5-8), a short-circuiting life of 40,000 hours can also be projected for ERC's design for atmospheric pressure operation. This was also verified in a recent study (5-9). However, for pressurized stack operation, Ni shorting may still be a concern.

Matrix

The matrix is a key component in carbonate fuel cell, providing ionic transport, reactant gas separation and perimeter seal formation. Under this program, the matrix was scaled up from 4,000 to 6,000cm² size and manufactured at FCMC's 2MW/yr pilot manufacturing facility. The scaleup matrix has been verified in stack tests.

During stack operation and thermal cycling, the matrix experiences both mechanical and thermal stress. Possible cracking of the matrix resulting from the above may result in gas leakage, lower efficiency, shorter life and power plant efficiency loss. Therefore, strong and tougher matrices to further improve good gas sealing capability are desirable. A matrix formulation was developed earlier (5-10), showing improved gas sealing characteristics in single-cell tests. The thermal cycleability of the improved matrix was evaluated under the present program. The stacks with the improved matrix have a better thermal cycleability, i.e., less increase of reactant cross leakage per thermal cycle. As an example, the 4,000cm² size stack AF-2-11 was thermally cycled six times, showing only small leakage increase during its 6,000 hour testing (Figure 5.3-3).

**Figure 5.3-2 NO SIGNIFICANT CHANGE IN NiO PARTICLE SIZE
AFTER 10,000h OPERATION:**
Cathode Life May be Projected to 40,000 Hours Under Atmospheric-Pressure Operation

Figure 5.3-3 STACK AF-2-11 OPERATING HISTORY:
Low Decay Rate Observed After 6,000 Hours and Six Thermal Cycles

Electrolyte Management

Electrolyte management has been recognized as one of the key issues in stack research. Electrolyte loss from the stack active components, mainly due to corrosion and creepage losses, electrolyte redistribution due to electrolyte migration, and evaporation loss can impact stack life if not alleviated. Excessive electrolyte loss during operation may cause matrix and electrode drying, resulting in increased gas cross-over, electrode polarization and ohmic resistance.

Electrolyte Loss to Hardware

Analysis of the post-test stacks has shown that electrolyte loss to the external hardware (manifold, end plates, etc.) and anode-side internal hardware is very low (<5% of BOL inventory after 40,000 hours projected). Electrolyte loss to the cathode-side internal hardware (mainly cathode current collector), either by creepage or by incorporation into the oxide scale, contributes significantly to the total electrolyte loss (>20% of BOL inventory). The creepage electrolyte (washable by dilute acid) is generally rich in potassium. The loss appears to be higher with high Cr steel. Also, electrolyte loss is significantly higher on CCC of higher surface area (Figure 5.3-4). Therefore, CCC of low surface area and minimal Cr content required for protective scale formation is recommended. The oxide was also completely digested to determine the amount of chemically attached Li and K (corrosion electrolyte loss). The lost electrolyte consists mainly of Li (>90%), due to the stable lithium ferrite scale formation. It is found that the Li loss to corrosion scale is not strongly affected by the CCC surface area. It is postulated that Li is mostly incorporated into the scale formed at or near the cathode-CCC interface, while potassium continues to travel on the surface away from the cathode. In summary, Li is preferably lost to the corrosion scale and potassium to the surface creepage. Therefore, it is important to estimate their relative loss rates to determine electrolyte compositional change during long-term operation. So far, post-test electrolyte analysis has not shown significant deviations from the pre-test eutectic Li/K composition.

Based on the above study, electrolyte loss to the internal hardware for cells with low surface area CCC's and with proper selection of materials may be projected to be less than 25% of the BOL electrolyte inventory after 40,000 hours.

Evaporative Electrolyte Loss

The continuous loss of electrolyte by evaporation in the fuel and oxidant streams may be a concern as a possible cause of long-term performance loss. The major evaporated species are KOH and K in the anode gas stream and KOH in the cathode gas stream (5-11). Electrolyte evaporative loss rate from stack testing has been reported to be <5% of BOL electrolyte inventory after 40,000 hours, which appears to be quite tolerable.

Figure 5.3-4 PROJECTED ELECTROLYTE LOSS TO INTERNAL HARDWARE (40,000h):

≤25% BOL Loss to Internal Hardware can be Achieved
with Current Collectors of Reduced Surface Area

Recently, a detailed thermodynamic calculation of vapor pressure of volatile species using a modified SOLGASMIX computer program (5-12) was performed. The program, expanded using Conforming Ionic Solution Theory to represent ionic species in the liquid carbonate phase, has been used at ERC to study the effect of contaminants on carbonate fuel cell (5-13). In the anode exit gas stream of a typical natural gas power plant, only KOH is the major volatile species (Figure 5.3-5), agreeing with the reported mechanism (5-11). The partial pressure of LiOH and K are significantly lower. Stack temperature has a very strong effect, therefore, about 95% of the evaporated species are expected to condense out of the exit gas stream by cooling to 550°C. Using the calculated partial pressures, the evaporative loss from the anode side is estimated to be <3% of BOL inventory after 40,000 hours. On the other hand, the calculation showed that the evaporative loss from the cathode side could be higher than the anode side, primarily due to the much higher cathode gas flow rate. However, cell and stack tests have not shown such a high evaporative loss from the cathode side (5-11). It is possible that the high-flow cathode gas stream is far from saturating with electrolyte vapor due to the short residence time.

Electrolyte Redistribution

Mitigation of electrolyte redistribution by migration has been an important electrolyte management item. Several approaches to mitigate migration (advanced gaskets and end-cell reservoir) were recommended in an earlier report to DOE (5-10). In this program, focused efforts were dedicated to implementing these designs.

**Figure 5.3-5 CALCULATED VAPOR PRESSURE OF VOLATILE SPECIES
IN ANODE ATMOSPHERE:**

KOH is the Major Volatile Species

An out-of-cell test fixture that simulates a 10-cell stack was used to evaluate different gasket designs. The test results verified that selected designs can significantly reduce migration rate. The gasket design with the best potential to mitigate migration (as shown in Figure 5.3-6) was selected for demonstration in 100kW-class stacks.

Several stack tests (250 cm² to 6,000 cm² size, and up to 10,000 hour test duration) were employed to evaluate the mitigation approaches. One of the 2kW stacks was tested for over 10,000 hours to verify an electrolyte management model developed previously; the model predicted a design life of 7,000 hours. After 7,000 hours of operation at 140 mA/cm², the stack indeed showed symptoms of low electrolyte requiring adjustments to the current density to extend the useful life. A 250 cm², 5-cell lab-scale stack, AL-0.15-3, was also tested for 7,300 hours to evaluate the selected gasket approach. The testing of such a small-area stack (with small electrolyte inventory) provided accelerated electrolyte migration condition to better verify advanced gasket designs, as well as the model developed. This vehicle provides about 15 times accelerated redistribution of electrolyte as compared to the larger (6,000 cm²) stacks planned for full-size demonstration. Post-test analysis confirmed the inhibition of electrolyte movement as well as ERC's model for predicting electrolyte redistribution. The stability of the advanced gasket design has been significantly improved by developing highly corrosion resistant material. Virtually no corrosion attack was observed after 6,000 hour stack use. Based on the above results, a 40,000 hour life for a full-area stack (e.g., 6,000 cm² size) from electrolyte redistribution consideration may be projected.

Figure 5.3-6 CARBONATE MIGRATION LOSS/GAIN IN END CELLS FOR 40,000h:
The Improved Gaskets Reduced Electrolyte Migration Significantly

Another approach to mitigate migration is the end-cell reservoir concept. End-cell reservoirs to provide additional electrolyte inventory were incorporated into several stacks for evaluation. This approach also provides better mechanical transition between the active cell package and end compression plate, resulting in better contact in the end cells. Post-test analysis of stacks with this design verified the concept of the source and sink. This advanced end-cell design is included in all 100kW-class stacks.

A 100kW-class stack, AF-100-2, was operated for approximately 1,800 hours. The stack included the advanced gasket design. The post-test electrolyte analysis of the gasket, as well as the active components, showed little indication of electrolyte redistribution (Figure 5.3-7). A relative electrolyte loss/gain projection for ERC's full-size stack after 4,000 hours is given in Figure 5.3-8.

Electrolyte Storage Scheme

At present, electrolyte is stored in the pores of the anode and cathode before start-up. Charging of additional electrolyte at the beginning may be desired to ensure a 5-year life. This requires that the electrode be filled with higher amounts of electrolyte at the beginning-of-life. Uniform filling of the electrodes for the high fill level may be difficult to achieve during manufacturing. In this program, an innovative electrolyte storage scheme was developed that can store large amounts of electrolyte in the cell. This approach was verified in several single cells showing very good performance. This approach has also been verified in 6,000 cm² size stack testing (AF-2-19).

HF0520
D4-F2-ZC

Figure 5.3-7 AF-100-2 ACTIVE COMPONENTS ELECTROLYTE ANALYSIS:
Electrolyte Redistribution has been Minimized

LD1259D

Figure 5.3-8 ELECTROLYTE LOSS PROTECTION OF ERC STACK:
Electrolyte Management for 40,000h Appears Achievable

Bipolar Current Collector Stability

A bipolar current collector consists of a bipolar plate and current collectors. Hot corrosion of this component presents a challenge to material selection. Hot corrosion attack impacts mechanical properties of current collectors, accelerates electrolyte loss and contributes to ohmic resistance increase. Therefore, a slow corrosion attack is desired for 40,000 hour stack operation. The Fe-Ni-Cr austenitic stainless steel 310S and 316L are the current choices for their acceptable cathode-side corrosion resistance and relatively low cost. However, because of their low corrosion resistance in the anode environment, a protective coating (e.g., Ni) is required there.

Nickel coating has been used to protect stainless steel at the anode side. With the protection provided by the Ni coating, the anode-side bipolar plate has shown virtually no corrosion attack for up to 10,000 hours of operation (Figure 5.3-9). Consequently, no significant ohmic loss due to anode-side contact interfacial resistance was observed. Although a small amount of Cr-rich oxide forms at the grain boundaries of the Ni clad layer (diffused into the coating from the substrate stainless steels), no deleterious effect on the corrosion protection is observed. The coating has also shown excellent thermal cycleability (up to six cycles in a stack test). The interdiffusion profiles in the Ni coating during the 5,000-10,000 hour testing is shown in Figure 5.3-10. The diffusion of Fe and Cr into the coating appears tolerable. Based on this result, a Ni thickness of 50 μm may be adequate for 40,000 hour use. To reduce the Ni coating cost, it is desirable to eliminate the need of Ni coating, and develop single-alloy bipolar current collector material. Significant cost benefit can be realized.

For the cathode side, the 316LS current collector has shown acceptable corrosion resistance for 40,000 hour use (Figure 5.3-11). Oxide scale formed at 316LS after long-term stack testing appears still compact. The 310S, due to its higher Cr content, has shown better corrosion resistance than 316L. However, more electrolyte loss has been observed for 310S.

Figure 5.3-9 Ni COATING AFTER 10,000h TESTING:
Excellent Protection is Provided

Figure 5.3-10 Ni-SUBSTRATE INTERDIFFUSION AFTER 10,000 HOURS:
50 μm (2 mil) Ni Coating Appears Adequate for 40,000h Use

Figure 5.3-11 CORROSION OF BIPOLAR CURRENT COLLECTOR:
316L Appears Adequate for 40,000h Use in Cathode Environment

The wet-seal simultaneously experiences reducing and oxidizing environments; only alumina-forming alloys are acceptable in such an environment. Aluminization is the method selected for protection. Aluminizing methods evaluated so far include painting, thermal spraying and vapor deposition. The resulting aluminized coating generally consists of iron aluminide structure. The selected coating has been shown to provide sufficient protection for the substrate stainless steels after 20,000 hour testing (Figure 5.3-12), furthermore, concentration of Al in the coating is still very high (30 mol%). Based on these results, it may be projected that the aluminized coating is sufficient for 40,000 hour use. The major development drive now is to investigate various aluminizing processes for cost reduction.

Figure 5.3-12 WET SEAL COATING APPEARS STABLE AFTER 20,000h:
Coating Provides Adequate Protection

Stack Decay Rate

Test results from several endurance stacks were analyzed to estimate stack performance decay. A 4,000 cm² 2kW stack was operated for 10,000 hours at the beginning of this program (1990-1991). The decay rate was found about 7mV/1000h. Performance decay was found to be caused primarily by increases in cell resistance. Material stability is the fundamental cause of increasing cell resistance. Near the end of this program (1994), a 6,000 cm² 2kW stack with many advanced design features was tested for over 6,000 hours with a decay rate of only about 2 mV/1000h, verifying the endurance improvement achieved in this program (Figure 5.3-13).

5.4 COST REDUCTION

ERC has projected the cost of the DFC stack for commercial production. This cost projection has been audited by an independent DOE-EPRI sponsored study and found to be reasonable (5-15). In the current program, the major stack cost drivers were addressed in order to approach the commercial cost goal. Significant progress has been attained in this area and an example is the anode. The present baseline anode contributes to about 30% of the stack material cost. Although an alternate material could be considered, the extensive research effort for such alternative materials has not yet come to fruition (5-15). Through a combination of competitive vendor development, reduction of material use by 70% and elimination of certain costly

manufacturing processing steps, ERC has reduced the cost by a factor of at least ten. Attainment of commercial cost goal, without sacrificing any functional properties, could be projected for this component. Following single-cell verification, this improved anode was adapted to the stack design and verified in a 3,000 hour 2kW stack test (AF-2-13). Good and stable performance and excellent creep strength was demonstrated. Following this, this low cost anode has been adapted to the baseline design towards the end of 1994 and was used in the latest 2kW Stack, AF-2-19.

Figure 5.3-13 PERFORMANCE LIFEGRAPH (2kW-CLASS STACK TESTS):
Stack Decay Rate Has Been Reduced Significantly in This Program

The wet-seal aluminizing process is also expensive. Initially, an IVD (ion vapor deposition) process was used. In the current program, a low-cost paint aluminizing process was adopted. Several vendors were developed for this process. As a result, aluminizing cost was reduced by a factor of 2. However, ERC believes that further cost reduction will be desired. An approach which projects to further significant cost reduction has already been defined and verified in out-of-cell tests. Scale-up of the process and verification in stack tests will be carried out in the future.

Similarly, cost and weight reduction efforts were extended to the internal reforming unit, manifold, manifold compression system, and stack end plates. Weight reduction is desired for minimization of materials use as well as transportation cost. Accomplishments in weight and cost reduction for these components are discussed in detail in Section 5.6.

5.5 OPERATION ISSUES

Stack Conditioning

Stack conditioning of a carbonate fuel cell stack is required for commissioning for power generation. The stack conditioning includes de-binding operation, electrolyte distribution and cathode stabilization. The organics used in fuel cell components (mainly in the tape matrix) include binder, plasticizer, deflocculant, and solvent. It is important to have complete matrix binder removal prior to electrolyte filling of the matrix. Carbon residue may interfere with matrix electrolyte filling and lead to high gas cross-over. Oxidizing environment is required for binder removal. However, the oxidizing condition needs to be controlled to avoid uncontrolled oxidation of the Ni cathode. Fast exothermic Ni cathode oxidation may cause rapid rise and unstable stack temperature. Furthermore, a reducing atmosphere needs to be introduced at a temperature to protect anode-side components. In summary, a well-thought but simple cost-effective start-up procedure is needed to ensure proper organic binder burnout and cathode stabilization, using the least amount of time while maintaining thermal stability.

The effects of gas atmosphere, ramp rate on binder removal and cathode stabilization have been evaluated in thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). A simplified start-up procedure to achieve the above goals has been developed. The start-up procedure was further verified in single-cell and stack (2kW, 20kW, and 100kW) testing.

Off-Design Operation

ERC has conducted detailed controlled single cell/stack tests simulating the different mechanisms such as fuel, oxygen, and CO₂ starvation. These experiments were used to understand the chemistry and stability implications of each of the causes of cell non-performance. In the ERC system, fuel starvation is the most likely situation that may occur due to the lower fuel flow rate.

Under fuel starvation condition, Ni anode is initially oxidized to supplement sufficient hydrogen fuel. Once the anode is fully oxidized, carbonate is then cathodically electrolyzed (reduced) to sustain the output current. High temperature can result from the irreversible heat generation. Higher corrosion and accelerated electrolyte loss can result in increased cross-over and further voltage loss. A single-cell, 7-192, was deliberately operated at 200% fuel utilization. The initial voltage drop to approximately -400mV can be attributed to Ni anode oxidation. Afterwards, oxygen concentration at the fuel exhaust increased due to the cathodic carbonate electrolysis. The cell voltage then stabilized near -700 mV for about 15 hours. Another cell, 7-389, was operated under the similar condition for more than 8,500 hours (Figure 5.5-1). The cell voltage stabilized at near -1 volt during most of the test duration.

A short stack with two cells at fuel starved mode was operated stably for over 6,000 hours. Based on the above results, long-term voltage stability under fuel starved condition is possible. However, stability beyond 10,000 hours still needs to be investigated.

**Figure 5.5-1 CELL VOLTAGE STABLE FOR 8,500h AT
~1.0 VOLT AT 200% UTILIZATION:**
Long Term Operation Under Fuel Starved Condition is Possible

5.6 HARDWARE DESIGN IMPROVEMENTS

Focused efforts were dedicated to improving performance and reducing weight as well as cost of the stack hardware components. The major goal was to develop all hardware components design, scaleup, if necessary, and get them ready for tall stack use (see Section 2 for tall stack design/verification). The program accomplishments in this area are summarized in Table 5.6-1. A brief discussion in each of these areas is presented next:

Indirect Internal Reformer

The baseline ERC stack design incorporates the direct-indirect internal reforming concept. In this design, the natural gas with minimal steam content is first introduced to the indirect internal reformer (IIR) which is in thermal communication with the fuel cell. Equilibrium reforming is achieved in the IIR using fuel cell reaction heat. Indirect reformer output is next introduced into the anode compartment where complete conversion of methane takes place as a result of direct mass and heat exchange with fuel cell reaction products. One reformer unit is placed every six or so cells. The baseline IIR design (RU-6, which was evaluated in the Stacks AF-8-2 and AF-8-4) incorporated the baseline heavy design which was simplified to a light weight design in two design iterations. The first improvement, RU-7, was evaluated in a 2kW Stack AF-2-16. The final design, RU-8, was verified in a 20kW stack, AF-20-5. This design in addition to weight and cost reductions by 40% and 60% (Figure 5.6-1), respectively, resulted in cell cooling uniformity. Oxidant stream is used for removing heat from fuel cell. The oxidant exhaust average temperature "approach" to the highest cell temperature is a measure of the thermal uniformity. A factor of five improvement in the "approach temperature" was achieved with the RU-8 design over the RU-6 design. The RU-8 design was selected for use in the tall stack.

Table 5.6-1 DESIGN IMPROVEMENTS OF MAJOR NON-REPEATING COMPONENTS:
Weight and Cost Reduced, Performance Enhanced; Verified in Stack Test and Made Ready for Tall Stack Use

COMPONENT	BASELINE	IMPROVEMENT	DESIGN ITERATIONS/VERIFICATION
Reformer Unit	Heavy unit	Lightweight unit	RU-6 (AF-8-4) → RU-7 (AF-2-16) → RU-8 (AF-20-5)
End Plate	Solid	Lightweight, cast	Baseline (AF-2-9) → Brazed (AF-20-4) → Welded (AF-8-4) → Cast (AF-20-5)
Manifold Body	Heavy, welded	Sheet metal, lightweight and corrosion protected	Heavy (AF-8-2) → Lightweight (AF-8-4)
Manifold Dielectric	One piece	Multi-pieces	AF-20-5
Manifold Compression System	Clamp-type	Compact, constant force leaf-spring type	AF-20-4 → AF-20-5
Stack Compression System	Belleville washer pack	Compact and constant support pack	Belleville (AF-20-4) → Constant Thermal Pack (AF-20-5)
Assembly Fixture	None	Rectangular alignment of cells maintained	AF-20-4
Container Vessel	None	Environment control and outdoor operation	AF-20-4
Thermal Insulation	Common industrial type	High performance special insulation	Baseline Insulation (AF-20-4) → Improved Ins. (AF-20-5)

5.7 COAL GAS OPERATION

A 20kW stack was operated on a coal gasifier slip stream at Destec, Plaquimine, LA plant. The stack was qualified first at ERC on natural gas and then truck transported to the gasifier site. The stack, contained in an environmental enclosure, was tested outside for 4,100 hours in a chemical processing plant environment. While the detailed post-test investigations into the coal gas contaminant effects is on-going, there did not appear to be any fundamental problems uncovered during the operation of this test. Details of this test are presented in a separate report (5-16).

End Plates

The stack end plates are used for uniformly distributing the compressive force, electrical current collection, minimizing heat loss, and providing manifold gas sealing surfaces. The baseline design used a solid end plate. A lightweight design was required for overall weight and cost reductions. Also, mechanical stability during thermal transients and a minimum heat loss are desired. Utilizing a detailed finite element analysis, a lightweight end-plate design preserving the required mechanical strength was developed. The design was implemented in three steps. As shown in Figure 5.6-2, weight reduction by a factor of five and cost reduction by a factor of three have been achieved. The first design was manufactured by the brazing approach and evaluated in the Stack AF-20-4. Next, the lightweight end plates were manufactured by the welding process and evaluated in the 8kW Stack AF-8-4. Both the designs met performance specifications, but the manufacturing was considered too expensive. Finally, the end plates were produced by mold casting. This design was successfully tested in several stacks, AF-2-15, AF-2-16, AF-2-18 and AF-20-5. This design has integrated the current terminal post for easy assembly and minimizing the resistance loss.

Manifold Body

ERC has selected an externally manifolded stack design. The baseline design at the beginning of the program used a heavy welded manifold which did not function satisfactorily and was technically challenging for scale up. Therefore, a lightweight, thin sheet metal design with selective reinforcement was designed. The manifold is aluminized for corrosion protection. After verifying the design in several stack tests, it was scaled up for tall stack.

Manifold Dielectric

The function of the dielectric insulator is to electrically isolate the stack from the manifold and avoid the electric shorting. The baseline design is an expensive one-piece picture frame. This design is not mechanically sufficiently strong, and is difficult to fabricate for tall stacks. In this effort, a simple and reliable multi-piece design was evolved through several design iterations. The final design was successfully tested in Stack AF-20-5 meeting all design requirements for full-height stacks.

FC0092

Figure 5.6-1 REFORMING UNIT DESIGN:
Improved Performance and Reduced Weight and Cost

FC0091

Figure 5.6-2 END PLATE DESIGN IMPROVEMENT:
Low Cost Lightweight End Plate was Produced by Mold Casting

Manifold Compression System

The prime function of manifold compression system is to provide adequate manifold sealing pressure. During stack temperature change, the manifold compression system should minimize thermo-mechanical interactions between the stack and the manifolds.

ERC had a clamp-type compression system as the baseline design. Relaxation of compression pressure with time was noticed with this design. A new advanced leaf-spring design was developed to ensure constant compressive force; it was verified in Stack AF-20-5 test. This new leaf-spring retention system is completely independent of the stack and provides constant compression force to the manifold. Finite element analysis indicated that this new leaf-spring system provides more uniform force than the old clamp-type system.

Stack Compression System

The major function of the stack compression system is to provide a steady and uniform compressive load to the stack even with a stack height change during stack operation. A set of belleville washer pack was ERC's baseline design for the stack compression system. These washers are bulky, heavy and functionally not adequate for tall stack use. A new compact, specially designed spring pack system was selected. This design provided a constant compression to the stack during stack temperature change. Scale-up and mass production of these systems can be easily achieved. The above new spring pack, tie bar and a high performance load bearing stack end insulation system was successfully verified in several stacks. The design was scaled up for tall stack.

Stack Assembly Fixture

To achieve rectangular alignment of cells in the stack, a stack assembly fixture was designed and verified by assembling Stack AF-20-4. The design was then scaled up for tall stack use.

Container Vessel

For environmental control and outdoor operation purpose, a container vessel was designed and verified in a 20kW stack test (AF-20-4). This stack was successfully shipped and then tested outdoor for 4,100 hours. An 8kW stack with vessel was shipped overseas by air, meeting all the functional requirements. This design was scaled up for tall stack use.

Thermal Insulation

The carbonate fuel cell operates at 550 to 650°C. Thermal insulation is required to reduce heat loss and maintain internal reforming. The baseline insulation material was replaced with a high performance insulation material and verified in the Stack AF-20-5 test. The new material reduced insulation thickness by 50%.

5.8 CONCLUSIONS

Significant advancement of the cell and stack technology has been achieved. The technology was successfully verified in long-term cell and stack tests, projecting a 40,000 hour commercial life.

About 35mV performance improvement was demonstrated in stacks by electrode improvement and resistance reduction. Electrolyte loss to the hardware was significantly reduced by using low surface area bipolar current collector design. Electrolyte redistribution is mitigated by using an advanced gasket design as well as a parallel end-cell electrolyte source and sink approach (successfully verified in stacks). NiO corrosion does not appear to be a concern for the atmospheric-pressure operation selected by ERC. Matrix thermal cycling strength is significantly enhanced by using advanced formulation and new reinforcement materials. The bipolar current collector materials have shown sufficient stability for 40,000 hour use. A significant improvement of stack decay rate has been realized with stack design improvements achieved under this program.

The improvements in terms of performance and endurance provide a sound basis for MW-size power plant demonstration and commercialization.

6.0 UNDERSTANDING CARBONATE FUEL CELL RESISTANCE ISSUES

Understanding of cell resistance contributing factors is important for developing a high performance and stable cell design. Investigation undertaken here has shown that the electrolyte matrix is the major resistance contributor, followed by the cathode-side hardware. The anode-side resistance is negligible. However, to attain this theoretical material resistance, proper contact between components needs to be maintained. Cell resistance can be reduced by increasing matrix porosity.

6.1 INTRODUCTION

The objective of this task is to develop an understanding as well as a quantification of cell ohmic resistance in a carbonate fuel cell. Results of this research provide a sound basis for defining a low resistance cell design.

The carbonate fuel cell has a design goal of a 40,000 hour life. Cell ohmic resistance stability for such a long-term operation is very important. Ohmic resistance loss in a state-of-the-art carbonate fuel cell at the design operation of 160 mA/cm² contributes about 65 mV loss at BOL (beginning-of-life), and may increase two times after 40,000 hours (6-1). Minimizing the BOL ohmic resistance as well as its rate of increase with life is desired to improve fuel cell power plant efficiency. The important resistance contributing elements/interfaces and their contributions in a baseline carbonate fuel cell are identified in Figure 6.1-1.

The ohmic loss is expected to be mainly caused by electrolyte matrix (ionic) and cathode-side hardware (electronic) (6-1, 6-2). However, the effect of material type, sealing pressure, etc., was not clear. The ohmic resistance of the electrodes was already found to be negligible (6-1). The ohmic resistance of the Ni-base anode is expected to be negligible due to its conductive metallic structure. Increase of cell resistance with operation time has been observed. This increase may be caused by matrix electrolyte loss (due to evaporation and hardware corrosion), thickening of the corrosion oxide scale at the contact area and loss of contact. However, the relative contribution of the above resistance increases was not clear.

Further understanding on ohmic resistance, particularly its increase, is desired for recommending approaches to further reduce the ohmic resistance. In this task, out-of-cell resistance experiments in carbonate fuel cell environment were performed to evaluate the long-term contribution of various components/interfaces.

6.2 EXPERIMENTAL

The test rig illustrated in Figure 6.2-1 was used in out-of-cell resistance experiments. The area of the test components is ~15 cm². The resistance is measured using an AC-impedance technique. Resistance contribution of individual components and interfaces can be determined. The experimental variables include current collector geometry, grain size of composition (310S and 316L), surface oxide (formed during annealing), compressive force and aging time (1,000-6,000 hours).

FC0078

Elements/Interfaces

FC0079

Resistance Contribution

Figure 6.1-1 IMPORTANT RESISTANCE CONTRIBUTING INTERFACES/ELEMENTS:

The Majority of the Resistance is Contributed by Matrix and Cathode-Side Contact

Figure 6.2-1 OHMIC RESISTANCE EXPERIMENTAL FACILITY:
Hot Corrosion and Ohmic Resistance are Characterized in a Single Experiment

The post-test analysis includes thorough washing and digestion of current collector and bipolar plate to determine electrolyte loss to the internal hardware. The cathode is digested to determine electrolyte fill level and the extent of lithiation. The current collector and bipolar plate surfaces are examined for the contact pattern. Cross-sectional analysis is performed to determine oxide structure and thickness, particularly at the cathode-CCC contact interface, using SEM/EDS. Advanced methods such as XRD, Auger were also utilized to better understand the oxide structure. The results and discussion are summarized as follows:

6.3 RESULTS AND DISCUSSION

Anode-Side: The baseline anode-side components are Ni-alloy anode and Ni-protected hardware. As mentioned before, the Ni-alloy anode is expected to cause only negligible ohmic loss due to its conductive metallic structure. The anode-side hardware is expected to contribute low ohmic loss because surface protection results in very little surface oxide formation. An out-of-cell resistance experiment of the baseline anode-side components has been conducted and the low total anode-side ohmic loss ($<10 \text{ m}\Omega \cdot \text{cm}^2$) was verified.

The test was conducted with small samples. Therefore, the samples have fairly even thickness and good component-to-component contact. However, for a large-size (e.g., $0.5\text{-}1 \text{ m}^2$ area) stack, any excessive component tolerances and inadequate control of protrusion may cause poor contact. Post-test analysis of the full-size stacks at ERC has shown that good contact has been maintained among the baseline anode-side components (anode, anode CCC and BP). Due to the slight sintering of Ni at the contact areas (all anode-side components contain significant Ni), a metallurgical bonding has in fact been achieved. Therefore, the present anode-side components maintain adequate contact.

Cathode-CCC Interface: The oxide formed at the cathode-CCC (corrugated current collector) interface has been found to contribute about $60 \text{ m}\Omega \cdot \text{cm}^2$ resistance at BOL ($\sim 10 \text{ mV loss @ } 160 \text{ mA/cm}^2$) for about 40% contact surface (6-1). A typical post-test oxide morphology is shown in Figure 6.3-1. Typical Auger results are shown in Figure 6.3-2. The oxide in general has a bilayered structure (Ni, Mn-doped LiFeO_2 outer and Cr-rich inner scales). The outer scale is doped with a large amount of Ni ($>20 \text{ mole\%}$, mainly from NiO cathode) and a small amount of Mn ($<3 \text{ mole\%}$, from stainless steel substrate). The Cr content here is very low ($<2 \text{ mole\%}$). The inner scale is very rich in Cr but also contains significant amounts of Fe and Ni. Cr-enrichment at the metal-oxide interface was verified by Auger (Figure 6.3-2).

The oxide scale formed on 310S appears thinner and more compact than on 316L. The XRD analysis showed that the oxide on 316L had less LiFeO_2 and more spinel (FeCr_2O_4). Because the spinel phase is less protective than chromia, the oxide on 316L is less protective than on 310S. Nevertheless, the corrosion resistance of 310S and 316L are both adequate for long-term use (6-3).

The overall scale specific resistivity, normalized for contact area and NiO porosity, is shown in Table 6.3-1. Not surprisingly, it is similar to that of the doped LiFeO_2 ($\sim 30 \text{ m}\Omega \cdot \text{cm}^2$ (6-4), the main constituent of the scale. The inner mixed oxide scale (spinel, chromia, etc.) and its specific resistivity cannot be as easily estimated as those of single oxides (e.g., chromia). The oxide formed on 310S stainless steel is thinner but more resistive, likely due to its more compact inner chromia scale ($\rho \sim 100 \text{ m}\Omega \cdot \text{cm}^2$). The inner scale on 316L is thicker as well as higher in Fe content (more spinel), therefore, it is less protective, but likely more electronically conductive. This may explain the lower overall specific resistivity for the oxide formed on 316L. The oxide formed on large-grained 316L is slightly thicker but with a slightly lower specific resistivity. The overall oxide ohmic loss is, therefore, similar to that on fine-grained 316L. In summary, 310S and 316L materials (fine or large grained) contribute similar overall oxide ohmic resistance. Therefore, electrolyte loss appears to be the more important selection criteria for choosing material for fuel cell hardware.

The oxide specific resistivity is also found to be decreasing with time for both 310S and 316L (Figure 6.3-3). This is likely due to the decreasing compactness of the oxide scale with time caused by the continuous carbonate attack. Based on the data of scale thickness and specific resistivity stability, the present cathode-CCC interfacial oxide ohmic loss is projected to be $<30 \text{ mV}$ after 40,000 hours.

Altering the structure and composition of the interfacial oxide has the potential of improving the oxide resistance (6-2). Improvement in conductivity of both the inner and outer oxide layers by modifying oxide structure and composition, but without sacrificing overall corrosion resistance, is desired.

a) 316L, 1400h Testing

10 μ m

b) 310S, 2100h Testing

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Figure 6.3-1 POST-TEST OXIDE MORPHOLOGY:
 Fe-rich Outer Scale and Cr-rich Inner Scale
 is Apparent in Both 316L and 310S Materials

Figure 6.3-2 AUGER ANALYSIS OF OXIDE SCALE AT CATHODE-CCC INTERFACE:
Cr-Enrichment at Metal-Oxide Interface is Evident

Table 6.3-1 OXIDE SPECIFIC OHMIC RESISTIVITY:

The Ohmic Resistivity of 310S Scale is Approximately Two Times Higher Than 316S, However, Because of Lower Oxide Thickness, Resistance Contribution is About the Same

MATERIAL	OHMIC RESISTIVITY ($\text{m}\Omega \cdot \text{cm}^2$)
310S	~40
316L Fine-Medium Grained	15-25
316L Large-Grained	~15

The compressive (sealing) pressure effect was also evaluated. Comparing the test results at 10 psi and the baseline 50 psi, no significant difference in cathode-CCC resistance was observed. However, for large-size stack components (e.g., 0.5-1 m^2) having manufacturing tolerances, lower pressure may cause poor contact and should be considered in scale up. To reduce the effect of compressive (sealing) pressure, CCC of low dimensional tolerances and adequate spring property should be designed to maintain a good contact, for cathode-CCC as well as CCC-BP interface.

Figure 6.3-3 OXIDE SPECIFIC RESISTIVITY WITH TIME:
Resistivity Decreased by Carbonate Attack

CCC-BP Interface: Another potential ohmic-loss area on the cathode side is the CCC-BP (bipolar plate) interface. This contact interface generally contributes to very low ohmic loss ($<10 \text{ m}\Omega \cdot \text{cm}^2$) for several thousand hours if the contact area remains adequate. If the contact is not adequate (e.g., individual contact area too small), oxide scale may eventually form at this interface and contribute to a higher resistance for longer-term operation. For a small contact, the interfacial resistance was found to increase to $>50 \text{ m}\Omega \cdot \text{cm}^2$ in 500 hours. Analysis revealed the formation of thick oxide at the contact area. To avoid high CCC-BP contact resistance, a good uniform contact of $>20\%$ is desirable. Pre-oxidation in the presence of carbonate has been evaluated before (6-2) for improving corrosion resistance. Although the corrosion resistance is improved, the ohmic resistance was found to be unacceptably high ($>100 \text{ m}\Omega \cdot \text{cm}^2$).

Matrix Ionic Resistance: The matrix ionic resistance is influenced by many factors: electrolyte conductivity, matrix porosity, tortuosity, electrolyte fill level and matrix thickness. At present, a baseline matrix may contribute to more than $300 \text{ m}\Omega \cdot \text{cm}^2$ ohmic resistance ($>70\%$ of the total cell ohmic resistance), and is the major cell resistance contributor. The baseline matrix contributes to $\sim 30 \text{ m}\Omega \cdot \text{cm}^2$ in resistance per $100 \mu\text{m}$ of thickness. Therefore, the matrix has the highest potential for further resistance reduction.

According to the Bruggman equation (an ideal case), the matrix resistivity is inversely proportional to the 1.5th power of the matrix porosity (i.e. $\rho \propto \epsilon^{-1.5}$). An actual carbonate fuel cell appears to have a larger affect than predicted by the 1.5th power factor. An increase of matrix porosity by a mere 5% percentage points (e.g., 45% to 50%) can reduce the matrix resistance by 15%. A switch from Li/K to Li/Na has the potential of reducing matrix resistivity by an additional 40%. Therefore, a matrix of low tortuosity and high porosity and with conductive electrolyte has the potential of reducing cell resistance significantly.

In addition to the intrinsic matrix properties (e.g., porosity) mentioned above, the contact between the matrix and electrodes can also have a strong effect on the matrix ionic resistance and electrode polarization. Cell testing showed that contact may be responsible for a BOL resistance variation of up to $100 \text{ m}\Omega \cdot \text{cm}^2$. To provide sufficient contact between the electrodes and matrix, and to reduce resistance variation, the matrix should have adequate pliability and plasticity. Tolerances, protrusion and spring property of the cell packages should be well designed and controlled to maintain good contact. By achieving adequate contact the theoretical material resistance could be attained.

6.4 CONCLUSION

The electrolyte matrix is the major resistance contributor, followed by the cathode-side hardware. The anode-side resistance is negligible. Contact between components should be adequately maintained by controlling dimensional tolerances, spring property and protrusion, to achieve the theoretical material resistance. Cell resistance can be further reduced by increasing matrix porosity.

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