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**Post-Test Analysis Of 20kW Molten Carbonate Fuel
Cell Stack Operated On Coal Gas**

**Final Report
August 1993 - February 1996**

May 1996

Work Performed Under Contract No.: DE-FC21-93MC30054

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

By
Energy Research Corporation
3 Great Pasture Road
Danbury, Connecticut 06813

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ABSTRACT

A 20kW carbonate fuel cell stack was operated with coal gas for the first time in the world. The stack was tested for a total of 4,000 hours, of which 3,900 hours of testing was conducted at the Louisiana Gasification Technology Incorporated, Plaquemine, Louisiana outdoor site. The operation was on either natural gas or coal gas and switched several times without any effects, demonstrating dual fuel capabilities. This test was conducted with 9142 kJ/m³ (245 Btu/cft) coal gas provided by a slipstream from Destec's entrained flow, slagging, slurry-fed gasifier equipped with a cold gas cleanup subsystem. The stack generated up to 21 kW with this coal gas. Following completion of this test, the stack was brought to Energy Research Corporation (ERC) and a detailed post-test analysis was conducted to identify any effects of coal gas on cell components. This investigation has shown that the direct fuel cell (DFC) can be operated with properly cleaned and humidified coal gas, providing stable performance. The basic direct fuel cell component materials are stable and display normal stability in presence of the coal gas. No effects of the coal-borne contaminants are apparent. Further cell testing at ERC confirmed these findings.

The overall program was cosponsored by the Electric Power Research Institute (EPRI), and the U.S. Department of Energy (DOE). Destec Energy, Inc. was responsible for facility operation. Energy Research Corporation provided the fuel cell stack and technical support and performed post-test analysis. The post-test analysis work, which is the focus of this report, was sponsored by the Department of Energy under Contract DE-AC21-93MC30054. A summary of stack test operation is provided as a background for post-test results.

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EXECUTIVE SUMMARY

This report presents results of post-test analyses of a direct carbonate fuel cell (DFC) operated on coal gas. The DFC system is being developed by Energy Research Corporation for power generation from natural gas, coal gas and other fuels. Detailed engineering studies have shown that DFC systems have the potential of offering high efficiency, competitive cost and environmentally superior power plants. The objective of this effort is to demonstrate the compatibility of a carbonate fuel cell stack with coal-derived gases, and to determine the effect of possible contaminants on the performance and life of a carbonate fuel cell. This is the first test of a carbonate fuel cell stack operating in an industrial environment on actual coal gas anywhere in the world. Due to the difficulty of measuring trace contaminants in the gas phase at high temperatures, and determining any possible interactions of these trace contaminants, it is quite challenging to predict and simulate all the conceivable effects on the carbonate fuel cell and electrolyte without experimental data in the coal gas environment. It is, therefore, imperative to test a carbonate fuel cell using coal gas and to monitor its performance relative to a standard, thereby determining if long-term operation can be expected with acceptable performance decay. If fuel cell performance decay is not acceptable, the responsible contaminant(s) and their effects on fuel cell performance can be determined and this data can then be used to modify fuel cleanup system designs.

The prime contractor for the overall demonstration program was Destec Energy Incorporated. The facility was designed and constructed by Haldor Topsoe Incorporated. Energy Research Corporation (ERC) supplied the stack and provided consulting support during operation. A separate report on the results of the operation was published by EPRI, as "Demonstration of a Carbonate Fuel Cell on Coal Derived Gases" TR-103285. ERC was the prime contractor for post-test analyses sponsored by DOE/METC under Contract DE-AC21-93MC30054, which is the focus of the present report.

This DOE-funded project is a follow up to an EPRI-sponsored program. Under the EPRI program, a truck-transportable skid-mounted test facility was designed and constructed. This facility is capable of testing 20kW to 100kW carbonate fuel cell modules on coal gas, natural gas, landfill gas, or biogas with appropriate modifications. A 20kW carbonate fuel cell stack, AF-20-4, was designed, constructed and tested at ERC under the EPRI-funded program. The stack was initially tested for approximately 100 hours on natural gas to establish a baseline prior to shipping to the test site. This stack was the very first produced at Fuel Cell Manufacturing Corporation, ERC's wholly owned fabrication facility.

The stack was installed at the Louisiana Gasification Technology Incorporated (LGTI) Plaquemine, Louisiana test site and was tested by Destec Energy, Inc. on coal gas and pipeline natural gas for a total of 3,900 hours. Testing at LGTI was sponsored by EPRI, DOE/METC, SEP, KEMA and ESEERCO. Following completion of the test, the stack was brought back to ERC for detailed post-test analyses to investigate and identify any coal gas related materials issues. This study has shown that the DFC can be operated with properly cleaned and humidified syngas with expected performance and stability. A 5-year life may be projected for the basic cell components for this application. Additional test experience will be useful to identify any issues related to different gasifier/cleanup systems and coal types. The specific test observations and post-test findings are discussed in this report, and the highlights are summarized below:

- Operability of ERC's direct carbonate fuel cell (DFC) stack on dual fuels, pipeline natural gas as well as coal gas, has been demonstrated in an outdoor industrial environment. A 20kW stack was tested for a total of 4,000 hours, of which 3,900 hours of testing was conducted at the LGTI site on coal gas as well as pipeline gas. This test included 1500 hours of operation on approximately 9142 kJ/m³ (245 Btu/cft) heating value syngas from a slip-stream of a 2,180 metric tons/day (2,400 tons/day) entrained flow, slagging, slurry-fed gasifier. The facility includes a cold gas cleanup system for bulk removal of H₂S and other contaminants. The DFC performance and stability were unaffected by the high CO-containing cold-cleaned and sulfur-polished syngas produced by the gasifier. The stack generated power of up to 21 kW with this coal gas. This test has shown that the DFC can be operated on dual fuels without performance and stability losses any higher than the expected thermodynamic losses due to reactant dilutions.
- The test was conducted outdoors using a stack enclosure, which performed as designed and protected the fuel cell from cold, humidity, rain, and hot environmental conditions during the 6-month test period. Industry-trained operators were able to maintain test operations with minimal supervision from EPRI and ERC.
- The carbonate fuel cell components operated as designed without producing any unusual results. The coal gas operation did not result in additional corrosion and/or loss of stability of the direct fuel cell components. No evidence of degradation of the fuel side cell hardware was apparent. A detailed post-test analysis showed no detectable accumulation of coal-gas-borne contaminants in the fuel cell electrolyte or in the hardware.
- This test experience has shown that proper selection of balance-of-plant materials and/or installation of particulate filters will be necessary to minimize collection of unwanted corrosion products in the piping and/or inside the fuel cell flow passages. Furthermore, the syngas humidification scheme needs to be reliable to avoid the possibility of carbon deposition.
- Parallel cell testing with controlled addition of selected coal gas contaminants was also performed to help rationalize the observations of the Destec test that the cell performance was not impacted by air and fuel-borne sulfur species. Tests were performed with ppm and ppb levels of SO₂ in the cathode gas. The results confirmed that although very high doses of SO₂ exposure >5-10ppm with ambient air may affect the cell resistance and performance, the normal expected continuous exposure of 5-10ppb is not expected to impact carbonate fuel cell life of 40,000h.

1.0 INTRODUCTION AND BACKGROUND

A 20kW carbonate fuel cell stack was endurance tested on actual coal derived syngas at Destec Energy's gasification combined cycle plant (160MW equivalent capacity) in Plaquemine, Louisiana. This was the first test in the world of a fuel cell on actual coal derived syngas. The primary objective was to determine the compatibility of the carbonate fuel cell with high carbon monoxide containing coal syngas. Endurance testing was followed by extensive post-test analyses to reveal any possible material issues related to coal syngas operation.

Power plant system studies indicate carbonate fuel cell systems integrated with coal gasification have the potential of offering the highest efficiency and lowest emissions of any other conceivable power plant operating on coal[1,2]. The objective of this project was to demonstrate the compatibility and endurance of a carbonate fuel cell stack on actual coal-derived gases. The primary issue of concern were the effect of possible trace contaminants on the performance and life of the carbonate fuel cell.

A 20kW carbonate fuel cell test facility was interfaced with the Destec coal gasification plant in Plaquemine, LA where the Destec process is being commercially demonstrated. The Destec coal gasification process uses a pressurized, entrained flow, slagging, slurry-fed gasifier with a continuous slag removal system. The sweet syngas has an energy value of approximately 9,142 kJ/m³ (245 Btu/cft). A slipstream of this sweet gas was interfaced with the carbonate fuel cell test facility. The facility is modular and truck transportable to enable testing at other locations. The facility has the capability to test 20kW to 100kW fuel cell modules on either natural gas or coal-derived gases. The facility is also suitable for use with landfill gas, waste water treatment digester gas or biogas.

Several major project tasks were completed under EPRI sponsorship. These include:

- Design of a 20kW Modular Test Facility,
- Construction of a 20kW Modular Test Facility.

The critical project tasks completed under DOE sponsorship include:

- Endurance Testing of the 20kW Carbonate Fuel Cell Stack,
- Data Analysis.

This report discusses the results and observations of the DOE sponsored tasks.

1.1 BACKGROUND

Destec Gasification Plant

The Destec coal gasification plant is situated at Louisiana Gasification Technology Incorporated (LGTI) in Plaquemine, Louisiana. The plant consists of a pressurized, entrained flow, slagging, slurry-fed gasifier with a continuous slag removal system. Approximately 2.2 x 10⁶ kg/day (2,400 tons/day) of low sulfur subbituminous coal is used per day to produce 160 MW of electrical power. The coal slurry mixes with oxygen in a reactor and produces a synthetic gas.

The syngas exiting the reactor is cooled by a conventional heat recovery boiler and water scrubbed to remove any particulates. After additional cooling, sulfur is removed with a Dow proprietary methyldiethanolamine (MDEA) process. The syngas is reheated to approximately 120°C (250°F) and sent to two Westinghouse WD501 gas turbines. A slipstream of this gas, approximately 50 kg/h (100 lb/h), is sent to the fuel cell test facility. The properties of the syngas are listed in Table 1.1. The syngas contains a high concentration of CO and will need humidification to make it stable at fuel cell operating temperatures.

Table 1.1 TYPICAL DESTEC SYNGAS PROPERTIES:
This High CO Containing Gas Requires Humidification for Fuel Cell Use

Raw Syngas	Vol. %
H ₂	43
CO	28
CO ₂	26
N ₂	1-2
CH ₄	1-2
HHV	8960-9330 kJ/m ³ (240-250 Btu/cft)

Test Facility Description

The fuel cell test facility was designed and built by Haldor Topsoe, Inc. prior to the start of this program. A brief description of the facility follows, a more detailed narrative can be found elsewhere[3].

The facility was designed with an emphasis on test endurance, high reliability and flexibility. It is entirely truck transportable to allow testing at other locations on alternate fuels. Fuel cell module size can vary from 20 to 100kW.

The modular test facility (a plot plan is shown in Figure 1.1) consists of seven skids designed for outdoor operation. The skids associated with the facility are: two process skids (Modules 1 and 2), a start-up skid, a skid-mounted fired heater for start-up purposes, a skid-mounted DC load bank, a carbonate fuel cell stack with enclosure, and a skid-mounted control building. The control building houses the distributed control system, electrical switch-gear, UPS and an electrical heat tracing control system. The required utilities, i.e., electricity, steam, compressed air, nitrogen, natural gas and demineralized water, were supplied by Destec. Compressed gas supplies are provided by way of storage cylinders furnished by a local supplier. Module 1 is a 3.7 m x 10.7 m (12' x 35') skid with a structural steel frame which contains the electric heaters, combustion air blower, and piping for flow measurement and control for process streams. Module 2 is a 3.7 m x 8.5 m (12' x 28') skid which houses the anode off-gas burner and control panel, vent gas structure, piping and associated valves and instruments. The test facility included an on-line gas chromatograph with automatic sampling from six locations.

A Foxboro Intelligent Automation System provided system control and data acquisition. This system is comprised of three work stations and is capable of modem interface, bulk data storage and retrieval. The modem interface allowed remote monitoring by ERC personnel from their Danbury, Connecticut location.

There were three major control loops for steady state operation: the fuel to air ratio for the feed gas to the fuel cell, steam to carbon ratio in fuel, and flow and pressure control of desulfurized fuel to the burner.

Figure 1.1 PLOT PLAN OF DESTEC TEST FACILITY:
The Modular Skid-Mounted Facility was Designed for Outdoor Operation

Facility Interface

The fuel cell test facility was interfaced with the gasification plant through a slipstream of sweet syngas. In the event that syngas was not available, fuel cell operation would be placed at hot standby open circuit conditions. Under these conditions, the fuel cell is off-load and maintained at approximately 600°C (1100°F) using hot streams of nitrogen, hydrogen and carbon dioxide on the anode, and nitrogen, air and carbon dioxide on the cathode. This operating mode was used instead of a natural gas backup fuel because the Destec plant flare header system is usually down when syngas is unavailable. As the fuel cell test facility vents and relief valves are tied into the flare header system, the test facility could not operate.

To ensure safe, reliable operation, balance of plant testing was performed with both natural gas and coal gas prior to connecting the fuel cell stack to the facility. Computer safety interlocks, control logic and plant equipment operation were all verified. Process flow control tuning and the fuel gas cleanup system were optimized. These tests also provided an opportunity for operator training.

Process Description

A process flow diagram of the test facility is shown in Figure 1.2. Syngas at approximately 100°C (200°F) is preheated (through electrical heater E-101) to approximately 220°C (430°F) and passed through a desulfurization/ dechlorination unit (R-101). This unit consists of alumina and zinc oxide beds which chemically absorb trace sulfur and chlorine compounds to less than 0.1 ppm. Steam is superheated in electric heater E-103 from approximately 290°C (550°F) to 400°C (750°F) and added to the desulfurized fuel. The stream is further heated (in E-104) to approximately 540°C (1000°F) before entering the fuel cell anode. A preconverter (R-102) was only used during natural gas operations to promote steam reforming of higher hydrocarbons.

Figure 1.2 DESTEC FUEL CELL FACILITY SCHEMATIC:
The Truck Transportable Skid-Mounted Test Facility was Interfaced with
Destec Energy Corporation's LGTI Coal Gasification Plant

Approximately 70% of the fuel electrochemically reacts within the fuel cell and produces electricity, CO₂ and water. The power produced is dissipated in the load bank. The unreacted (oxidizer) fuel is combusted in the anode off-gas oxidizer (H-101) with additional desulfurized fuel and excess air provided by the combustion air blower (K-101). The product from the oxidizer goes to the fuel cell cathode where CO₂ and O₂ are consumed. Thermal equilibrium is maintained by adjusting the air flow. The cathode exhaust is vented to the atmosphere.

Fuel Cell Stack

A 20kW carbonate fuel cell stack was designed and constructed under the EPRI-funded program. The stack (AF-20-4) was designed to operate on both natural gas and coal-derived gas. This 20kW stack incorporated several special features:

- Lightweight end plates to reduce weight and improve thermal management,
- Lightweight compression system,
- Double electrical isolation of the facility from the stack to ease safety concerns, and
- Cylindrical enclosure vessel to protect the stack from the environment and to ease shipping and handling.

The end plates are used as a structural *foundation* of the stack. The baseline design was a solid end plate. A cost reduction effort under EPRI funding resulted in the design of an eggcrate type end plate. The design reduced the weight by 50% while maintaining the desired strength.

The electricity produced by the fuel cell stack is circuited to the resistive load banks. The plant piping is normally isolated from this circuit by dielectric manifolds. In the facility, dielectrics were also placed in the pipe connections for added electrical isolation.

A stack enclosure was designed and fabricated for outdoor operation. A blanket gas within the container maintains a pressure equal to or slightly higher than the inlet manifold reactant gas pressure. This minimizes reactant leakage through the manifold seals while allowing higher reactant pressure relative to atmosphere. The containment system is shown in Figure 1.3 and consists of a lower part, cylindrical dome and couplings. This system also acts as a shipping container.

The stack was comprised of 54 cells and 9 reforming units of 0.6m x 0.9m (2' x 3') size. All the repeating components were made at ERC's manufacturing subsidiary, Fuel Cell Manufacturing Corporation (FCMC). This was the first stack tested with all the active components made at FCMC. A view of the stack during assembly is shown in Figure 1.4.

In order to effectively monitor stack voltage, the cells were divided into ten groups. Groups 1 and 10 contain three cells each and Groups 2 through 9 contain six cells each. All group voltages were monitored. In addition, individual cell voltage was monitored in the four end cells: Cells 1 and 2 on the bottom of the stack and Cells 53 and 54 on the top of the stack.

1.2 TECHNICAL TASKS

The overall objective of this effort was to analyze the compatibility of a carbonate fuel cell stack with high CO containing coal-derived gases that are scrubbed of known contaminants using currently available technology. The technical approach of this program was to analyze carbonate fuel cell stack performance using fuel from a coal-fired gasifier and perform an intensive post-test analysis of fuel cell components to assess the impact of syngas, specifically trace contaminants, on fuel cell life.

Figure 1.3 STACK ENVIRONMENTAL ENCLOSURE:
The Containment System is Comprised of Sections for Ease of Assembly

Figure 1.4 FUEL CELL STACK DURING ASSEMBLY:
The Stack was Built Using Components Fabricated at FCMC

The tasks under DOE Contract DE-AC21-93MC30054 are described below.

Task 1 NEPA INFORMATION

This task requested fuel cell stack emission data which would be used to determine the potential environmental impact of fuel cell operation. It was established that fuel cell stack emissions are well within the clean air act guidelines and present no environmental impact. Therefore, stack testing was allowed to continue under the DOE program.

Task 2 FUEL CELL OPERATION

This task encompassed monitoring both the fuel cell stack operation and the fuel gas cleanup system. ERC monitored test data by remote access from its Danbury, CT facility as well as monitoring at the Destec site by test operators.

The following parameters were routinely monitored:

- Power Output,
- Total Stack Voltage,
- Individual Group Voltage,
- Individual Cell Voltage of Cells 1, 2, 53, and 54,
- Amperage,

- Fuel and Oxidant Utilization,
- Stack Efficiency,
- Bulk Gas Composition at the Anode Inlet and Outlet,
- Bulk Gas Composition at the Cathode Inlet and Outlet,
- Stack Temperature, and
- Reactant Gas Pressures.

In addition, trace contaminant analysis was conducted on the inlet and outlet streams of the anode. This trace contaminant analysis included arsenic, selenium, lead, manganese, beryllium, cadmium, antimony, mercury, chromium, zinc and nickel. Analysis for major contaminants such as sulfur and chloride, were also performed.

Task 3 DATA ANALYSIS

After the stack test, the carbonate fuel cell stack was shipped back to ERC and disassembled for analysis and post-test inspection. The following analyses were performed:

- Electrolyte Analysis
 - Trace contaminants
 - Wet chemical analysis
 - Atomic Absorption Spectroscopy
- Electrode Analysis
 - Porosimetry
 - Trace contaminants
- Catalyst Analysis
 - Trace contaminants
 - Electrolyte pickup
- Corrosion Analysis
 - Metallography

Laboratory tests were conducted using subscale (17 cm x 17 cm) carbonate fuel cells. These tests were performed to determine if trace contaminants impact fuel cell performance under stable operating conditions. The test results and observations are discussed next.

2.0 STACK TESTING

A 20kW carbonate fuel cell stack was tested on natural gas and endurance tested on coal syngas at Destec's coal gasification plant in Plaquemine, Louisiana. This demonstrated the dual fuel capability of ERC's direct carbonate fuel cell stack technology. The endurance test at the Destec site lasted over 4,000 hours, with 1,500 hours operation on actual coal derived syngas. Stack performance comparison on natural gas and coal syngas matched thermodynamic prediction. Operation on the high carbon monoxide containing coal syngas appeared to cause no change in fuel cell endurance stability relative to natural gas operation.

Following assembly and preconditioning, the stack underwent approximately 100 hours of testing on natural gas to establish baseline performance. The stack produced 32 kW operating on methane at a current density of 160 mA/cm² (78% fuel utilization; 50% CO₂ utilization). The power voltage and current relationship is shown in Figure 2.1. Stack voltage exceeded the design goal.

Figure 2.1 QUALIFICATION TESTING AT ERC:
Stack Performance Exceeded the Design Goal

A performance comparison at natural gas conditions with previous ERC tests (Figure 2.2), shows that state-of-the-art performance was achieved. Individual cell group voltages shown in Figure 2.3 illustrate that performance uniformity was obtained[4,5,6]. This verified FCMC's fuel cell manufacturing processes.

160 mA/cm² , 75/50% Util.

Figure 2.2 STACK PERFORMANCE COMPARISON WITH PREVIOUS ERC TESTS:
State-of-the-Art Performance was Achieved with the Destec Stack (AF-20-4)

Figure 2.3 DESTEC STACK (AF-20-4) INDIVIDUAL GROUP VOLTAGES:
Uniform Group Voltages Were Obtained

The stack was qualification tested for 75 hours then cooled down and inspected using an endoscope. The test article was found to be in normal condition. The enclosed stack was shipped by truck to the test site in early April 1993. A photograph of the stack being loaded onto the flatbed truck is shown in Figure 2.4. As seen in the photograph, the stack was shipped with the containment system to provide weather protection.

Figure 2.4 STACK SHIPMENT TO THE DESTEC COAL GASIFICATION PLANT:
The Containment Vessel Serves Multiple Functions,
Including Shipping and Weather Protection

The stack was installed in the EPRI 100kW facility in August 1993, and stack operation began in September under EPRI Project RP-3195-1. A photograph showing the stack installed in the facility is given in Figure 2.5. The stack was initially operated on natural gas to allow a direct comparison with initial stack performance during the qualification testing at ERC, and for later comparison with syngas performance. As illustrated in Figure 2.6, stack performance on natural gas at the Destec facility is comparable with the performance obtained at ERC prior to shipping. The stack produced 28 kW at 140 mA/cm² (700 amps) at the Destec site. There was minimal effect on stack performance as a result of thermal cycling and transportation to the Destec facility. The effect of fuel utilization on stack performance was determined at Destec during the initial natural gas run. Increasing the fuel utilization from 57% to 68% resulted in a total voltage drop of 0.9 volts, or a 2% power loss at 100 mA/cm² current density (500 amps).

Following the initial 60-hour test on natural gas, the stack was placed in *hot standby mode* for 300 hours due to gasifier plant maintenance. The stack was then restarted on syngas and generated 21 kW at 500 amps and 42 volts. A comparison of stack performance on gasifier syngas and natural gas is shown in Figure 2.7. The stack showed the expected 26 mV/cell loss in performance due to the lower energy content of the syngas; this equates to approximately 4.6% less power at 100 mA/cm² current density. No performance penalty due to high CO in the fuel was observed.

Figure 2.5 STACK INSTALLATION AT THE DESTEC COAL GASIFICATION FACILITY:

This Stack is the World's First Test of a Fuel Cell on Actual Coal Gas

Figure 2.6 PERFORMANCE COMPARISON ON NATURAL GAS AFTER TRANSPORTATION:

Thermal Cycling and Transporting had Minimal Effect on Stack Performance

Figure 2.7 PERFORMANCE COMPARISON ON NATURAL GAS AND SYNGAS:
Syngas Operation Resulted in a Predicted 4.6% Drop in Stack Power

During stack operation, bulk gas compositions of the inlet and exhaust streams were routinely monitored with a gas chromatograph. Typical dry gas compositions and flow conditions are given in Table 2.1. The anode inlet is humidified to contain approximately 40% water. The syngas contained proportionately a large amount of CO which was mostly consumed in the fuel cell.

Table 2.1 TYPICAL BULK GAS COMPOSITIONS:
A Significant Portion of CO was Consumed by the Carbonate Fuel Cell
(100 mA/cm², Fuel Util. ~70%, Oxidant Util. ~12%)

Component	Anode, Vol% (Dry Basis)		Cathode, Vol% (Dry Basis)	
	Inlet	Exhaust	Inlet	Exhaust
Flow Rate, kg mole/h	1.5	1.8	15.3	14.9
Temperature, °C	605	604	580	660
H ₂	44.9	12.9	---	---
O ₂	---	---	6.4	5.3
N ₂	---	---	81.7	84.0
CO	29.4	4.2	---	---
CO ₂	25.7	82.9	11.9	10.8

Trace contaminant analysis was conducted on the fuel inlet stream by Destec. These results are reproduced in Table 2.2[9]. The syngas contains about 50ppm total sulfur compounds, mainly, H₂S and COS. These were removed in desulfurization reactor (R-101 of Figure 1.2)

Table 2.2 COAL GAS CONTAMINANT ANALYSIS:
Sulfur Concentration was Reduced to <0.1 ppm for Fuel Cell

Component	Before Cleanup, ppm	Concentration After Cleanup, ppm
H ₂ S	~30	<0.1
COS	~25	<1.0
Benzene	~170	<1.0
Higher Hydrocarbons	~1,000	N.A.

Possible metal contaminants from the coal gas were analyzed by Destec prior to the start of stack testing. These results are given in Table 2.3, with detectable limits indicated in parentheses. Mercury is the only contaminant that is above the detectable limit.

Table 2.3 TRACE CONTAMINANT ANALYSIS FOR METALS[9]:
Only a Small Quantity of Mercury was Detected in the Syngas

Heavy Metal Contaminant	Concentration, ppb
Arsenic	N.D.* (<0.3)
Beryllium	N.D. (<0.8)
Cadmium	N.D. (<0.2)
Lead	N.D. (<0.9)
Mercury	0.3
Selenium	N.D. (<0.2)
Zinc	N.D. (<1.1)

* N.D. = Not Detected

The stack operating history is shown in Figure 2.8. This stack operated for a total of 4,022 hours, with approximately 1,500 hours of syngas operation. The syngas operating time is less than the total time at Destec because of initial testing on natural gas and various gasifier outages. In addition, the stack was placed on hot standby mode (open circuit conditions) on numerous occasions due to facility related interruptions. Most of these incidents are indicated in the top portion of Figure 2.8. The major test interruptions and their possible impacts are described in the figure table.

Trip Description	Stack Hours	Description	Possible Effects
High Fuel	622	Fuel flow to the oxidizer was doubled, increasing cell temperatures ~16% (from 630°C to 740°C).	Mechanical Stress
Oxidizer Air	1557	Rapid fluctuations in the air flow to the oxidizer (+16% to -30%) were encountered.	Mechanical Stress
Thermal Shock	1766	Cold air was directed to the cathode resulting in a 40% drop in cell temperatures (630°C to 350°C).	Mechanical Stress
H ₂ O Oxidizer	2000	A solenoid valve in the water line failed; the stack tripped, the oxidizer was flooded and water backed up into the anode exit pipe and fuel cell stack. Cell temperatures dropped ~32% (to 420°C).	Mechanical Stress
H ₂ O IIR	2118	Water entered the IIR manifold through a safety gas humidifier valve malfunction.	Carbon Deposition Mechanical Stress (Four cells were severely affected)
High COS	2220	High levels of COS were recorded at the desulfurizer outlet. The desulfurizer catalyst was replaced.	Sulfur Poisoning
Oxidizer Upset	3900	Carbon buildup in the oxidizer.	Carbon Deposition

Figure 2.8 STACK OPERATING HISTORY:
This Test Provided First-Hand Coal Gas Industrial Operation Experience

The major cause of test interruptions was gasifier shutdowns. As stated previously, whenever coal gas was not available, the fuel cell went to hot standby open circuit conditions. The test facility itself was only responsible for approximately 10% of the total time spent at hot standby open circuit conditions. Most of these upsets were the result of oxidizer shutdowns. Oxidizer operation was one of the inputs to the safety system which would automatically shut down the stack. Fluctuations in oxidizer air flow and a weak flame scanner signal were the main causes of oxidizer shutdowns. Maintenance was performed on the system after about 3,000 hours of stack testing, and the oxidizer stability did increase following this operation. Operator error accounted for approximately 3% of stack downtime.

The sulfur cleanup system was routinely monitored for sulfur breakthrough using low level sulfur detection tubes. These tubes have a detection range from 5 to 200 ppm total sulfur. High levels of COS were recorded at the desulfurizer exit after approximately 2,200 hours of testing. The stack was placed in hot standby conditions and the desulfurizer catalyst was replaced.

Stack performance remained fairly stable in spite of all the upsets. The performance history of a typical group is shown in Figure 2.9. There is minimal performance change from the beginning-of-life (BOL) performance on coal gas and end-of-life (EOL) performance. Operation on actual coal gas did not adversely affect fuel cell performance.

Figure 2.9 PERFORMANCE HISTORY OF A REPRESENTATIVE 6-CELL GROUP:
Minimal Performance Change After 4,000 Hours of Testing

After testing, the fuel cell stack was shipped back to ERC for intensive post-test analyses. Laboratory testing of lab-scale 250 cm² carbonate fuel cells were conducted under conditions which simulate or accelerate the coal gas test conditions. These results are discussed next.

3.0 POST-TEST ANALYSIS

An extensive post-test analysis of the 20kW stack was performed at ERC following the coal syngas endurance test at Destec. Analyses focused on fuel cell operability in an outdoor, industrial environment and the effect of syngas operation on materials stability, contaminants accumulation and electrolyte loss. Results thus far indicate no problems associated with outdoor operation or the use of a coal derived syngas fuel. The fuel cell components operated as designed with no additional corrosion or degradation in coal syngas. No accumulation of coal-borne contaminants was detected in the hardware, active components or electrolyte. These findings were confirmed by labscale cell testing at ERC.

3.1 STACK COMPONENT ANALYSIS

The objectives in this task were: a) to evaluate fuel cell stack operability in an outdoor, industrial environment, and b) to determine materials stability in the presence of coal gas, i.e., any material degradation, contaminant accumulation and electrolyte loss.

The stack was shipped from the Destec plant back to ERC for disassembly and was removed from the environmental enclosure. The stack enclosure provided complete protection from outdoor conditions. No evidence of water accumulation, corrosion or any form of degradation of the container was observed. The insulation was removed next. A stack photograph taken at this phase of post-test is shown in Figure 3.1. The stack hardware (manifold, compression system, and insulation) was found to be in very good condition and performed as designed. Table 3.1 details the compression system post-test analysis. The stack compressive load change was typical with previous tests as well as within the design specifications. The observed clamping pressure changes which resulted from gasket compression during operation were also within the design specifications.

Figure 3.1 STACK AFTER RETURNING FROM DESTEC COAL GAS TEST:
The Stack Hardware was in Excellent Condition

Table 3.1 COMPRESSION SYSTEM EVALUATION:
The Compression System Performed as Designed

Component	% Change	
	End-of-Life	Design Goal
Compressive Load	14	15
Horizontal Manifold Retention	35	35
Vertical Manifold Retention	35	35

Once the insulation and manifolds were removed, the stack faces were examined. Carbon deposition was partially blocking some cells on the fuel inlet face, especially near the reforming unit inlets (Figure 3.2). Cell 10, 11 (in Group 3), 16, 18 (in Group 4), 34 (in Group 7), 40 (in Group 8), 46 (in Group 9), and 52 (in Group 10) showed more carbon deposition than the central cells. The deposits were verified as carbon by Auger spectroscopic analysis. The deposits were sufficient to block some flow channels and cause fuel flow maldistribution. Most of these cells were located right above the reforming units. Off-design operations may have contributed to carbon build up. One instance of off-design operations occurred after about 2,100 hours of operation when a valve failed in the water line and water leaked into the reforming units. The syngas and steam flow rates at that point indicate that carbon deposition would occur if local temperatures dropped below 520°C (970°F). Performance of four cells was severely affected by this event. Another instance of off-design operation occurred (at about 3,100 hours of operation) when the steam flow to the anode inlet was inadvertently lowered after the water pump was recalibrated. In fact, the burner was shut down due to carbon deposition approximately 45 hours after the stack was placed back on load following this incident.

It is also possible that carbon could have been deposited resulting from unheated nitrogen flow through the reforming units. Since the reforming units (RU's) were not used during syngas operation, a nitrogen purge was maintained through the units. This nitrogen purge was not heated and, therefore, stack temperatures near the RU's dropped into range where carbon deposition would occur. A typical syngas flow rate of 24 m³/h (850 scfh) and a steam flow of 9 kg/h (20 lb/h) would result in carbon deposition if the surrounding temperature goes below 530°C (990°F).

The carbon deposition explains why some of the fuel cell groups showed lower performance during the last 100 hours of testing. Group 4 voltage dropped considerably, and during post-test analysis it was found that the fuel inlet of two cells in this group (cell 16 and 18) were blocked by carbon deposition, inhibiting fuel flow in the flow channels. As a result, these cells were probably forced to operate at an excessively high fuel utilization.

The carbon deposition appears to be a major contributor to the test difficulties encountered. In all likelihood, the deposition was caused by test upsets which led to insufficient water in the fuel gas. The facility design needs to be made robust to eliminate these situations and avoid carbon deposition in future tests.

Figure 3.2 FUEL INLET FACE AFTER SYNGAS TESTING:
Some Carbon Deposition and Flow Channel Blockage is Seen
(Probably Casued by Unplanned Test Upsets)

An accumulation of particulates was observed on the cathode inlet face (shown in Figure 3.3) and at the bottom of the cathode inlet manifold. Most of the stack face was covered with particulates. Gas flow through several cells could have been affected by the deposits. Some particulates appeared to have been blown through the stack to the cathode exhaust face. These deposits were black in color. The analysis of these particulates is listed in Table 3.2 by EDS (Energy Dispersive Spectroscopy) analysis. Low molecular weight elements such as oxygen were not analyzed. The black particulates are mostly iron/nickel/chromium oxides with a negligible amount of potassium. X-ray diffraction analysis identified the iron species as hematite (Fe_2O_3). Small quantities of black particulates, collected in the zinc oxide bed, the fuel feed pipe to the oxidizer and inside the oxidizer itself, had a composition similar to those found in the cathode manifolds (see Table 3.2). The quantity of these deposits is uncertain because prior to sample collection, preparations for facility shipment had already begun. These high iron and non carbonate containing deposits have not been observed in previous stack tests suggesting that these particulates may have originated in materials upstream of the fuel cell and were blown into the fuel cell leading to the conclusion that proper balance-of-plant equipment selection and/or installation of particulate filter at strategic location should be considered.

Figure 3.3 OXIDANT INLET FACE AFTER TEST:

Flow Passages were Clogged with Metal Oxides Originating from Upstream Equipment

Table 3.2 PARTICULATE ANALYSIS BY EDS:

The Black Particles on the Cathode Side Inlet and Exhaust Faces are Comprised Mostly of Iron, Possibly Originating from the Balance-of-Plant Equipment
(Three samples were analyzed at each location)

Element	Deposit Composition Atomic Weight, %		
	Oxidant Inlet Manifold	Oxidant Exit Manifold	Oxidizer
Cr	6-18	2-20	10-19
Fe	73-87	65-98	60-100
Mn	5-7	6	—
Ni	7	4-8	10-30
Total	100	100	100

A small quantity of particulates were also observed in the cathode exhaust manifolds. These contained potassium and chromium (determined by EDS). Such particulates have not been observed in previous stack tests at ERC, suggesting that the oxide particulates blown into the oxidant manifolds from upstream have contributed to the formation of such particulates after

reaction with KOH vapor from the carbonate electrolyte. It is unlikely that the small quantities of the particles on the cathode exhaust face will have any effect on performance other than electrolyte loss.

The bottom end plate insulation at the fuel inlet/oxidant outlet corner showed signs of water damage. This is attributed to a facility upset that occurred after approximately 2,000 hours of operation when a valve in the water line failed and water entered the fuel cell stack.

Stack height measurements were used to characterize creep behavior. The average height change in the active area was within the design goal. The sheet metal components of the cell did not show any measurable thickness change. Most of the height shrinkage was contributed by the stack cathodes, consistent with baseline natural gas stack tests. ERC has recently developed a design to minimize cathode shrinkage and verified it in 100 kW-Class endurance tests. The anode was found to be dimensionally stable and thickness change was minimal, less than the design goal, <5% in 40,000h (<1% in 4,000h).

The fuel cell stack was disassembled and individual cells were submitted for a thorough metallographic analysis. The performance of some cells was affected after off-design conditions such as uncontrolled thermal swings and high fuel utilizations resulting from carbon blockage of the fuel inlet. The cells with lower performance due to upsets were also found to have a higher amount of corrosion. The post-test analysis, therefore, focused on normal cells to identify syngas related effects. Cell hardware corrosion rates are compared with natural gas data in Figure 3.4. The corrosion rates for the cathode and anode current collectors and the separator plate of normal cells were found to be in line with baseline data. The test results suggest that the projected five-year life goal for syngas operation could be attained with present cell hardware. Some concern was raised by process subcontractors for possible metal dusting of the anode side hardware in the presence of coal gas. However, visual observations of the anode side hardware during disassembly did not show any possible indications of such an effect. In addition, cross-sectional analysis of the anode hardware did not show any increased corrosion which would have been present had any metal dusting occurred. Haldor Topsoe, Inc. placed metal coupons in the facility piping to check for metal dusting. No metal dusting was however, detected[8].

Electrolyte loss to the fuel cell hardware was evaluated. Figure 3.5 shows electrolyte loss due to surface creepage to the cathode current collector over time. The loss data is in the normal range. The projected electrolyte losses (relative to the BOL inventory) after 40,000 hours of operation are about 5.5% and 1% for cathode-side and anode-side internal hardware, respectively (including electrolyte incorporated into the corrosion oxide scale). These losses are within the normal range for the stacks operated with natural gas fuel. The electrolyte inventory in the electrodes has been analyzed. The results show that the anode and cathode inventory in the central cells are still adequate after approximately 4,000 hours of testing. The electrolyte inventories of the end and central cells showed little electrolyte migration, even with early design electrolyte migration barriers (Patent No. 5110692). The post-test analysis of this stack found, as expected, corrosion of the metallic barriers. In the current stack design, the metallic barriers have been replaced with a stable ceramic material.

Figure 3.4 POST-TEST CORROSION DATA:
Corrosion of the Current Collector and Separator Plate was within Acceptable Limits

Figure 3.5 ELECTROLYTE CREEPAGE LOSS:
The Electrolyte Loss Due to Cathode Current Collector Creepage was in the Normal Range

The fuel cell anode, cathode and matrix were inspected and appeared normal. The anode nickel coating (Figure 3.6) demonstrates that there is no corrosion of the substrate stainless steel at the fuel inlet due to coal gas. As expected, some carburization and sensitization of the substrate occurred (as revealed by metallographic etching) but did not enhance corrosion, due to the protection provided by the dense Ni coating. Surface Auger analysis confirmed carbon deposition in small area of fuel inlet region as discussed earlier in this section. No sulfide and chloride were detected by Auger analysis. The anode microstructure, magnified in Figure 3.7, shows no change after 4,000 hours of testing. Anode thickness shrinkage was uniform and well within the design goal (<5% shrinkage).

a) Before Test

b) After Test

Figure 3.6 ANODE-SIDE NICKEL COATING AT FUEL ENTRANCE:
Some Carburization and Sensitization was Apparent as Expected,
but no Metal Corrosion was Observed
(Substrate Etched to Reveal Grain Structure, Carburization, and Sensitization)

a) Before Test

b) After Test

Figure 3.7 ANODE MICROSTRUCTURE BEFORE AND AFTER TEST:
There is No Change Due to Testing

3.2 POST-TEST ANALYSIS OF COAL GAS CONTAMINANTS

Coal contains variable amounts of largely incombustible mineral matter. During the coal gasification process, most of the inorganic mineral matter is separated from the coal gas as slag. Some elements, however, may form volatile species during the process and end up as trace contaminants in the coal gas. An overview of coal contaminants and their estimated concentration in coal gas is reproduced in Table 3.3[7]. Based on this understanding of possible coal gas contaminants, the elements that we selected for analysis in the fuel cell were sulfur, chlorine, arsenic, beryllium, cadmium, lead, mercury, selenium and zinc. Analysis of the coal gas for trace metals and metalloids detected only mercury (Table 2.3 in Section 2), however, trace levels of these species could possibly accumulate in the fuel cell components over time.

Table 3.3 OVERVIEW OF COAL CONTAMINANTS[7]:
Elements were Chosen for Analysis Based on this Guide

Contaminant	Estimated Coal Gas Concentrations (ppmv)
<u>Majors</u>	
S	15,000
Cl	500
Na	300
<u>Trace-metalloids</u>	
As	3.0
Se	1.0
Sb	0.1
<u>Trace-metals</u>	
Zn	100
Pb	3.0
Cd	0.2
Hg	0.01
Cr	4
Ni	3
Mn	19
Be	2.3
<u>Additional</u>	
K	
Co	1.5
Fe	
<u>Generally Also Present</u>	Ti Al Si Ca Cu Ga Ge Mo Br

The active fuel cell components were sampled from two cells (Cell 24 and 32) and analyzed for trace levels of possible coal gas contaminants. These cells belonged to Groups 5 and 6, both of which were relatively unaffected by off-design conditions and are representative. It is assumed that the impact of coal gas contaminants on these cell remained undisturbed by other degradation processes. The elements analyzed included: arsenic, beryllium, cadmium, chlorine, lead, mercury, selenium, sulfur and zinc. Both cells were sampled at two locations corresponding to fuel inlet and fuel outlet. The anode, cathode and matrix were analyzed separately. The internal reforming catalyst was also analyzed from three sample locations. Each component sample was further broken down into electrolyte portion and non-electrolyte portion. Thus, a total of 30 samples were prepared and each was analyzed for nine different elements.

The electrolyte was separated from the samples by an aqueous or an organic acid extraction. The non-electrolyte portion of the samples was acid digested and put into aqueous solution. The solutions were then analyzed for possible metal contaminants by atomic absorption and I.C.P. - atomic emission spectrometry. The analyses were performed in duplicate by two independent laboratories for positive confirmation. Whenever a discrepancy occurred, the analysis was repeated, either in-house or by an external laboratory, until the results of duplicate analyses agreed. Chlorine and zinc are difficult to analyze by ICP and were also analyzed by neutron activation in two independent laboratories. Sulfur was analyzed by evaporation IR spectroscopy.

The results of the analyses showed no significant difference due to sample location. All four samples showed approximately the same level of contaminants. Typical results are summarized in Table 3.4 which gives the contaminant levels found in the electrolyte portions of an anode, cathode and matrix from one location (Cell No. 32, anode inlet). Table 3.5 gives typical results obtained for the non-electrolyte portion of the anode, cathode and matrix from the same sample. As seen from the tables, the concentrations of all the metal contaminants were below the method detection levels. No accumulation of any trace metal could be found in any of the fuel cell components at both the fuel inlet and outlet locations analyzed, including the reforming catalyst. Auger spectroscopic analysis of the anode and anode-side current collector surfaces did not reveal any contaminants (other than deposited carbon), indicating little surface adsorption or reaction. The element which was detected was sulfur in the 100 ppm range. This level of sulfur is low and would not be unusual even for a pretest, unused component. It is clear from this data that the cleanup system at the Destec facility performed as designed. The chlorine accumulation in the electrolyte (200 to 500 ppm) is speculated to have originated from steam added to the syngas plant. Low chloride-containing water source is desired to ensure low chlorine contamination. The data show that trace contaminant accumulation in the fuel cell from LGTI coal gas was not an issue for the duration of this test (1,550 hours on coal gas).

**Table 3.4 COAL GAS CONTAMINANT ANALYSIS IN ELECTROLYTE
OF CELL #32 FUEL INLET LOCATION:**

Results have not Shown Any Accumulation of Coal Contaminants in Electrolyte

	Element Concentration, ppm								
Element	As	Be	Cd	Cl	Hg	Pb	Se	Zn	S
Method Used	ICP	ICP	ICP	ICP Neutron Activation	ICP	ICP	ICP	ICP Neutron Activation	IR
Anode Electrolyte	ND (<10)	ND (<10)	40	200-250	ND (<10)	81	ND (<20)	<100	100*
Matrix Electrolyte	ND (<20)	ND (<2)	ND (<2)	216	ND (<2)	ND (<10)	ND (<10)	<100	70*
Cathode Electrolyte	ND (<5)	ND (<2)	ND (<2)	500	ND (<2)	ND (<10)	ND (<20)	<100	90*

* Sulfur analysis includes electrolyte and non-electrolyte sample portions.

**Table 3.5 COAL GAS CONTAMINANT ANALYSIS IN WASHED COMPONENTS
OF CELL #32 FUEL INLET LOCATION:**

Results have not Shown Any Accumulation of Contaminants in Hardware

	Element Concentration, ppm							
Element	As	Be	Cd	Hg	Pb	Se	Zn	S
Method	ICP	ICP	ICP	ICP	ICP	ICP	ICP	IR
Anode	ND <30	ND <1.0	ND <10	ND <1.0	ND <10	ND <40	<50	137
Matrix	ND <30	ND <1.0	ND <10	ND <1.0	ND <10	ND <40	<150	95
Cathode	ND <30	ND <1.0	ND <10	ND <1.0	ND <10	ND <40	<50	ND <40

3.3 SUBSCALE CELL TESTING

In support of the coal gas test and post-test efforts, contaminant testing of single subscale (250 cm²) carbonate fuel cells with low-level contaminants was conducted under conditions which simulate or accelerate the coal gas test conditions. Post-test analysis of the Destec carbonate fuel cell stack (AF-20-4) revealed higher levels of chloride and sulfur relative to other species. Slippage from the desulfurizer can result in up to 100ppb sulfur species in the anode stream. Sulfur may also be introduced into the fuel cell cathode as sulfur dioxide (SO₂) via both ambient air (5-10ppb) and combustion of any sulfur species present in the anode exhaust during recycle from anode to the cathode.

In the cathode, sulfur dioxide may form an alkali sulfate:

Sulfate ions migrating through the electrolyte can be reduced at the anode:

At anodic potentials, the sulfide ions may react to form nickel sulfide:

Sulfide ions may also react with anode gases to form H_2S

which out-gases with the anode exhaust.

Additional sulfur species which enter the anode with the fuel may react in a similar manner. Some studies have suggested a sulfur accumulation cycle. It is reported in the literature[10] that fuel cell performance suffers when sulfur levels exceed 5ppm, and hardware corrosion becomes significant when sulfur levels exceed 10ppm.

The sulfur effects were investigated in several lab-scale single cell tests. A summary of these tests is presented in Table 3.6. The first test was performed to evaluate using an alternative room temperature sulfur cleanup system. Natural gas containing approximately 3ppm H_2S was introduced to the cleanup system where sulfur levels were reduced to <10ppb. This is a ten fold reduction in the amount of sulfur entering the fuel cell compared with the cleanup system used at Destec. Ambient air was used to simulate the cathode gas composition. No additional sulfur was added to the cathode gas. A cell operated for 4,500 hours with no appreciable performance loss or deterioration of the reforming catalyst. The catalyst activity projected over a 40,000 hour life remains within the baseline range. Sulfur was not detected in the anode exhaust, and post-test analysis found minor sulfur accumulation only in the reforming catalyst. This cold gas cleanup system shows promise for future coal gas/natural gas systems.

The oxidant-borne sulfur effects were investigated in a series of tests by doping the cathode gas with sulfur dioxide. The first set of tests was performed by spiking the cathode gas with ten times the sulfur level in ambient air and monitoring fuel cell performance over extended endurance tests. The SO_2 was added using a Dynacal tubular permeation device. One cell was operated for 1,200 hours with 60ppb SO_2 in the cathode inlet. Trace contaminant analyses of cell

components did not indicate increased sulfur levels in the cell hardware. A second test was conducted with 90ppb SO₂ in the cathode gas and the test duration was increased to 3,000 hours. These sulfur dioxide additions did not appear to affect cell performance. This test is equivalent to 27,000 to 54,000 hours operation with respect to exposure to normal level of SO₂. Trace contaminant analysis of this cell also did not indicate increased sulfur levels. ERC conducted yet another test where 1ppm of SO₂ is being introduced to a cell with the oxidant gas. The cell was on test for 360 hours in this mode and then 20ppb SO₂ was introduced for ~800 hours. The whole test represents a total exposure to sulfur equivalent to 40,000 hours with 10ppb SO₂. The cell has been exposed to total SO₂ equivalent to 50,000 to 100,000 hours. No effect on cell performance or the resistance has been noticed.

Table 3.6 LABSCALE (250 cm²) SINGLE CELL TEST SUMMARY:

The Normal Amount of Ambient SO₂, 5-10ppb Range, May Not Effect Carbonate Fuel Cells

CELL #	TEST CONDITIONS	RESULTS	POST-TEST
7-440	Natural Gas with Cold Gas Cleanup Duration ~4,500h.	No appreciable performance loss or deterioration of reforming catalyst.	Some accumulation of sulfur on reforming catalyst.
7-423	~60ppb SO ₂ in Cathode Inlet Duration ~1,200h.	No effect on performance and no increased levels of sulfur were found in cell hardware.	Some sulfur found in catalyst.
7-438	~90ppb SO ₂ in Cathode Inlet Duration ~3,000h.	No effect on performance and no increased levels of sulfur were found in cell hardware.	Catalyst not analyzed for sulfur.
7-538	1ppm SO ₂ in Cathode Inlet for ~360h 20ppb SO ₂ for ~800h - the sum represents a total exposure to sulfur equivalent to 40,000 hours with 10ppb SO ₂ @ 75% util.	Poor cell performance (high resistance) after removing 1ppm permeation tube. Performance improved after adjusting inlet flow piping.	
7-499	10ppm SO ₂ in Cathode Inlet Duration ~1,000h.	Immediate effect on cell performance. Cell could only operate at 20A. High EOL resistance, (1800mΩ • cm ²).	High sulfur levels in cathode and anode ~7ppm sulfur in anode exhaust.
7-457	1wt% K ₂ SO ₄ in Electrolyte.	Performance deteriorated after 100 hours due to high resistance.	20ppb H ₂ S in anode exhaust. High sulfur levels in reforming catalyst, low levels in anode.
7-486	0.5wt% K ₂ SO ₄ in Electrolyte.	Poor performance, average resistance (400mΩ • cm ²).	7ppb H ₂ S in anode exhaust. High sulfur levels in reforming catalyst.
7-477	0.5wt% K ₂ SO ₄ in Electrolyte.	Poor performance, resistance increased (400 to 750 mΩ • cm ²).	7ppb H ₂ S in anode exhaust. High sulfur levels in reforming catalyst.

Another test was conducted with 10ppm SO₂ in the cathode inlet. This is a highly accelerated test condition with the SO₂ concentration 1,000 times what would be encountered in an actual power plant. The high concentration was chosen to help with the analytical quantification of sulfur species in the various gas streams. This test was designed to investigate the fate of SO₂ in the carbonate fuel cell. Analysis of the cathode exhaust showed <10ppb SO₂. The anode exhaust was closely monitored for H₂S and contained approximately 6ppm at full load and up to 30ppm at open circuit potential. Sulfur balance around the cell components and gas streams did not close. This lack of a sulfur balance which is consistent with previous sulfur contaminant carbonate fuel cell testing[13] may be uncertainties of the analytical procedures used for sulfur.

A different approach to SO₂ testing was pursued in which all the SO₂ that could possibly accumulate over a 40,000 hour test period was initially loaded into the cell electrolyte as potassium sulfate. Assuming that ambient air contains 10ppb SO₂ on the average, this amounted to approximately 1 weight percent of the electrolyte. The cell initially showed normal performance, but, after 100 hours of operation, the internal resistance of the cell increased and the internal reforming catalyst activity declined. Trace amounts of H₂S were measured in the anode exhaust (20ppb). Two other subscale cells were tested with half the amount of potassium sulfate of the original cell (0.5 weight percent) and similar performance effects were observed. Post-test analysis of all three cells showed that there was no sulfur left in the cathode or the electrolyte. High sulfur levels were detected in the reforming catalyst with lower levels in the anode. Total sulfur recovery was low, only 25% of the sulfur put into the system was accounted for in post-test and exhaust gas analyses. The remaining sulfur may have reacted with the current collector and other stainless steel hardware which were not analyzed.

These results confirm earlier studies[10-14] which indicates that although high doses of sulfur may cause detrimental damage to currently designed fuel cell systems, the normal amount of ambient SO₂, 5-10 ppb range, may not affect carbonate fuel cell performance. This was also confirmed in the Destec test. The stack was in contact with coal gas for 1,500 hours. Hot air was directed to the cathode during off load conditions of 2,200 hours. In this test the total oxidant passed through the cell was approximately three times greater than operation with natural gas. SO₂ content in Destec air was measured to fall within the U.S. average, 5-10ppb. The Destec stack test did not show any effects attributable to sulfur. The post-test analysis of the stack also did not show any increased corrosion of the fuel cell hardware, although some sulfur was present in the anode electrolyte (see Section 3.2).

4.0 CONCLUSIONS

For the first time anywhere in the world a carbonate fuel cell has been operated with coal gas. A 20kW direct carbonate fuel cell stack has been operated with coal gas from an entrained flow, slagging, slurry-fed gasifier for a total of ~4,000 hours with 1,550 hours on coal gas. The important conclusions of this study are listed below.

- The Direct Fuel Cell can operate with high CO-containing coal gas and interchangeably with natural gas providing normal performance and stable operation. Dual-fuel operation capability was also demonstrated.
- Carbonate fuel cell operation outdoors with properly designed enclosure and by industrial operators is feasible.
- The baseline carbonate fuel cell components are stable for coal gas operation with cold gas cleanup. No accumulation of coal-borne contaminants in the cell hardware was detected based on detailed post-test analyses of electrolyte and cell hardware. Additional cell testing with controlled additions of sulfur on fuel as well as oxidant sides confirmed the results of the field testing.
- Proper selection of balance-of-plant materials is necessary to minimize accumulation of unwanted corrosion products in the pipings and/or inside the fuel cell flow passages. The syngas humidification scheme needs to be made reliable to avoid carbon deposition.
- This study has shown that the DFC can be operated with properly cleaned and humidified coal gas with expected performance and stability. A 5-year life may be projected for the basic cell components for coal applications.

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LIST OF ACRONYMS AND CONVERSION FACTORS

AA	Atomic Absorption Spectroscopy
BOL	Beginning-of-Life
DFC	Direct Fuel Cell
DOE	Department of Energy
DFC	Direct Fuel Cell
EDS	Energy Dispersive Spectroscopy
EOL	End-of-Life
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ERC	Energy Research Corporation
ESEERCO	Empire State Electric Energy Research Corporation
FCMC	Fuel Cell Manufacturing Corporation
I.C.P.	Inductively Coupled Plasma
IIR	Indirect Internal Reforming
IR	Infrared
LGTI	Louisiana Gasification Technology Incorporated
MDEA	Methyldiethanolamine
RU	Reforming Unit

Conversion Factors

To Convert:	to:	Multiply by:
J/kWh	Btu/kWh	9.47×10^{-4}
J/m ³	Btu/scf	2.68×10^{-5}
kPa	psig	1.45×10^{-1}