CONSULTANT REPORT

PIER
Public Interest Energy Research
CALIFORNIA ENERGY COMMISSION

Environmentally-Preferred
Advanced Generation

MOLTEN CARBONATE FUEL CELL DEVELOPMENT AND DEMONSTRATION

Gray Davis, *Governor*

DECEMBER 1999

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RESOURCES AGENCY

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Legal Notice

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliability energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million through the Year 2001 to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

In 1998, the Commission awarded approximately $17 million to 39 separate transition RD&D projects covering the five PIER subject areas. These projects were selected to preserve the benefits of the most promising ongoing public interest RD&D efforts conducted by investor-owned utilities prior to the onset of electricity restructuring.

What follows is the final report for the Molten Carbonate Fuel Cell Development and Demonstration project, one of six projects conducted by San Diego Gas & Electric. This project contributes to the Environmentally-Preferred Advanced Generation program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

Purpose

This project was designed to develop and demonstrate molten carbonate fuel cell (MCFC) technology by integrating system design modifications to the demonstration plant at the Marine Corps Air Station Miramar (Miramar), San Diego, California. It also assessed the applicability of other technologies (microturbine generation and proton exchange membrane (PEM)).

Lessons learned during Phase I of the 250 kW demonstration conducted at the MCFC plant at Miramar formed the basis for this project. Phase I identified the need for plant system modifications to improve system performance and conduct balance-of-plant (BOP) component tests.

Objectives

The primary objective of this project was to:

- Modify and test the Miramar MCFC balance of plant (BOP) processes and components

Two secondary objectives were to:

- Assess microturbine generation technology for incorporation into the demonstration MCFC plant
- Assess PEM fuel cell technology and its applicability to serve as a distributed resource option.

Detailed information on the Microturbine project and the PEM project is presented in Appendix I and II respectively.

Outcomes

- The plant was successfully modified and readied to accept the 75 kW MCFC fuel cell stack of M-C Power design.
  - The provision of supplemental natural gas to meet the thermal energy needs of the microturbine generator's combustor.
- The present cost of PEM technology makes it unacceptable at this time.

Conclusions

- Existing packaged microturbine generator technology could be integrated as part of the BOP at Miramar but to do so will require potentially cumbersome and costly piping modifications.
- PEM fuel cell technology has the potential for entering the early commercial market in distributed generation applications by 2003.

Recommendations

- A more detailed analysis is needed to quantify plant performance improvement.
- More detailed assessment of the performance and economics of integrating fuel cell and microturbine technology is needed.
- Further development for a compact, low-cost, and fast acting reformer technology (converting natural gas / methane gas into hydrogen) for PEM fuel cell applications is needed.

Abstract

Molten carbonate fuel cells (MCFC) are considered a moderate to high temperature fuel cell technology. The nominal operating temperature is nearly 600°C (about 1200°F), which is the typical operating temperature found in conventional utility power plants. Theoretically, MCFC has a high fuel-to-electricity efficiency (~55 to 60 percent) and minimal environmental emissions such as Nitrogen Oxides (NOx) (<1 ppm).

These performance characteristics make MCFC technology an ideal candidate for distributed generation applications and, potentially, for repowering conventional fossil fuel power plants. But the technology has to be packaged in such a way to make it acceptable to the market. The operating characteristics of this technology can only be verified when it is demonstrated as part of a complete power plant system, including balance-of-plant components and a power conditioning system.

The objective of the 250 kW demonstration MCFC plant, located at the Marine Corps Air Station Miramar in San Diego, California, was to verify the performance characteristics of a thermally integrated power plant. This plant was operated, by M-C Power Corporation and San Diego Gas & Electric (SDG&E), for nearly 3000 hours in 1997. The lessons learned from this initial operation identified the need for plant system modifications to improve system performance and to create the capability of performing balance-of-plant component testing.

The California Energy Commission, through the Public Interest Energy Research (PIER) program, approved a proposal from SDG&E to fund a portion of the plant process modifications costs. The modifications include piping, components, and control system changes to enable the plant to operate with a 75 kW fuel cell stack. In addition, anode gas recycle capability was added to test its effect on plant performance.

Two additional activities of the PIER sponsored project included evaluation of microturbinegenerator technology for incorporation into the demonstration MCFC plant and an assessment of proton exchange membrane fuel cell technology and its suitability as a distributed resource option.

1.0 Introduction

Fuel cells are electrochemical devices that consist of two electrodes (anode and cathode) separated by an electrolyte. While similar to an automobile battery, the fuel cell uses fuel rather than becoming charged and storing energy. Because the electrochemical process is not bound by the Carnot or Bryton cycle limits of performance and efficiency, fuel cells have the potential to nearly double the fuel-to-electricity efficiency, of conventional generation technology, while producing minimal emissions.

Molten carbonate fuel cell (MCFC) technology operating in a pressurized mode has the potential of a fuel-to-electricity efficiency in the range of 55 to 60 percent with NOx emissions of less than 1 ppm. The operating temperature at nearly 1200°F is typical of the operating temperatures found in conventional utility steam power plants.

There are two major developers of MCFC technology in the US, M-C Power and Fuel Cell Energy (previously known as Energy Research Corporation). Each provides a different fuel cell stack design.

Fuel Cell Energy has an internal reforming process of natural gas with external manifolding for gas distribution and a plant design, which operates at lower than 3 atmospheres. M-C Power, has an internal manifolding heat exchanger design for gas distribution, but requires external reforming of natural gas. M-C Power’s power plant design operates at a pressure from 3 to 5 atmospheres.

High temperature fuel cell technologies have some technical obstacles to overcome. The high temperature BOP equipment, such as valves and piping, is generally large. This is necessary to handle the mass transfer of gas required. The operating characteristics of MCFC technology can only be verified through the demonstration of a complete power plant system that includes balance-of-plant (BOP) components and a power conditioning system.

The current equipment has a large footprint when compared to competing technologies such as advanced gas turbines. And some of the BOP components require further development to provide acceptable level of reliability, durability, and performance.

San Diego Gas & Electric (SDG&E) anticipates that MCFC technology may be applicable to repowering fossil fuel power plants as well as in distributed generation. But its acceptability will depend on its meeting cost targets and being packaged in a form acceptable to the market.

SDG&E elected to participate with M-C Power in the development and demonstration of their MCFC technology. A demonstration power plant was constructed at the Marine Corps Air Station Miramar (Miramar), San Diego, California to test and verify the performance of a thermally integrated MCFC system.

This project’s primary purpose was to develop and demonstrate MCFC technology by integrating system design modifications, identified during Phase I, to the existing 250 kW demonstration power plant at Miramar. These modifications would enable the Miramar plant to be a test facility for MCFC fuel cell stack and balance-of-plant components.

The California Energy Commission, through the Public Interest Energy Program (PIER), approved a proposal from SDG&E to fund a portion of the costs associated with this project.

1.1 Project Objectives

Objectives

The primary objective of this project was to:

- Modify and test plant processes and components

Two secondary objectives were to:

- Assess microturbine generator technology for incorporation into the demonstration MCFC plant
- Assess proton exchange membrane (PEM) fuel cell technology and its applicability to serve as a distributed resource option.

1.2 Background and Overview

1.2.1 Background

The 250 kW demonstration MCFC plant located at Miramar was completed in 1997. It was operated for nearly 3,000 hours. M-C Power submitted a report to SDG&E in October 1997 that identified lessons learned during Phase I operation of the plant.

Plant system modifications were needed both to improve system performance and to allow BOP component testing. The modifications would allow the Miramar plant to serve as a test facility for MCFC technology.

The process modifications include piping, components, and control system changes to make it possible for the plant to operate with a 75 kW fuel cell stack. In addition, an anode gas recycle capability was added to test its effect on plant performance. The process modifications would enable the MCFC plant to test and verify the performance of different MCFC stack configurations (co-flow to counter-flow and cross-flow) and balance-of-plant (BOP) components.

Phase I Lessons Learned

- Improvement in thermal energy management needed to balance the system gas temperature from the cathode output through the input to the reformer’s catalytic combustor.
- Improvement in turbocharger design needed to provide a more reliable and efficient pressurization process. A backup to the turbocharger may be required to increase system’s reliability in testing the fuel cell component.
- Design improvements to the hot gas blower needed to provide greater reliability from a key plant component.
- Fine-tune and reconfigure the control system to improve the control of plant components and overall system control.
- Modify the DC-AC inverter to operate with a smaller 75 kW fuel cell stack.

1.2.2 Project Overview and Scope

The primary focus of this project was to implement the required plant modifications and improvements identified in Phase I. M-C Power made the system and component engineering changes and system modifications required to improve the performance and reliability of the fuel cell stack and BOP. The modifications would ready the plant at Miramar to accept different plant components for testing under actual operating conditions.

An improved design of MCFC stacks and other BOP components, including a new hot gas blower and turbo charger, were tested and demonstrated under a separate effort by M-C Power. Based on SDG&E's experience with the Miramar test facility and its continued participation with M-C Power, the project was the lowest-cost approach to performing the modifications and testing of the technology.

The PIER contract with SDG&E provided $300,000 of the nearly $1.4 million effort to accomplish the MCFC plant modifications as part of the overall scope of work under the M-C Power contract with the DOE. The DOE, Electric Power Research Institute, and SDG&E provided the remaining $1.1 million.

PIER resources were specifically allocated to labor costs (engineering, technical assistants, technicians, laborers, and plant operators) associated with the plant modifications and subcontractor costs in performing the technology assessments of turbo-generator and PEM fuel cells.

Other Activities

- Assessments of microturbine generator and PEM fuel cell technologies were also performed. Details on these projects can be found in Appendix I and II respectively.
- As part of the BOP modifications, SDG&E also provided:
  - Engineering and plant operation support to M-C Power in process design
  - Plant Operator training
  - Engineering support to turbocharger supplier to modify the original turbocharger design

1.3 Report Organization

This report focuses on the BOP and system modifications and improvements identified during Phase I. While the microturbine generator and PEM technology assessment projects are briefly discussed, greater detail on them is provided in the appendices.

The body of the report contains the following sections:

- Section 2 – Discussion (modifications, improvements, testing, and results.
- Section 3 – Project Outcomes
- Section 4 –Conclusions and Recommendations

2.0 Discussion

2.1 System Modifications

To minimize the cost of testing the new fuel cell stack, M-C Power built a smaller stack of 75 kW capacity to fit the existing plant configuration. This approach made better use of limited research and development resources. If the smaller stack proved successful, M-C Power would construct a larger stack that used the full capacity of the Miramar plant.

Plant process modifications included:

- piping changes around the fuel cell vessel to change gas flow conditions from co-flow to counter-flow and from counter-flow to cross-flow
- modification of the original turbo-charger design
- modification of hot gas blower to provide mass gas flow to the smaller fuel cell stack addition of anode recycle and cathode bypass
- cathode heater new control module
- refurbishment of electrical heat-trace and insulation on six sample lines
- inverter modifications (to operate at a lower capacity than the original 250 kW design,)
- safe gas injection

2.1.1 System Improvements

SDG&E worked with the turbocharger supplier, Turbonetics, to redesign the turbocharger to perform in the operating conditions at the Miramar plant. Turbonetics was very responsive to changes needed to reach the desired compression ratio and unit efficiency.

A back-up air compressor was installed to supply the system pressure and air mass flow in the event the turbocharger failed. The original turbocharger operated below the expected efficiency and at 90,000 RPM the turbocharger surged. This turbocharger had difficulty in sustaining self-operation at the designated operating speed of 120,000 RPM. The new turbocharger design improved the area to radius (A/R) ratio of the impellers and increased its efficiency to the extent that the turbocharger no longer surged during the start up and it self sustained at a shaft speed of 110,000 RPM.

The original hot gas blower failed to perform because the shaft would bend as the temperature of the system increased to meet operating temperature of 1200ºF. The hot gas recycle blower was redesigned to compensate for thermal expansion and to improve the hot gas mass flow. Designed and fabricated by Robinson Blower, the new blower included equipment to monitor the shaft temperature and speed. Robinson Blower also provided a smaller impeller to meet the operating characteristics of the smaller 75 kW MCFC stack.

The hot gas recycle blower was initially provided with a graphite packing seal. Because the packing seal continued to fail under plant temperature and pressure conditions, the blower was fitted with a mechanical seal that included an air purge system. The new seal worked well with a lower leak rate than specified by the engineering and plant process design.

Other system improvements included heat tracing of sample lines for the gas chromatograph (GC). In the Phase I demonstration, the sample gas reaching the CG was cooler than the temperature of the gas at the extraction point. Consequently the gas analysis in Phase I was not accurate enough to have confidence in the results.

To improve on the on-line gas analysis system, the sample lines had to be reworked with new thermal insulation and heat tracing to ensure that the sample gas at the GC was nearly at the same temperature of the originating location. Improvements at the Miramar test plant included additional system changes to test other operating concepts including the recycling of anode gases that could potentially increase system efficiency.

The digital control system console was reprogrammed and input/output capacity of the system was increased to accommodate the new components and changed system configuration. A Bailey representative performed the necessary modifications. System control changes to include new fittings and calibration of process control. The Ishi Kawajima Heavy Industries (IHI) reformer was able to operate at the turn-down ratio that provided the required amount of reformate for the smaller 75 kW MCFC stack.

A load bank was added to ensure that the fuel cell test would continue even if the inverter did not perform or failed during plant operation. The load bank gave the plant an alternate mode of operation without having to deliver power to the Miramar electric grid.

2.1.2 Component Testing

The piping changes required testing of the complete piping system for pressure and leaks. During the piping modifications, all welds were X-ray and inspected to ensure no hydrogen leaks would be present during operation.

The turbocharger, hot gas blower, and inverter were the primary focus of component testing. Lines to the gas chromatograph, desulfurizers, and the digital control system were periodically verified.

The hot gas blower was tested by rotating the blower at operating speeds and temperature. A heater used for plant start-up is used to bring the entire BOP to operating temperature. The blower was operated for nearly 300 hours to test for gas leaks across the seal.

Vibration tests were conducted by placing vibration instrumentation on the rotor shaft and turning the shaft up to 3600 RPM in increments of 300 to 400 RPM. The incremental speed changes are possible because a variable speed controller controls the blower.

M-C Power established a bench test at Stewart & Stevenson in Houston, Texas to do a performance test on the mechanical seal eventually installed on the hot gas blower. The bench test for this mechanical seal included over 3000 hours of rotation at temperature of nearly 1200ºF and with pressure differential across the leas of up to 3 atmospheres.

The anode recycle loop was not tested during the process and control test because it requires the fuel cell to be in operation in order to recycle the anode gas. This test was to be tested during the operation with the fuel cell stack in place.

The cathode heater was energized and tested with the digital control system (DCS) to ensure it would operate across the range of different loads from zero to full temperature of 1300ºF.

The direct current to alternating current (DC / AC) inverter was initially designed to operate at 250 kW and it was necessary to make modifications to ensure that the inverter could operate at lower power levels without creating power quality problems.

In Phase I, the inverter failed in several occasions because of its internal process control system. Each time the inverter would go off-line, the plant had to be placed on hot stand-by. The sudden change in operations caused problems to the fuel cell stack with high pressure differential between the anode and cathode.

To eliminate this problem, a load bank was implemented as part of the plant system modifications. In the event the inverter would go off line, the load bank would automatically pick up the load and the plant would remain operational. The power, however, would be dissipated across the load bank instead of delivering it to the electric grid in the base.

To test the inverter and load bank, a portable generator set was installed to provide the DC power input to the inverter. A technician from the inverter supplier, Inverpower, made the unit modifications and was part of the test.

2.1.2.1. Testing Procedures

Temperature, pressure, and rotation parameters for individual components were tested to evaluate their ability to operate as specified during operating conditions. Components were tested at an operating temperature of 1200ºF, a pressure of 28 pounds per square inch gauge (psig), and a gas volume flow of 1500 to 2000 standard cubic feet per minute (SCFM).

A process and control (PAC) test of all plant components controlled by the digital control system was performed. This ensures that the components operate within the specified parameters. The PAC test was conducted upon the completion of plant modification and individual component testing.

Tests were performed under actual operating conditions in two steps:

- Without the fuel cell stack during the PAC test
- With the fuel cell stack in place.

The gas volume flow across the fuel cell stack was not tested during the PAC test.

SDG&E personnel tested the inverter to ensure that the output met SDG&E's limits of harmonics (<5 %) and voltage variation (<10%) as well as the inverter's ability to operate at the lower capacity (75 kW). A portable generator set was rented to provide the power necessary for the inverter.

Table 1 summarizes the testing procedures for the fuel cell BOP Components at the Miramar plant.

Table 1. Testing Procedures for Fuel Cell BOP Components

Component	Test Conditions	Specific Test Milestones
Turbocharger	Test at ½, ¾, and full speed (130 KRPM) to achieve self-sustained operation and reduce surge.	Achieve 22 psig from compressor. Verify optimum A/R* ratio for performance.
Hot Gas Blower	Vibration test at various shaft speeds. (1200, 1800, 3600 RPM)	Verify gas mass flow and seal leak rate below 5 SCFM.
Gas Chromatograph Sample Lines	Verify temperature on sample lines.	Temperature of samples should be as close to the temperature at point of extraction. (+/- 5 ^oF)
Desulfurizers	Verify reaction of Calgon and Tospix catalyst.	Analysis should have non-detectable sulfur.
Digital Control System	Verify control system operates within specified limits.	Eliminate all nuisance trips.
Inverter	Test at various current levels up to 1500 Amps (400, 800, 1200, 1500 Amps)	Inverter must meet Rule 21 and IEEE 519 for harmonics and voltage distortion

*A / R (area to radius) ratio defines the geometry of the turbocharger's compressor to provide the specified amount of gas mass flow at a given pressure

Notice: Specific flow conditions for each component test is proprietary to M-C Power as part of the plant design and specific numbers can not be disclosed here.

2.1.2.2. Test Results

The PAC testing started in January 1999 and was completed in March 1999. This completed successfully the first objective of this project.

The turbocharger was successfully redesigned and tested at the Miramar plant. Seal and impeler modifications allowed the turbocharger to meet the test requirements indicated in Table 1.

The hot gas blower satisfactorily met the requirements specified in Table 1.

Gas Chromatograph Sample Lines were satisfactorily tested for gas temperature from the originating point to delivery to the GC. The temperature difference was within the limits specified in table 1.

Natural gas was flowed through the desulfurizers and the sulfur content of the output gas was sampled. The sulfur content of the gas was well below the limits set forth in Table 1.

The digital control system was tested with all components including line sensors, load bank, backup air compressor, and modified inverter. It tested within the specified limits.

The inverter modifications met the voltage fluctuation and harmonics requirements of Institute of Electrical and Electronics Engineers (IEEE) 519 standard and Rule 21.

The 75 kW fuel cell was received in May 1999 and installed in the existing fuel cell vessel. Subsequent PAC tests were performed to verify that all BOP components met design criteria and the process system performed as expected.

3.0 Project Outcomes

3.1 Plant Modifications

The plant modifications were successfully completed in December 1998. Following the installation of 75 kW fuel cell stack, operation of the plant began in June 1999 and continued through November 1999. The plant operated without any significant equipment or component failure.

Minor operational interruptions occurred because of the turbocharger performance, but this was quickly repaired without significant down time.

Plant operators received training on the operation of the new 75 kW plant-operating procedures and to prepare them for the PAC test.

3.1.1 Microturbine Generator Assessment

The microturbine generator assessment indicated that the existing packaged microturbine generator technology would have difficulty in being integrated into the BOP at Miramar. The fuel cell process does not produce enough thermal energy to provide the microturbine generator combustor with its required energy. It would be necessary to supplement the thermal energy needs by burning natural gas directly into the combustor.

Microturbine generator technology is still under development. It is unlikely that products will be available before late 1999 or mid 2000.

The microturbine generator assessment project is detailed in Appendix I.

3.1.2 PEM Assessment

The PEM fuel cell assessment was completed.

The technology has the potential to be used as a distributed resource option, but because of the present cost of the technology and the lack of an adequate gas processing system makes it unlikely that a PEM fuel cell system before the 2003 time frame.

The PEM assessment project is detailed in Appendix II.

3.2 Benefits to California

It would not be fair to MCFC technology to judge its economic potential using the results of this project. Significant cost reductions in the technology itself and the required BOP modifications are needed to reach market acceptance.

The potential of the technology to increase the efficiency of fossil fuel energy resources while reducing emissions would be of great benefit to California. The fuel to electricity efficiency of MCFC would increase even more if thermal energy could also be used in a cogeneration application.

Since the manufacturing of MCFC components requires a relatively dry environment, an additional economic benefit to California could be economic development if MCFC manufacturing facilities were located in the state.

4.0 Conclusions and Recommendations

Modifications to the MCFC demonstration plant at Miramar to enable it to operate with a 75 kW fuel cell stack were successfully accomplished. Tests conducted after the 75 kW fuel cell was installed verified that all BOP components performed as expected.

The MCFC project resulted in the following conclusions and recommendations.

4.1 Conclusions

- Significant cost reductions in MCFC technology are required to reach commercial target costs and market acceptance. Currently MCFC technology demonstration costs are over $8,000 / kW, compared to conventional generation technology that ranges in cost from $600 / kW to $1,000 / kW. Likewise, the cost of PEM fuel cell technology applied to distributed generation must come down to below $800 per kilowatt in order to be competitive with conventional current technologies.
- Existing packaged microturbine generator technology could be integrated as part of the BOP at Miramar but to do so will require potentially cumbersome and costly piping modifications.
- PEM fuel cell technology has the potential for entering the early commercial market in distributed generation applications as early as 2003. The unavailability of a compact, low cost, and quick responding natural gas processor will limit the application of PEM fuel cell technology use in residential applications.

4.2 Recommendations

- A more detailed analysis is needed to quantify plant performance improvement and cost optimization.
- More detailed assessment of the performance and economics of integrating fuel cell and microturbine technology is needed. Detailed information on the Microturbine project and the PEM project is presented in Appendix I and II respectively.
- Further development and demonstration of a compact, low-cost, and fast acting reformer technology (converting natural gas or methane gas into hydrogen) for PEM fuel cell applications is needed.

Appendix I

Assessment of the Applicability of Microturbine-generator to the Molten Carbonate Fuel Cell Power Plant at Miramar

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Executive Summary

San Diego Gas & Electric (SDG&E) has been operating and maintaining a 250 kW carbonate fuel cell test power plant, for M-C Power Corporation, at the Marine Corps Air Station Miramar. The test power plant has undergone modifications to test balance of plant components A smaller (75kW) new design fuel cell stack delivered to the Miramar plant in 1999 from M-C Power. The temporary measure of the smaller stack was to alleviate the costs of verifying the redesign.

Objective

The objective of this project is to make an assessment of available packaged microturbine technology and evaluate its potential for integration with the fuel cell test power plant at Miramar.

Evaluating the economics of integrating these products was beyond the scope of this effort.

Technology Assessment

Microturbine generator technology is derived from the automotive and aerospace applications used today. Improvements in materials and methods have allowed the development of more compact and simple to operate system than the large power generation turbines used by utilities in central power plants. Microturbines are now being developed and packaged with a heat recovery (recuperated) cycle to improve their performance.

Twelve different microturbine generator systems are currently in development or near commercial status. The systems vary in capacity size from 30 kW to 250 kW. Most of these systems are still under development and only four domestic suppliers were considered for this effort.

The target prices for commercial products based on thousands of units to be manufactured and sold per year range from $400 to $1,000 / kW. The average cost of demonstration systems today are nearly $2,500 / kW plus installation costs.

The microturbine generator suppliers increased their efforts hoping to place commercial products in the market as early as 1998. But commercial products that can be ordered off the shelf at the target cost do not yet exist. The closest is the 30 kW system from Capstone Turbines, but it is still considered in the demonstration stage and its costs are higher than target.

VFL, as a subcontractor for this effort have identified potential improvements in the balance of plant for carbonate fuel cell power plants including the direct integration of a microturbine generator to increase system efficiency and reduce overall plant cost.

Outcomes

Four domestic suppliers of packaged microturbine generators that have the potential for integration with the carbonate fuel cell power plant at Miramar were identified. Integration of the microturbine generators would require:

- Relatively minor piping modifications.
- The provision of supplemental natural gas to meet the thermal energy needs of the microturbine generator’s combustor.

Conclusions

- These products could be integrated with a molten carbonate fuel cell power plant with rating capacity of 250 kW and larger, but the physical connections between the two technologies may be cumbersome and costly.
- The overall performance of the fuel cell power plant with an integrated microturbine generator would be improved.

Recommendations

- More detailed analysis to quantify the performance improvement and economics of integrating fuel cell and microturbine generator technology.
- The threshold at which a fuel cell power plant could support the operation of a microturbine generator should be determined. Molten carbonate fuel cells below 250 kW in capacity may have difficulty providing the necessary mass-flow and energy to operate a microturbine.

Abstract

Fuel cell technology, such as molten carbonate and solid oxide, operate at temperatures of nearly 1200ºF and 1900ºF respectively. This temperature is within the range of the combustor temperature of gas turbines. The U.S. Department of Energy supports a research and development project to integrate solid oxide fuel cell technology with combustion turbines.

Microturbine generator (MGT) technology is being developed by a number of suppliers for application as distributed generators. Microturbine generators work on the same principle as combustion turbines to compress a gas and expand it through a turbine to produce work. It is the size of this technology that lends it to integration with high temperature fuel cells as a bottoming cycle.

The high temperature at which molten carbonate fuel cells (MCFC) operate allow their potential integration with combustion turbine technology as a bottoming cycle or as the primary source of energy for the turbine's expander.

Integrating MTG with MCPC plants would make the system more complex, but it could increase overall system efficiency and reduce the costs of power plant.

This project assessed available microturbine technology and evaluated the potential for integrating it into molten carbonate fuel cell power plants. The 250 kW MCFC test power plant at the U. S. Marine Corps Air Station Miramar was used for this project. The plant is operated by San Diego Gas & Electric and M-C Power.

Twelve different MTGs were identified ranging from 2.5 kW to 250 kW. Only four US products that were near to commercial status were considered for this assessment.

1.0 Introduction

Micro-turbine generator technology was derived from automotive and aerospace applications. Improvements in materials and methods resulted in the development of compact and simpler to operate systems than the large power generation turbines used by utilities in central power plants.

Micro-turbines are being developed and packaged with a heat recovery (recuperated) cycle to improve their performance.

The microturbine generators are primarily single-stage rotor systems operating from 70,000 rpm to 116,000 rpm. The shaft drives and alternator produce high frequency alternating current. The current is then conditioned to reduce the frequency to 60 Hz alternating current through power electronics. The units operate with a variety of fuels including natural gas, diesel, and gasoline.

During this assessment the microturbine's combustor would not burn fuel. Instead, the thermal energy from a molten carbonate fuel cell (MCFC) would be used to operate the microturbine.

The plant at operates at an average temperature of 1200^{o}F with the cathode outlet temperature slightly higher. This condition is nearly perfect for the operation of a microturbine as part of the balance of plant (BOP) to provide pressure to the oxidant loop of the system.

Currently, the M-C Power fuel cell balance of plant operates with a turbo charger that provides the system pressure to the oxidant portion of the process cycle. Integrating a microturbine generator instead of the turbo charger may improve overall system performance and plant efficiency.

1.1 Technical Overview

Microturbine technology has made significant advancements over the past few years. The technology is being packaged as small distributed power generators as a distributed resource option. The technology is also being considered as a component to improve the performance of other power generation technologies such as high temperature fuel cells.

Solid oxide and molten carbonate fuel cells are high temperature fuel cells, which are being considered as the heat source to a combustion turbine. Molten carbonate fuel cell technology operates at a lower temperature (1200 ^{o}F), which may not be sufficient to provide the energy necessary for a combustion turbine, but its process gases may have enough energy to provide the energy and air mass flow to a microturbine's combustor.

1.2 Project Approach

SDG&E received an award from the Public Interest Energy Research (PIER) transition program, managed by the California Energy Commission to perform an assessment of microturbine generator technology that could be integrated into a MCFC power plant system.

SDG&E subcontracted this effort to VFL Energy Technologies, Inc. (VFL). VFL has experience in the oil and gas energy production area, MCFC technology, and assessments of technical applications for distributed generation options. They were instrumental in the design and fabrication of the Stewart & Stevenson BOP skid at the Miramar plant.

VFL performed the work and provided a perspective on integrating existing packaged microturbine generator products into power plant designs. The MCFC power plant located at the U.S. Marine Corps Air Station Miramar (Miramar), San Diego, California was used as the basis for this assessment. The plant is operated by San Diego Gas & Electric (SDG&E) and M-C Power.

1.1. Project Objective

This project assessed if existing packaged microturbine technology could be readily integrated into a MCFC power plant system and augment plant performance.

2.0 Technical Assessment

Twelve different microturbine generator products were identified, worldwide, that are currently in development or near commercial status varying in capacity size from 2.5 kW to 250 kW (Table 1).

Table 1. List of Microturbine Generator Developers Worldwide

Developer	Country	Size (kW)	Commercially Available
Allied Signal	USA	75	1999
Allison Engine Co.	USA	250	1998
Bowman Power Systems, Inc.	UK	45	1999
Capstone turbines, Inc.	USA	30	1997
Elliot Engine Systems	USA	45	1999
Kawasaki Heavy Industries	Japan	200	1978
Nissan Motors	Japan	2.5	1996
Northern Research & Engineering Corporation	USA	70	1999
Solar Turbines	USA	300	TBD
Teledyne Ryan	USA	50-55	TBD
Volvo Aero Turbines	Sweden	100	TBD
William International	USA	TBD	TBD

The packaged systems considered in this assessment are from domestic suppliers that either had a pre-commercial product under test or were committed to provide a commercial MTG product by the date listed in Table 2. The suppliers are domestic and are in the process of completing alpha and beta tests with packaged systems.

Table 2. Packaged Microturbine Generator Systems Considered

Supplier	RPM (1000)	Size (kW)	Fuel	LHV Efficiency (%)	Emissions (ppm-NOx)	Price ($/kW)	Overhaul Time (hrs)	Commercially Available
Allied Signal	70	75	Natural Gas	30	<11	~400	10,000	Late 1999
Capstone Turbines	96	30	Natural Gas	26	<9	~500	8,000	1996
Elliot Energy Systems	116	45	Various	17	<9	~350	27,000	1998
Northern Research & Engineering Corp.	23	70	Natural Gas	33	<5	<1000	60,000	1999

The prices shown in the table are target prices for commercial products based on the manufacture and sell of thousands of units per year. The average cost of demonstration systems was nearly $2,500 per kW. This does not include installation costs.

The developers of microturbine generators range from very small developers to large corporations such as Allison Turbines. All are attempting to capture a portion of the market for distributed generation.

Suppliers have been stepping up their commercialization efforts to place commercial products in the market as early as 1999. As of December 1999, commercial products that could be ordered off the shelf at the target cost did not exist. The closest was the 30 kW product from Capstone Turbines, but their system is are still considered in the demonstration stage and the price is higher than the target for commercial products.

2.1.1. Capstone Turbine, Inc.

Capstone continues to produce demonstration field units with rating of 30 kW (59^{o}F) with an expected heat rate of about 12,600 Btu / kWh, HHV on natural gas. The field demonstration units are fuel with natural gas fueled and have a single shaft connected to a high-speed (96,000 RPM) alternator. The microturbine uses an air bearing.

The system has an attractive package with a relatively small footprint of about 3'LX2'WX6'H (Figure 1). The system can also be supplied with a gas compressor to pressurize the natural gas in the event that supply gas is below 55 PSI.

Figure 1. Capstone 30 kW Microturbine Generator
(Photograph is courtesy of Capstone's web page)

2.1.2. AlliedSignal

The AlliedSignal product is a 75 kW system in which the turbine and generator are on a single high-speed shaft. AlliedSignal incorporated a permanent-magnet generator and air bearings previously developed and used in auxiliary power units.

This system has a heat rate of about 12,500 Btu / kWh (HHV) and operates at a pressure ratio of 3.8 and shaft speed of over 70,000 RPM. It requires an external compressor for the fuel. The direct drive rotates a high-speed, high-frequency generator. With power electronics, the system delivers conditioned power at 480 V, 3 PH, 60 Hz. This system is also in a compact package of about 7'LX3'WX7H (Figure 2).

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Figure 2. AlliedSignal 75 kW Microturbine Generator
(Photograph is courtesy of AlliedSignal's Web page)

2.1.3. Elliot Energy Systems

The Elliot Energy Systems product is a 45 kW microturbine with a single shaft driving an alternator at nearly 115,000 RPM. It uses an oil-cooled bearing. The heat rate of this recuperated system is about 12,500 Btu / kWh (HHV) with an efficiency of about 30 percent. The system has a pressure ratio of 4:1 and requires an external compressor to deliver fuel pressure of about 70 psi to the combustor.

The package system is nearly 3'wX6'LX4'H (Figure 3).

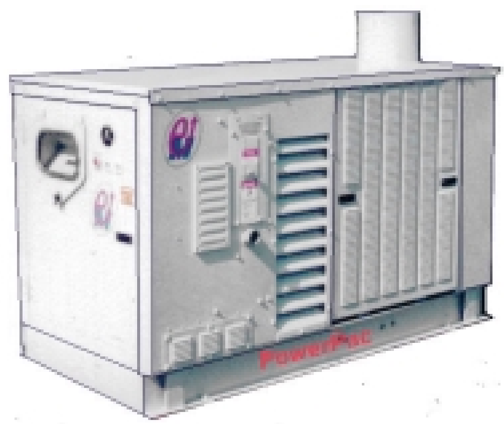

Figure 3. Elliot 45 kW Microturbine Generator
(Photograph is courtesy of Elliot's Web page)

2.1.4. Northern Research & Engineering Corporation (NREC)

The NREC product is a derivative from a natural gas chiller driver. This recuperated system has a dual shaft in which the induction generator is connected through a gearbox to deliver 70 kW of power. The system is currently in test mode at the NREC facilities in Woburn, MA and is expected to deliver over 30 % efficiency with a heat rate of about 11,400 Btu / kWh, HHV and a shaft speed of about 23,000 RPM. The package system has dimensions of about 3'LX4'WX7'H as shown in Figure 4.

Figure 4. NREC 70 kW Microturbine Generator
(Photograph is courtesy of NREC's web page)

2.1.5. Microturbine Schematic

With the exception of the NREC system, all the packaged systems reviewed were single stage (single-shaft) microturbines. NREC's microturbine is a dual-shaft, recuperated system using a gear reduction box to drive the generator at lower speeds. The product derives from a system to operate a chiller and was repackaged with an electric generator.

Although the NREC system was not selected, Figure 5 is provided as a general example of how mircroturbines operate.

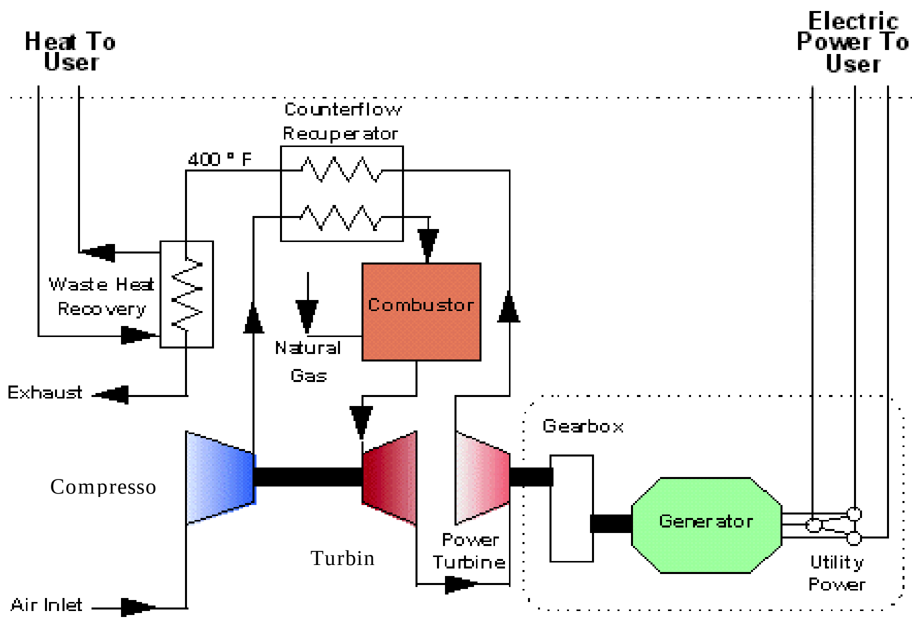

Figure 5. Schematic of NREC Dual Shaft Microturbine Generator
(Figure is courtesy of NREC's web page)

2.2. System Analysis

A simple system analysis was performed to evaluate the potential performance of a microturbine system operating as an integral part of the Miramar MCFC power plant.

Because of proprietary issues, microturbine generator suppliers would not share publicly the operating characteristics of their system. But many of the products share similar characteristics. Most have a relatively high-pressure ratio, approximately 3 to 4, and require the fuel gas to be pressurized by a compressor.

These conditions are potentially congruent with MCFC operating at 3 to 5 atmospheres. The Miramar power plant operates at nearly 3 atmospheres. This looks promising for the integration of a microturbine generator into Miramar’s BOP system.

Figure 6 provides the operating parameters of the Miramar plant at rated conditions for 250 kW AC output. Assuming that the compressor of the microturbine can deliver the mass flow and temperature required for the fuel cell, the cathode output would have sufficient energy to drive the microturbine. In fact, the energy from the cathode output may be more than the microturbine would require. To avoid over-driving the microturbine, a by-pass line would divert the extra energy to the fuel cell process.

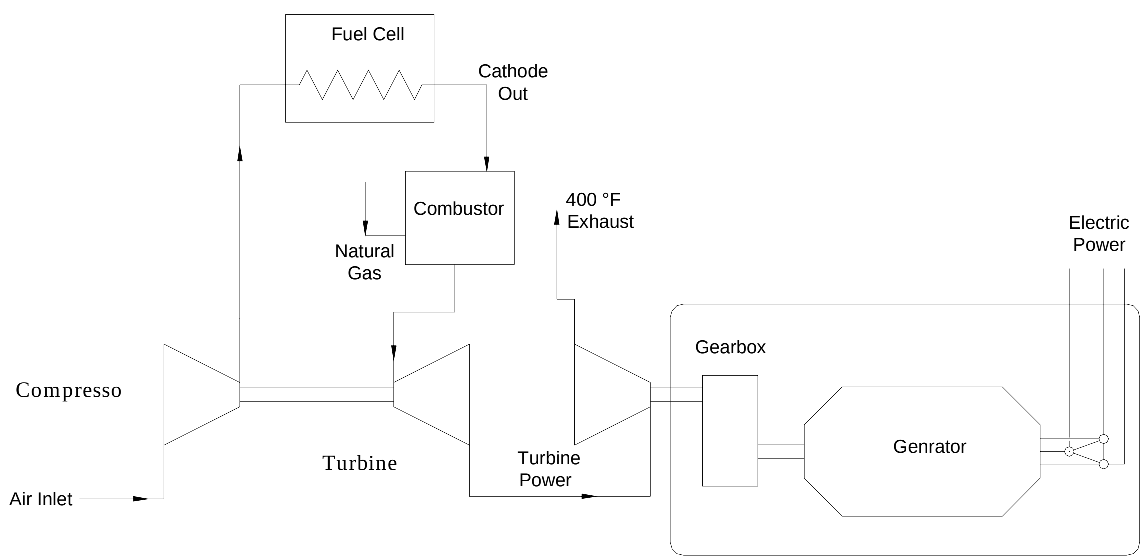

Figure 6. Dual Shaft Microturbine with a Fuel Cell as the Energy Source

In the event that the fuel cell process does not provide sufficient energy to the microturbine combustor, the combustor could be supplemented with additional fuel. From the 250 kW MCFC plant at Miramar the available energy from the fuel cell to microturbine’s combustor is nearly 287,000 Btu / hr or about 83 kW / hr under adiabatic conditions.

The LHV efficiency of the four microturbines evaluated ranged from a low of 17 percent to 33 percent (See Table 2). The maximum efficiency of a microturbine using fuel cells as its energy source is 27 kW. This is not meant to imply that a 27 kW microturbine system could be driven entirely by the energy available since the performance of a microturbine depends on the site-specific conditions of the inlet air temperature—as temperature increases, energy efficiency decreases.

The physical connections between the existing packaged microturbine products and the fuel cell would require such extensive system modifications that it might not be cost effective. The economics of integrating these products was not performed as it was beyond the scope of this assessment.

3.0 Conclusions and Recommendations

3.1. Conclusions

Existing microturbine generator packages are still in the development phase, but are making significant strides towards delivering a commercial product by late 1999. Based on the assumptions made in this assessment, there is no question that packaged microturbine products could be integrated with a molten carbonate fuel cell power plant with rating capacity of 250 kW and larger, but the physical connections between the two technologies may be cumbersome and costly.

The available energy from the 250 kW MCFC plant at Miramar would provide a portion of the energy required by a microturbine, but because of site specific conditions it is likely that supplemental natural gas would be necessary to supply the energy required by the a microturbine’s combustor.

Assuming 70ºF ambient conditions for the Miramar location, the available energy would not be sufficient to provide the energy requirements of the smallest microturbine (Capstone) considered in this assessment. Additional analysis is required with specific site conditions to appropriately determine the size of the microturbine to be integrated with the Miramar plant.

Technology suppliers anticipate a number of microturbine generator products to enter the market place by 1999 and 2000. As the microturbine generator product evolves and fuel cell technology develops towards a commercial product in 2003, the potential for integrating these two emerging technologies to provide high electric efficiency with minimal emissions, and at a reasonable cost, is great.

3.2. Recommendations

It would be advantageous for a more detailed assessment of performance and the economics of integrating these two technologies.

The subcontractor for this effort identified potential improvements in BOP for MCFC power plants. This includes the direct integration of a microturbine generator to increase system efficiency and reduce overall plant cost.

A process flow to determine the amount of available energy from MCFC power plants with capacity ratings lower than 250 kW needs to be designed and analyzed.

Appendix II

Proton Exchange Membrane Fuel Cells — Overview of Technology Status and Targeted Applications

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Executive Summary

A fuel cell is an electrochemical device, similar to a car battery, which produces direct current (DC) electricity by using an electrochemical process. Unlike batteries, fuel cells do not release energy stored in the cell, but operate as long as fuel is supplied.

The four types of fuel cells used for terrestrial applications in power generation are Proton Exchange Membrane, Phosphoric Acid, Molten Carbonate, and Solid Oxide. The names correspond to the type of electrolyte or media used to enable the electrochemical process to take place.

Unlike the other types of fuel cells, which use a hydrogen-rich gas as fuel, current PEM fuel cell technology has to operate with pure hydrogen as the membrane tends to become contaminated from impurities in the gas. Hydrogen fuel and oxygen from the air are electrochemically combined in the fuel cell to produce electricity. With pure hydrogen as the fuel, the only by-products are heat and water vapor.

Objectives

This project performed an assessment of existing Proton Exchange Membrane (PEM) fuel cell technology suppliers that could produce a product that could potentially affect the U.S. market in distributed generation applications by 2003.

The scope of this effort did not include an economic analysis.

Background

Although the PEM fuel cell technology has been under research for decades only three suppliers have seriously pursued commercial products during the last five to ten years. Until three years ago, commercial expectations for PEM fuel cells were targeted to transportation applications.

This changed when the electric utility restructuring took place in California. PEM fuel cells are now being developed by a number of suppliers with the intent of providing onsite or distributed power generation.

Outcomes

- The present cost of fuel cells stacks operating with pure hydrogen is approximately $20,000 / kW. Some small PEM fuel cells have even higher costs of nearly $40,000 / kW.
- Only a couple of fuel cell stack suppliers were willing to share the product cost.
- Most PEM fuel cell suppliers target 2003 for a commercial product with target costs of less than $1,500 / kW.
- PEM fuel cell products for the early market in distributed power generation are likely to be less than 10 kW rating

Conclusions

- In order to make PEM fuel cell technology commercially available for distributed generation, the following factors need to be resolved:

  - The cost of PEM technology must be below $1,000 per kilowatt to be competitive with optional distributed generation technologies
  - A reliable, compact, quick-responding, and low cost natural gas / methane reformer has to be available in the market place

Recommendations

- The product endurance, reliability, safety, and performance of the entire fuel cell system (plant) must be demonstrated over a period of time representing the expected five-year life span of the fuel cell stack
- A small, quick responding, and low cost fuel processor to convert natural gas to hydrogen at the rate and volume required by the fuel cell to respond to load changes has to be developed and commercialized.

Abstract

A fuel cell is an electrochemical device, similar to a car battery, which produces direct current (DC) electricity by using an electrochemical process. Unlike batteries, fuel cells do not release energy stored in the cell, but operates as long as fuel is supplied. In general, the characteristics that all types of fuel cells have in common are high efficiency, low NOx emissions, and low noise.

Proton Exchange Membrane (PEM) fuel cell technology is one of the four types of fuel cell technology being considered for distributed power generation. The others are phosphoric acid fuel cells, solid oxide fuel cells, and molten carbonate fuel cells. Each of these technologies operates with distinct characteristics that make them unique for particular applications in electric power generation.

PEM fuel cells have operating characteristics that lend themselves to relatively fast start-up and quick response to load changes. This characteristic also makes PEM technology a good candidate for automotive applications. Developers of PEM technology have received overwhelming interest from auto manufacturers including significant financial investment into product development as an option technology to meet future air emission regulations for automobiles. The fast response to load changes are also attractive to developers of PEM technology targeting stationary power generation from 2 kW to 250 kW for residential and commercial applications.

In this project, nine active PEM fuel cell developers were identified nationwide. Only three of these developers are attempting to develop products larger than 20 kW. The rest are focusing on products less than 20 kW in size.

In addition to reducing PEM fuel cell system cost, the biggest challenge is to develop and commercialize a compact, quick-responding, low cost fuel reformer to convert natural gas to hydrogen to allow PEM fuel cells to respond to load changes.

1.0 Introduction

Fuel cells are electrochemical devices, which consist of two electrodes (anode and cathode) separated by an electrolyte. This is very similar to an automobile battery. The difference is that the fuel cell uses fuel rather than being charged as a battery for the storage of energy. Because the electrochemical process is not bound by the Carnot or Bryton cycle limits of performance and efficiency, fuel cells have the potential of nearly doubling process efficiency of fuel-to-electricity with minimal air emissions.

San Diego Gas & Electric (SDG&E) received an award from the Public Interest Energy Research (PIER) transition program, managed by the California Energy Commission, to perform an overview of the state-of-the-art of Proton Exchange Membrane (PEM) fuel cell technology and its potential as a distributed energy resource.

SDG&E subcontracted VFL Energy Technologies, Inc. (VFL) to look at the existing PEM fuel cell technology suppliers that could potentially affect the U.S. market in distributed energy resource applications by 2003.

VFL has performed technical services in the oil and gas energy production area, molten carbonate fuel cell technology, and technical assessments of technology applications for distributed generation options. Although VFL has had peripheral exposure to PEM fuel cell technology, their focus has been predominantly on technologies supporting stationary power sources rather than transportation applications.

2.0 Discussion

2.1. Approach

To identifying state-of-the-art of PEM fuel cell technology, we performed a data search; communicated with PEM fuel cell suppliers, research institutes, and utilities; and attended technical symposia.

The data was evaluated for content on specific technical programs, on the advancements of PEM fuel cell technology, including commercialization, by private and governmental organizations. The intent was not to duplicate details of the technology attributes, but to focus on PEM fuel cell technology's potential to enter the distributed generation market on or before 2003.

An economic analysis was not performed as it was beyond the scope of this effort.

The data search included review of documents from the U.S. Department of Energy (DOE), the Electric Power Research Institute (EPRI), and Internet publications. To discover product availability and projected commercial product targets, PEM fuel cell suppliers were visited whenever possible. The information was provided for this report in confidence. We used it to verify projected targets and statements regarding the technology current progress.

2.2. Technology Overview

PEM, phosphoric acid, molten carbonate, and solid oxide are the four common types of fuel cells used in terrestrial applications for distributed power generation or transportation. The names describe the type of electrolyte or media used to enable the electrochemical process to take place.

Table 1 lists the different operating characteristics of the four types of fuel cells.

Table 1. Operating Characteristics of Various Fuel Cells

Fuel Cell Type	Operating Temperature ^{o}F	Capacity Range of Projected Commercial Products	Projected Electrical Efficiency %
PEM	200	1kW - 250 kW	36
Phosphoric Acid	400	200 kW - 1000 kW	36 - 42
Molten Carbonate	1200	250 kW - 2000 kW	50 - 60
Solid Oxide	1800	250 kW - 3000 kW	45 - 60

2.3. Proton Exchange Membrane Fuel Cell

Unlike the other types of fuel cells, which can use a hydrogen-rich gas as fuel, PEM fuel cells have to use a high quality of hydrogen with very low levels of CO. Hydrogen fuel, which can be obtained by reforming natural gas or methanol and oxygen from the air, are electrochemically combined in the fuel cell to produce electricity. With pure hydrogen as the fuel, the only by-products are heat and water vapor.

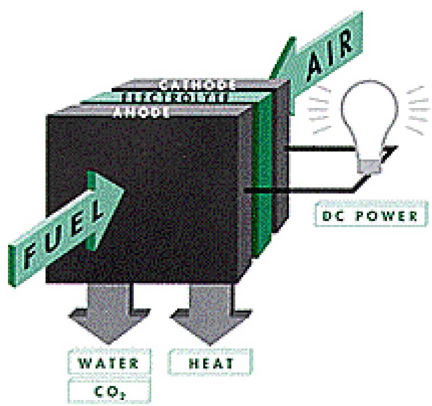

Figure 1. Schematic of a Fuel Cell

Fuel cell sketch is courtesy of the US DOE web site

A fuel cell consists of two electrodes, the anode and the cathode, separated by an electrolyte as shown in Figure 1. The basic chemical reaction taking place between the electrodes is:

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O + \text{Heat}$$

What makes the PEM fuel cell distinct from other types of fuel cells is the polymer membrane electrolyte. Each electrode is coated on one side with a thin layer of platinum catalyst. At the anode, hydrogen fuel catalytically dissociates into free electrons and protons (positive hydrogen ions).

The free electrons become the direct current once an external circuit is completed. The protons can migrate through the membrane electrolyte to the cathode where they combine with oxygen from air to form pure water and heat. Individual fuel cells are combined into a fuel cell stack to provide the amount of electrical voltage and power required.

Typical life expectancy of a fuel cell stack is targeted at five years. At that time, the fuel cell stack would be replaced as part of a power plant overhaul. Maintenance for fuel cells is estimated as very low because there are no moving parts. The balance of plant (BOP) components that comprise the power plant system would require regular maintenance.

In general, the fuel cell stack would account for about one third and the BOP for two thirds of the capital cost. The BOP consists of the fuel processing unit, the electric conversion (inverter) unit, controls, and thermal handling unit.

2.4. PEM Fuel Cell Technology

Initially, PEM fuel cell technology was targeted for transportation applications because the only fuel the cells can use is pure hydrogen. The membrane used in PEM fuel cells to induce the electrochemical reaction is susceptible to impurities in the fuel gas, which results in the accelerated decay in membrane performance.

PEM fuel cell technology for use in distributed generation for electric utility applications became of interest in only the last three to five years. The interest resulted from electric utility restructuring in California. Since then the industry has seen the number of PEM fuel cell technology suppliers pursuing commercial applications in earnest increase from three to nearly a dozen.

Reformer technology, to convert natural gas and methane gas into hydrogen is still in the development stage. The major objectives of this development are to reduce the reformer's physical size and its cost while producing hydrogen pure enough to be tolerated by the PEM fuel cells without significantly affecting the long-term performance of the membrane.

PEM fuel cell suppliers assessed the status of natural gas reforming technology from near-term to two or three years for product availability.

2.4.1. Suppliers

A surprising number of PEM fuel cell technology suppliers have emerged over the past three years. But while PEM fuel cell technology has been researched for decades, only three suppliers during the past ten years have seriously pursued commercial products. Most commercial expectations for PEM fuel cells were targeted to transportation applications.

The growth in the number of PEM suppliers is attributed to two primary drivers:

- Recent large investments by the automotive industry in companies such as Ballard Power because of their interest in PEM fuel cells as an option for powering zero emission vehicles.
- Recent advances in reformer technology to convert natural gas and other fuels into hydrogen and hydrogen containment vessels have made the use of hydrogen as a fuel more widely acceptable.

Based on the level of activity by the PEM fuel cell suppliers, the initial market in distributed generation is probably for products that are less than 10 kilowatts. Only three suppliers are actively developing larger capacity (up to 250 kilowatts) products. Most of the PEM fuel cell technology suppliers are targeting their products for residential use, uninterruptible power systems, and transportation

2.4.1.1. Ballard Generation Systems

Ballard Generation Systems (BGS) is a subsidiary of Ballard Power Systems (BPS), located in Vancouver, Canada. Ballard has alliances with Daimler-Benz for the development and commercialization of fuel cell for automotive applications.

Ballard is also testing PEM fuel cell technology for stationary power generation applications up to 250 kW in capacity. Ballard is considered the leader in the commercialization of PEM fuel cell technology. They have strong alliances with the power providers GPU International and ALSTOM.

Ballard is developing a natural gas reforming technology to complement their fuel cell products. They target 2003 for a commercial fuel cell product applicable to the distributed generation market.

2.4.1.2. Plug Power

Plug Power, located in Latham, New York, is in the process of developing alpha and beta fuel cell systems for evaluation during 1999 and 2000. They are developing fuel cell systems for residential, small commercial and automotive applications. Products are scheduled to be commercially available by late 2001.

Although initial tests of their fuel cell systems will likely use hydrogen as a fuel, they plan to have systems with a multi-fuel capability. Plug Power anticipates their products to be powered by natural gas, propane, or methanol.

Plug Power has an agreement with GE Fuel Cell Systems to install and service their designed and manufactured systems worldwide. The targeted Plug Power's product range for stationary and automotive applications is from 1 kW up to 50 kW.

2.4.2. Analytic Power

Analytic Power, a privately held Massachusetts corporation, operates out of its headquarters in the Boston area. Their expertise is in mechanical, chemical, and electrochemical engineering.

Analytic Power's fuel cell systems range from 150 Watts to 2.5 kilowatts. Target applications are stationary and military.

Analytic Power is developing a reformer to convert natural gas into hydrogen as fuel for the fuel cell and a 2.5 megawatt fuel cell system for marine and power applications. They are also developing an ammonia cracker as a portable fuel reformer. Target date for commercial availability of the reformer and fuel cells is 2001.

2.4.3. H-Power

H-Power is a privately held company headquartered in Belleville, New Jersey with a subsidiary in Quebec, Canada. H-Power's products are targeted to small power (1 kilowatt range) applications. They anticipate products up to 250 kilowatts for residential, commercial, and automotive applications.

The small fuel cell systems, operating with hydrogen as a fuel, have been sold to the New Jersey Department of Transportation to provide power to alert signs. Larger stationary power systems are targeted for commercial availability in 2003.

2.4.4. Avista Laboratories, Inc.

Avista Laboratories, Inc., located in Spokane, Washington, is a subsidiary of Avista Capital, a wholly owned subsidiary of Avista Corp. Avista Corp. is an energy services company with utility and subsidiary operations located throughout North America.

Created to commercialize environmentally beneficial energy technologies, Avista Labs has initially targeted PEM-based fuel cells at commercial applications, particularly industrial processes that generate hydrogen as a byproduct, uninterruptible power supplies (UPS), and portable generators.

Currently, they are developing a 720 watt modular system operating with pure hydrogen as an UPS. The modularity of their design is unique in that if an individual fuel cell within a stack fails, that cell can be replaced on-line. The product is designed to provide primary and backup power for the residential and small commercial markets.

Avista Labs is investigating various types of hydrogen reformers. A number of independent developers are working on different types of solutions. Avista Labs has development projects in place for some of the more promising technologies. A commercial product using natural gas as fuel may be available in 2001.

Figure 2 shows a bench test of a modular fuel cell stack operating on hydrogen.

Figure 2. Avista Labs' Modular Fuel Cell Stack
Fuel cell photograph is courtesy of Avista Labs web site.

2.4.5. Dais Corporation

Dais is in Albany, NY. It is a developer of electrochemical materials that could supply the PEM fuel cell technology industry. Dais has fuel cell products in the 10 watt to 20 watt range that operate on pure hydrogen. Dais prices their fuel cell stacks in the $4,000 to $13,000 range. It is uncertain if Dais will produce a product for a distributed generation application.

2.4.6. BCS Technology, Inc.

BCS, Bryan, Texas, started operation in 1990 to carry out product oriented research in electrochemical areas. They focused on developing PEM fuel cells to operate at higher temperatures without external humidification.

BCS does not yet have a product, but are working on technology with power output ratings of 10 to 500 watts.

2.4.7. Electrochem, Inc.

Electrochem, located in Woburn, Massachusetts, supplies electrochemical materials, including fuel cell stacks and laboratory equipment, to the PEM fuel cell industry. Electrochem offers a fuel cell stack with an output of 45 kilowatts DC.

2.4.8. Proton Energy Systems, Inc.

Proton Energy is located in Rocky Hill, Connecticut. They were founded in 1996 for the sole purpose of commercializing PEM products for hydrogen gas generation and energy storage applications.

The company has an EPRI funded program to develop unitized regenerative fuel cells for applications where reliable, efficient, low cost energy conversion and storage is necessary. The system, known as UNIGENÔ, was designed for applications in off-grid renewable energy storage, on-grid load leveling / peak shaving, and zero-emissions transportation systems.

No fuel cell stack product is under production at this time.

Table 2 summarizes the information on the fuel cell suppliers. National laboratories, universities, and other suppliers not listed in the table are also pursuing research and development work to advance the technology.

Table 2. PEM Fuel Cell Suppliers and Characteristics

Provider	Rating (kW)	Intended Market	Target Year Commercial Natural Gas Product	Contact
Ballard Generation	30 – 250	Transport. & Comm.	2003	Jorge Barrigh (609) 951-2241
Plug Power	1 – 50	Transport., Resid. Small Comm.	2001	Dr. W. P Acker (518) 785-2112
Analytic Power	2.5 – 2500	Resid. Comm. & Military,	2001	D. Blumfield (617) 542-6352
H-Power	1 – 250	Transport. Resid. Small Comm.	2003	A. Kaufman (973) 450-4400
Avista Laboratories	0.720	Small. Comm., UPS	2001	Robyn Dunlap (509) 495-4817
Dais Corporation	0.01 -0.02	Resid. , Small & Comm.	Not-Announced	G. Doell (727) 375-8484
BCS Technology	0.01 - 0.500	Unclear	Not-Announced	Dr. Hari P. Dhar (409) 823-7138
Electrochem	Components	Equipment for Fuel Cell Industry	Not-Announced	Dr. Radha Jalan (781) 938-5300
Proton Energy Systems	45	Unclear	Not-Announced	T. M. Moler (860) 571-6533

2.5. PEM Fuel Cells for Transportation Applications

Chrysler, Ford, GM, Daimler Benz, and other auto manufacturers are investing in the development of PEM fuel cell technology for automotive applications. Their general position is that hydrogen has to be processed from gasoline on-board the vehicles because hydrogen is not currently a practical fuel choice.

The transportation fuel supply infrastructure is unlikely to change because car companies have fuel cell prototypes that run on hydrogen or methane. Since hydrogen, unless pressurized, occupies almost 3000 times more space than gasoline at atmospheric pressure, storing hydrogen storage on board a passenger vehicle would be difficult.

Carmakers looking at on-board hydrogen storage envision lightweight advanced materials pressure tanks similar to compressed natural gas tanks already in use that store hydrogen at several thousand pounds per square inch. By developing an on-board fuel processor, the consumers' need to still refuel their vehicles the same way would be met. And the gasoline tanks on their vehicles could actually be smaller than they are today.

Also needed is a small (approximately a foot in diameter and a foot long) air compressor/expander to manage the fuel cell system's air supply. In the Chrysler display configuration, the compressor is under the hood. Compressor/expander improvement is a high priority topic in the U.S. Department of Energy's fuel cell development program.

2.6. Costs

Cost remains a major issue. While fuel cell costs have come down dramatically, from approximately 1000 times that of a conventional internal combustion power train cost ten years ago to approximately ten times it today, it is still too expensive. For PEM fuel cells used in stationary applications, suppliers quote commercial target costs from $800 per kW to $1,500m per kW. The range is broad because of the uncertainty of natural gas reforming systems and BOP costs.

If mass-produced with current production techniques, fuel cells cost about $200 per kilowatt. Conventional internal combustion power train engines, with radiator, transmission, catalytic converter, starter battery, alternator, etc., cost about $30/kW. A fuel cell system for a vehicle would cost approximately $30,000 compared to the $3,000 for conventional internal combustion power train systems.

This analysis of costs does not take into account increase efficiency, environmental, or other factors, which may be available to fuel cells but not to conventional technologies.

The US Department of Energy has a number of programs to develop PEM and fuel processing technologies for both stationary and automotive applications. These programs are conducted and managed by various industry and national laboratory groups in partnership with other industry research groups.

2.7. Outcomes

The investigation of PEM fuel cell technology revealed that:

- The present cost of fuel cells stacks operating with pure hydrogen is approximately $20,000 / kW. Some small PEM fuel cells have even higher costs of nearly $40,000 / kW.
- Only a couple of fuel cell stack suppliers were willing to share the product cost.
- Most PEM fuel cell suppliers target 2003 for a commercial product with target costs of less than $1,500 / kW.
- PEM fuel cell products for the early market in distributed power generation are likely to be less than 10 kW rating.

For distributed generation applications the cost of PEM fuel cells and the entire power plant system must come down below $800 per kilowatt to be competitive with alternate technologies. In automotive applications, the cost of PEM fuel cells has to be reduced by nearly the same order of magnitude to be competitive.

3.0 Conclusions and Recommendations

3.1. Conclusions

Low cost, compact, and fast acting reformer technology would enable PEM fuel cell technology to expand its application from the demonstration stage to a commercial product.

Using natural gas and methane as a fuel source, PEM fuel cells would have a niche market in distributed generation applications.

PEM fuel cell technology has the potential for impacting the commercial market in distributed generation applications if an adequate natural gas reformer is available and the cost for the fuel cell plant is below $1,000 per kW. This price may not be realized for a few years.

PEM products with capacity rating of less than 10 kilowatts may enter the early market in 2003 at a price of approximately $2,500 per kilowatt.

The use of PEM fuel cells to produce power in residential applications will likely not take place until such time as the fuel cells can use natural gas directly. Two reasons for this are:

- The Occupational Safety and Health Administration (OSHA) code requirements will likely prevent the use of hydrogen for power production in residential use. OSHA codes require a 50-foot radial clearance of occupied facilities from a hydrogen production facility or source.
- Most small businesses and residences do not have experience using hydrogen. A pressurized vessel or cylinder(s) would be required to provide fuel while the fuel cell operated as a power generator.

3.2. Recommendations

The product endurance, reliability, safety, and performance of the entire fuel cell system (plant) must be demonstrated over a period of time representing the expected five-year life span of the fuel cell stack

A small, quick responding, and low cost fuel processor to convert natural gas to hydrogen at the rate and volume required by the fuel cell to respond to load changes has to be developed and commercialized. Until such a reformer is developed, PEM fuel cell technology will remain with those who have experience in the use of hydrogen and consider its use as low risk.