

Abstracts

**1986
Fuel Cell
Seminar**

**October 26-29, 1986
Tucson, Arizona**

**Sponsored by the
National Fuel Cell
Coordinating Group**

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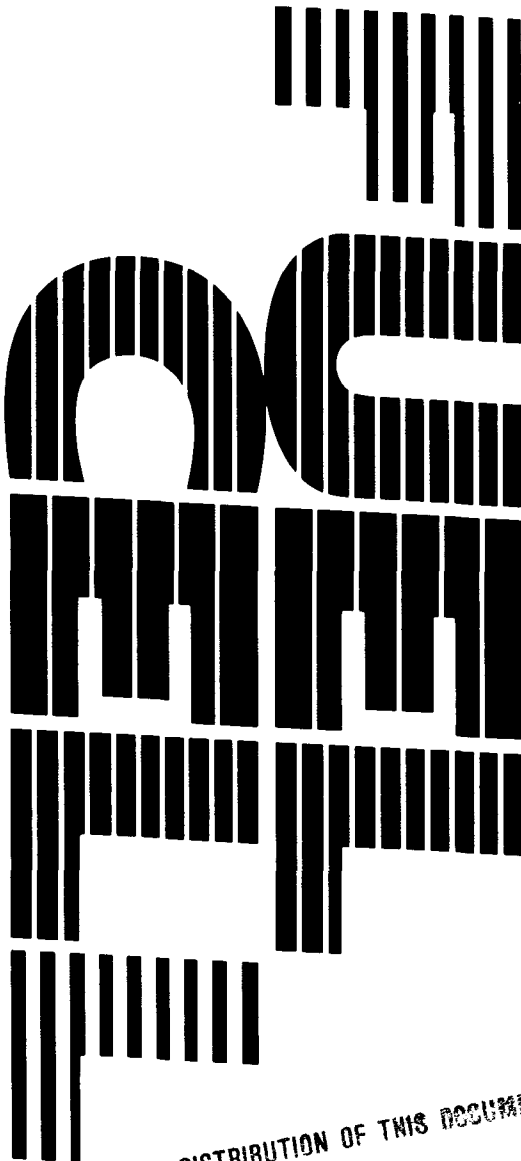
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**1986
Fuel Cell
Seminar**

**Program
and
Abstracts**



**October 26-29, 1986
Sheraton El Conquistador
Tucson, Arizona**

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In Cooperation with
Department of Defense
Department of Energy
Electric Power
Research Institute
Gas Research Institute
National Aeronautics
and Space Administration

Seminar Coordinated by
Courtesy Associates, Inc.
Washington, D.C.

Preface

The members of the National Fuel Cell Coordinating Group (NFCCG) welcome all national and international participants to this, the tenth in the series of Fuel Cell Seminars. While the level of participation has increased significantly over the decade since the initial Seminar, the objectives have changed very little.

The objective of the initial Seminar, as stated in its Program and Abstracts document, was to bring together participants in the major U.S. fuel cell research, development and demonstration programs to: give participants the opportunity to learn more about the various activities; make contact with others working towards similar objectives; and to help establish an integrated national program.

For the second Seminar in the series, this objective was expanded to increase participation levels by potential users of the technology, including gas and electric utilities as well as industrial, military and aerospace organizations. Providing a forum for the interchange of information between developers and users has been the underlying motivation for organizing all subsequent Seminars including this tenth in the Series.

Presentations in the initial Seminars dealt almost exclusively with U.S. programs and applications. The seventh Seminar, in 1982, was the first to have a significant number of international presentations describing development programs or applications in Canada, Europe and Japan. International participation has increased in each of the subsequent Seminars both in numbers of presentations and in the numbers of countries from which they originate. This certainly reflects the rapidly growing international interest in the technology.

Another measure of the increasing interest in fuel cell technology is the number of papers that will be presented in this Seminar. The poster sessions, introduced at the previous Seminar, will contain many more presentations this year. It is interesting to note that the number of presentations to be made in the 1986 Fuel Cell Seminar exceeds the number of people who attended the initial Seminar just a decade ago. I believe this continually growing interest also reflects the technical progress being achieved which in turn improves the prospects for the successful commercialization of fuel cells in the near future.



E.A. GILLIS
Chairman
National Fuel Cell Coordinating Group

Agenda

Sunday, October 26, 1986

3:00–7:00 pm Registration

5:00–7:00 pm Welcoming Reception
Hosted by American industry sponsors

Monday, October 27, 1986

8:00 am Continental Breakfast

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Chairman: Edward Gillis
Electric Power Research Institute

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D. Bruce Merrifield, Assistant Secretary of Commerce for Productivity,
Technology and Innovation

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“Overview of R&D Activities on the Fuel Cell in Japan” 2
Noboru Itoh, New Energy Development Organization

“Fuel Cell Activities in the United States” 6
Fritz R. Kalhammer and Edward A. Gillis, Electric Power Research Institute

11:30 am–1:00 pm Buffet Luncheon

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Gas Research Institute

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Solid Oxide Fuel Cell Technology

Chairman: Charles M. Zeh

U.S. Department of Energy—METC

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**3:30–
6:00 pm**

Poster Session on Solid Oxide Technology

Please note: The letter and number designations following each title of a poster presentation match those that will appear on the poster displays themselves. These will enable you to easily locate each presentation.

Chairperson: Alayne A. Adams

U.S. Army Belvoir RD&E Center

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U.S. Army Belvoir RD&E Center

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Tuesday, October 28, 1986

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11:30 am

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Technology Transition Corporation

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11:30 am

Chairman: Frank D. Gmeindl

and

U.S. Department of Energy—METC

1:00–

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3:00 pm**

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NASA Lewis Research Center

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U.S. Army Belvoir RD&E Center

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U.S. Army Belvoir RD&E Center

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7:30 pm**

Japanese Reception

Hosted by NEDO/MITI and Japanese industry sponsors

Wednesday, October 29, 1986

7:30 am

Continental Breakfast

8:30–

11:30 am

Fuel Cell Power Plant Designs

Chairman: D.M. Jewell

U.S. Department of Energy—METC

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Electric Power Research Institute

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**11:30 am–
1:00 pm**

Buffet Luncheon

**1:00–
2:30 pm**

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**2:30–
4:30 pm**

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Chairman: John J. Cuttica

Gas Research Institute

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“Commercialization of Engelhard Phosphoric Acid Fuel Cell Technology” 375
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4:30 pm

Conclusion of the 1986 Fuel Cell Seminar

STATUS OF FUEL CELL TECHNOLOGIES
JAMES R. HUFF
LOS ALAMOS NATIONAL LABORATORY

An abstract of this presentation was not available
at press time.

OVERVIEW OF R&D ACTIVITIES ON THE FUEL CELL IN JAPAN

Noboru Itoh

New Energy Development Organization (NEDO)
Higashi-ikebukuro, Toshima-ku
Tokyo 170 Japan

The Agency of National Resources and Energy of MITI is promoting the "21st Century Energy Vision Investigative Committee" to investigate policy themes and the energy supply structure for the year 2000. One of the themes regards the impact of technological development for the year 2000, and a wider selection at the supply and demand levels for energy resulting from utilization and energy conversion technologies such as cogeneration and fuel cells. It will also examine the possibilities for diversification of the energy supply sources. The final report "21st Century Energy Vision" will suggest us how to introduce fuel cell into the energy supply system after the year 2000.

Phosphoric Acid Fuel Cell

On the manufacturers' side, development of a component technology has centered on manufacturers of heavy electrical industry, but with the everincreasing possibility of the adoption of this technology by users, joint research between both sides has steadily increased.

Tokyo Gas Co. and Osaka Gas Co. participated in the GRI project, and introduced a 40 kW PC-18 fuel cell from UTC. and began field tests from March 1982. Tokyo Gas installed a fuel cell in a swimming pool at Tsurumi, Kanagawa Pref. while Osaka Gas installed a fuel cell in a restaurant to determine the total performance of a fuel cell and its continuous performance with an actual load. They were both used to verify a cogeneration system and to determine changes in the state of PAFC when subject to long-term use. Both Tokyo Gas and Osaka Gas participated in the field test project and each acquired improved fuel cells between Oct. and Nov. 1984. Tokyo Gas demonstrated the cell's operation at the Gas Pavilion of the Tsukuba Expo'85, while Osaka Gas demonstrated its fuel cell in a similar restaurant so that a parallel demonstration could be conducted with the proto-type PC-18. Both companies have stopped using their proto-types, but Tokyo Gas began operating an advanced PC-18 at the Dai-ichi Inn in Tokyo in January 1986, while Osaka Gas has been making headway with the operating of its advanced PC-18.

Tokyo Electric Power Company introduced the 4.5 MW plant No.2 of UTC. This plant was developed for generating electricity and for the possibility of using a fuel cell as an electric power supply facility. This was installed at the Goi Power Generation Plant in 1981, undergoing PAC test, and in Feb. 1984, it became the first fuel cell to attain full output operation. Phase I of the verification testing conducted by TEPCO was to attain 4.5MW rated output, and Phase II was to confirm the durability of the plant itself with tests completed in December 1985.

Total generated power output is 5428 MWh and total operating time 2887 hrs. Part of the fuel cell was dismantled to deter-

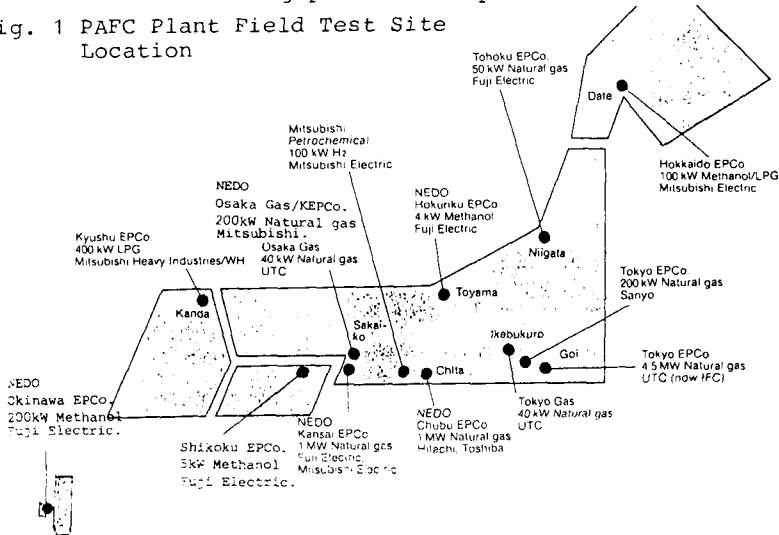
ine the operational effects and the results will be used for valuable information on PAFC. The above has been a description of the R&D that has taken place between Japan and US, but independent R&D has also been taking place in Japan.

Japanese manufacturers are competing in the manufacture of their own fuel cell plants and some have reached the development level. In the later half of the 1970s, the electrode area of cell had been enlarged to 3600 cm² and the manufacture of pressure-type stacks became possible. Stacks of 20-50kW have been manufactured by Hitachi Ltd., Fuji Elec. Co., Toshiba Co. and Mitsubishi Elec. Corp. respectively, and investigations are being carried out on operating temperature, pressure influence, gas utilization and the effects of water-cooling. Many research results have been announced for making cells larger and improving the fuel cell itself.

As a result, the Fuel Cell Power Generation Development Project carried out by the NEDO was based on the Moonlight Project formulated by the Agency of Industrial Science and Technology in Fall 1981. Previous four manufacturers cooperated in this project and constructed two 1 MW PAFC plants at the end of 1985. These were installed at the Sakai-ko Power Plant of Kansai EPCo. and at the Chita No.2 Power Plant of Chubu EPCo. to undergo operational testing until 1987.

In fields other than ML Project, Tohoku EPCo. has a signed a joint research agreement with Fuji Electric Co. so that it can determine the electric power system operating characteristics of a 50 kW water-cooled PAFC system that uses methanol as fuel. It announced that operational research will be conducted at the Niigata Thermal Power Station from the latter half of '86 and will continue until the end of '88. It has already entered the stage of fuel cell design. Hokkaido EPCo. is also investigating into the use of fuel cells as power sources for isolated islands and remote areas, and has installed a PAFC test plant with verification testing planned. It plans to use a 100 kW

Fig. 1 PAFC Plant Field Test Site
Location



water-cooled PAFC at the Date Power Station. Preparations for a joint research project with MELCO are being set from April '86 to Sept.'89.

Fig.1 shows the sites where PAFC testing is being conducted or under constructions.

As part of the government measures for promoting a new type of power generating technology, many plans for the introduction and verification of PAFC for practical use, and for a community type power supply system are underway. This has brought about the near commercialization of PAFC.

Molten Carbonate Fuel Cell

Since 1960, universities, government and private research laboratories have been conducting fundamental research on MCFC, but significant progress has only been made since the Moonlight Project. From 1981 to '83, research to find MCFC materials was conducted at government research laboratories while manufacturers performed element research for 1 kW cell stack. From 1984 to '85, Hitachi, Toshiba, Fuji Electric, MELCO and IHI respectively succeeded with the development of a 1 kW cell stack.

Initially, the development was for the forming of electrolyte plates by the hot-press method, but flexible paste and the tape casting methods, which have proved to give large electrolyte plates that have a longer working life, are being used. They are more resistant to the heat cycle and will enable the development of a larger fuel cell which will be a step closer to practical use.

The development objectives of NEDO have ranged from 25-70 cells, a size of 3600 - 1600 cm², for their developments of a 10 kW stack with continuous operation over a period of several thousand hours. Recent state of R&D in 5 sisters is settled in Table 1.

Table 1 MCFC Cell, Stack Tests in Japan (State of R&D)

Hitachi Ltd.	Toshiba Corp.	Mitsubishi Electric	Fuji Electric Corp.	I. H. I.
(May) 900cm ² x 3 cells 0.7V, 150mA/cm ² 1500hr	(Apr) 600cm ² x 10 cells 0.7V, 150mA/cm ² 1800hr U _{H₂} = 20 %	(Jan) 1000cm ² single cell Internal Reforming 0.65V, 150mA/cm ² U _F = 40 % 2,000hrs	(Feb) 200cm ² single cell New tape casting 0.82V, 150mA/cm ²	(May) 3600cm ² single cell 0.8V, 150mA/cm ² U _{H₂} = 50 % U _{O₂} = 50 % 400hrs
(June) 900cm ² x 15 cells 0.71V, 150mA/cm ² 1200hr U _{H₂} = 20 %	(July) 1600cm ² x 10 cells 0.76V, 150mA/cm ² U _{H₂} = 40 % U _{O₂} = 40 % 250hr	(May) 300cm ² x 3 cells Tape casting 0.8V, 150mA/cm ² U _{H₂} = 40 % 500hrs	(Apr) 2900cm ² single cell 0.6V, 150mA/cm ² 300hrs	1,000cm ² single cell 0.75V, 150mA/cm ² 1,000hrs
(Aug) 3600cm ² x 3 cells 0.77 - 0.73V, 150mA/cm ² 300hr, continuing U _{H₂} = 20 % U _{O₂} = 50 %		(Aug) 2,000cm ² x 3 cells 0.81 - 0.80V, 150mA/cm ² U _{H₂} = 40 % U _{O₂} = 40 % 400hrs, Continuing		(July) 3600cm ² single cell 0.81V, 150mA/cm ² U _{H₂} = 50 % U _{O₂} = 50 % 700hrs

Fuel Cell Application Fields and Their Potencial Markets

During April 1983 through March 1986, NEDO has conducted the survey and fiesibility study on the fuel cell generating system concerning introduction into market under the charge of ANRE, MITI. As a result, the possible areas of FC application and their potential markets are summerized in Table 2.

Table 2 Possible areas of introduction & application system

Possible area of introduction		Introduction case
Large-scale power generation	A Thermoelectric power plant substitute use	* Establishment as a front-line power plant. * Establishment of fuel cell power plants at primary substation level and above (substitute for superannuated power plants, etc.)
	B Substation installation use	Introduction as a dispersed power supply at primary substation levels and above, up to the distribution line level (Capacity: 20MW - 30MW)
On-site power generation	C Regional installation use	Introduction in regions where concentration of heat demand is high, as in regional heat supply works in city planning, etc.
	D Factory installation use	Introduction in a private company to supply power or heat. Direct utilization of D.C. Power generation utilizing hydrogen produced as a by-product of factory processes.
	E Business use	Introduction in such business-use buildings as hotels, hospitals, restaurants, etc.

	B.E.Cost (\$/kW)	Potential Market (MW)	
		1985 level	2000 level
A	1,263 - 1,325	4,000 - 8,000	6,700 - 13,400
B	1463	2,000 - 4,000	3,350 - 6,700
C	1,288 - 1,620	3,000 - 6,000	5,000 - 10,000
D	1,238 - 669	500 - 1,000	840 - 1,680
E	1,669 - 2,813	3,500 - 7,000	5,800 - 11,600
Total		13,000 - 26,000	21,690 - 43,380

cf) 1\$ = 160 yen

FUEL CELL ACTIVITIES IN THE UNITED STATES

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Fuel cell development activities have been underway in the United States for nearly thirty years. The level of effort and duration of these activities in the U.S. has been greater than in any other country or continent, and there can be little doubt that the developmental programs currently underway in Europe and Japan are based on U.S. technology.

Most of the U.S. developmental activities were begun long before the formation of the Department of Energy (or its predecessor Energy Research & Development Agency), the Electric Power Research Institute, and the Gas Research Institute. The National Aeronautics and Space Administration and the Department of Defense were the principal public sector R&D sponsors in the nineteen sixties. However, there were a number of privately sponsored programs underway as well aimed at many different applications, all of which contributed to the current technology base. This paper will summarize some of the early U.S. fuel cell R&D programs and trace them to the present time. In addition, the near-term plans for public-sector sponsored R&D will be described.

ONSITE FUEL CELL FIELD TESTING RESULTS

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In December, 1983, the Gas Research Institute (GRI), the United States Department of Energy (DOE), 36 gas and electric utilities and an industrial participant began field testing onsite fuel cell power plants manufactured by International Fuel Cells (IFC). These 40-kW power plants were installed at 36 different utility-selected sites throughout the USA and in Japan. A total of 42 plants were installed and are being tested in a variety of building types with wide variations in use patterns and energy system configurations.

This field testing effort is one part of an overall Onsite Fuel Cell Program. The Program has three parts: a Field Test Project to evaluate fuel cell technology in real-world applications and define the requirements of an energy service business; a Technology Development effort to advance fuel cell technology and reduce its cost; and an Onsite Fuel Cell Users Group to direct and evaluate commercialization efforts for the utility industry.

GRI and DOE coordinate the Program to promote and foster dialogue between the manufacturer and the participating utilities. The technical and market issues that are being evaluated under the Field Test Project are continually fed back to the Technology Development Project for product improvement. Results of all these efforts, as well as the findings from utility market/business assessments of commercial onsite fuel cells, will define the Onsite Fuel Cell power plant to be introduced into the marketplace.

POWER PLANT INSTALLATION EXPERIENCE

Each utility participant was responsible for power plant site selection, site design and installation of one or more onsite fuel cell power plants. Participants selected field test sites which are compatible with the unique operating characteristics of the onsite fuel cell: high electrical efficiency, availability of useful by-product heat, electric load following capability, low air pollutant emissions, low noise generation and utility quality power output. Thirty-six sites in 18 different market segments were selected for power plant testing.

Two-thirds of the utility participants did the site/power plant interface designs using in-house engineers and the remainder employed engineering firms to do the design work. Two-thirds of the utilities hired construction contractors to perform the site preparation and power plant installation activities. The other utility participants used in-house crews to install the plants. An average of 5 weeks were required to prepare a site for onsite fuel cell delivery and 4 weeks were needed to complete fuel cell power plant

installation once the power plant was delivered. The average cost of design and installation of these small field test units was \$1,000/kW. Utilities experienced no major problems completing the design and installation activities. Based on their field testing experiences, utilities have projected substantially reduced schedules and costs for commercial service power plant installation.

One goal of the Field Test Project was to test power plants serving a variety of electrical and thermal loads. Eight sites used the fuel cell power plant to serve an electrical load independent from the electric utility grid. At these sites, the power plants were operated in a load following mode. At the remaining 28 sites, power plants were electrically connected to the grid and operated at a constant 40 kW output. Building electric load demands above 40 kW were served from the utility.

Thermally, the power plants were used for domestic water heating, space heating and process heating. The following processes obtained heat from an onsite fuel cell during the field testing: photograph developing, swimming pool heating, food processing, fuel pre-heating, plant propagation, and aluminum parts processing.

The majority of power plants were sited outdoors. However, six plants were located inside. The most notable of these was the Tokyo Gas Company plant which was located in the Gas Pavilion at the Tsukuba Exposition. Three other plants were located indoors at hotels due to space and aesthetic considerations. Two additional plants were placed indoors to increase maintenance personnel comfort during the winter.

POWER PLANT OPERATING EXPERIENCE

The overall operating goals for the Field Test Project were to achieve 300,000 hours of total power plant operation at an availability of 55-65 percent. These goals were met. Total operating time exceeded 300,000 hours with an overall availability of 63 percent. Fourteen plants had availabilities of 70 percent or more. Thirteen plants operated over 8,000 hours and there have been 71 individual, uninterrupted runs of over 1,000 hours. The longest continuous operating run was 2,165 hours.

Utility operating experience indicates that the power plants meet the electrical efficiency specification. Figure 1 illustrates power plant efficiency measurements over a 15 month operating period for a grid-independent, load following power plant. Data collected from all power plants indicate that only 16 power plants operated at average efficiencies below the specification, while the remainder operated at or above the electrical efficiency expectations. The field testing also verified the onsite fuel cell's high part-load electrical efficiency specification.

Measured thermal performance of the power plants averaged about 10 percent below specification. Figure 2 illustrates low grade heat recovered from one power plant as a percentage of the specification. As with the majority of power plants, actual heat produced averages about 10 percent below specification. Even with this reduced thermal output, the power plants produce one thermal kW-hr for each electrical kW-hr generated. Improved power plant designs which produce greater quantities of useful heat per electrical kW-hr have been prepared in the Technology Development Project.

During the field test, there were very few operating problems with the main power plant components; the fuel processors, fuel cell stack and inverter have operated well. Most of the operating problems encountered during the field test involved ancillary equipment such as pumps, valves, fittings and controls.

The major operational problems involved the stack coolant system and electrical/electronic controls. The fuel cell stack coolant system has shown a propensity to plug after about 2,000 hours of operation. This has required power plant shutdowns each 1,500 to 2,000 hours to clean and flush the coolant system. Electrical/electronic control failures have been a primary cause of power plant grid-disconnects and forced outages. Problems with both of these systems have been communicated to the Technology Development Project, and improved prototype designs are being tested as part of that project.

CONCLUSIONS

1. The utility participants encountered no insurmountable problems in designing, installing, operating and maintaining the power plants at their customers' sites.
2. The power plants met the project's availability and electrical efficiency goals.
3. The onsite fuel cell sites represent numerous market segments and provide varied electrical and thermal interfaces for power plant testing.
4. Operational problems discovered during field testing are being resolved in a technology development effort.

ACKNOWLEDGMENT

The work reported on in this paper was sponsored by the Gas Research Institute, 8600 W. Bryn Mawr Avenue, Chicago, Illinois 60631. Science Applications International Corporation (P.O. Box 2351, La Jolla, California 92038) is GRI's coordinating contractor for the Onsite Fuel Cell Field Test Project.

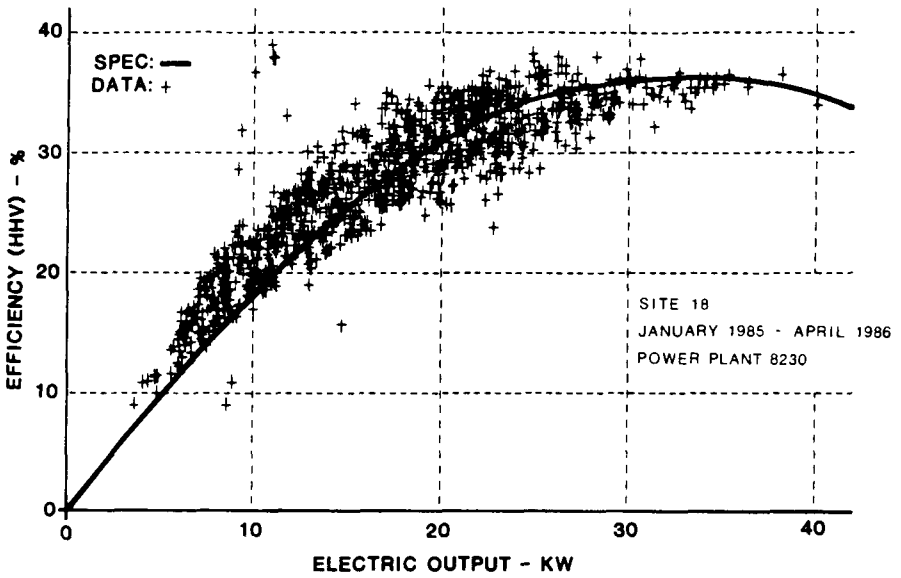


Figure 1. Electrical Efficiency vs. Electric Output for Single Load Following Power Plant

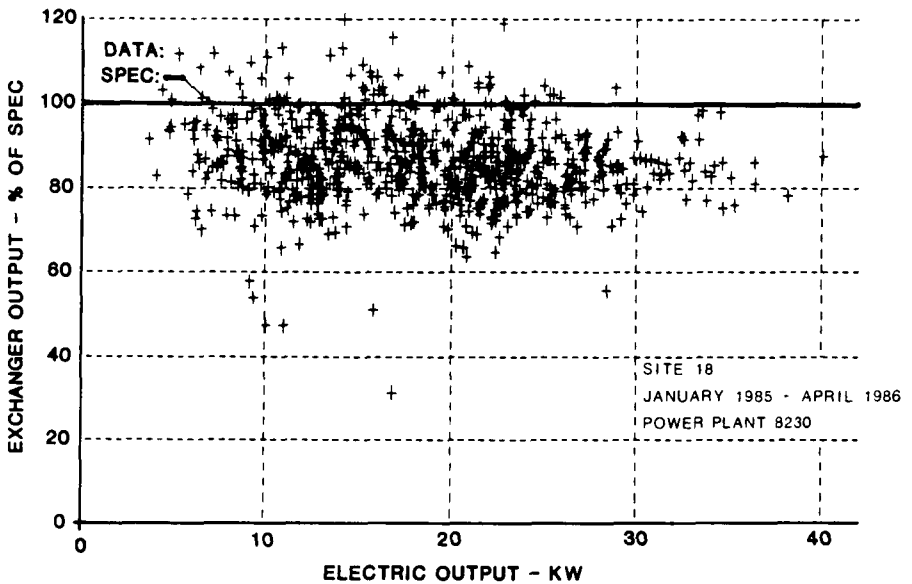


Figure 2. Low Grade Heat Exchanger Output vs. Electric Output for Single Load Following Power Plant

UTILITY EXPERIENCES - A PANEL DISCUSSION
BROOKLYN UNION GAS COMPANY

An abstract of this presentation was not available at
press time.

SPECIAL TESTING OF ELECTRICAL AND
THERMAL CHARACTERISTICS
OF A 40 KW ONSITE FUEL CELL

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INTRODUCTION

This abstract summarizes the purpose and results of special tests performed by Con Edison on a 40 kW fuel cell power plant at the Skyview Haven Nursing Home located in Croton-on-Hudson, New York. Con Edison is one of the 30 gas, electric, and combined utilities participating in the Gas Research Institute (GRI) 40 kW phosphoric acid fuel cell field test. Con Edison's unit began operation on June 3, 1985 and had accumulated 1590 hours of service when the field test was interrupted to perform the special tests to characterize thermal and electrical characteristics of the fuel cell. The testing took place during the week of October 7-11, 1985.

FUEL CELL DESCRIPTION

The 40 kW fuel cell power plant was designed and manufactured by International Fuel Cell (IFC), formerly a division of United Technologies Corporation. It is a packaged unit which includes the fuel cell stack, inverter, fuel processing, water cooling system, water treatment, and microprocessor controls. An auxiliary grid-connect unit (GCU) has been added to allow interface with the utility grid.

The power plant was designed to operate unattended in either a line commutated dispatchable mode (grid-connect) or self-commutated load following mode (grid-isolated). Electrical protection features are included as part of the microprocessor control scheme. Out-of-limit conditions can be sensed and appropriate action is initiated by the fuel cell to protect itself and the load. In addition, the protection features include an automatic return to service, depending on the type, duration, and severity of the out-of-limit condition.

Performance data for the field test is continually collected by an onsite data acquisition system (DAS). The system scans pertinent instruments, converts the measurements into engineering units, and logs the data on to quarter-inch magnetic tape. The tapes are collected about once a month and sent to Science Applications International Corporation (SAIC) for processing and analysis.

SPECIAL TEST OBJECTIVES

Although data were continuously recorded by the onsite DAS and processed on a monthly basis, Con Edison wished to conduct additional testing. These "special" tests were performed to assess partial load electrical and thermal performance, and to simulate certain overrated conditions. An exercise of distressed grid-isolated and grid-connected operating conditions permitted an evaluation of the 40 kW fuel cell's intrinsic electric protection system. Specifically, the special test objectives were:

- o To determine the electric and thermal conversion capacities and efficiencies of the IFC 40 kW fuel cell over the load range,
- o To characterize the power output quality in terms of load response, signal distortion, load and voltage tracking, and power factor,
- o To evaluate the intrinsic electrical protection features of the power plant, and
- o To assess the unit's environmental emission characteristics (exhaust, discharge water, noise output, and electromagnetic interference (EMI)).

TEST PROCEDURES

The additional fuel cell tests were a joint effort by SAIC and the Con Edison engineering staff. They were responsible for planning, coordinating, and supervising the tests. In addition, two IFC engineers were present during the tests to give additional support and to advise in the test setup. Con Edison staff performed all "hands on" aspects of the test.

Tests were conducted for grid-connect and grid-isolated fuel cell operating modes. Many of the tests were redundant between the two operating modes, but features characteristic of a particular operating state were tested when possible. The redundant tests included:

- o Fuel input/electrical and thermal energy output performance testing over the load range,
- o Electrical output quality, i.e., power factor, harmonic distortion, over the load range,
- o Loss of phase and grounded phase tests,
- o Exhaust emission and discharge water sampling and analysis,
- o Sound level measurements.

The fuel cell is a load-following generating system when placed in the grid-isolated operating mode. Therefore, to simulate a load the fuel cell tests utilized a variable resistive load bank. The load bank was interconnected to the fuel cell via a 200 amp three-phase disconnect switch by wiring it to the GCU side of the isolated load transfer switch.

In the grid-connect mode the fuel cell requires a reference frequency and voltage to be present on the grid in order to synchronize and adjust its supply voltage to initiate a positive power flow. The protection features limit the frequency and voltage tracking ability of the fuel cell by setting out-of-limit trip set points. In order to test these set points a grid circuit was simulated by interconnecting the fuel cell to the resistive load bank parallel with a variable voltage, variable frequency 24 kVA signal generator.

TEST RESULTS

ELECTRIC AND THERMAL PERFORMANCE

In the grid-isolated operating mode, the combined thermal and electric conversion LHV conversion efficiency range was measured to be from 48.2% @ 1.7 kW to 79.6% @ 30.2 kW. Full load (39.9 kW net) grid-isolated electric conversion LHV efficiency was 36.5% (10,350 Btu/kWhr HHV heat rate). Peak thermal output was 142,344 Btu/hr @ 39.9 kW with a 72.6°F heat exchanger supply water temperature.

Grid-connected combined thermal and electrical LHV efficiency ranged from 62.8% @ 9.7 kW to 60.5% @ 40.4 kW. The decrease in the composite efficiency is due to an increase in the temperature of the water (117°F) supplied to the fuel cell's heat exchanger. This inhibits the removal of heat through the low-grade heat exchanger and subsequently the fuel cell manages the thermal waste by rejecting it to the atmosphere. Electric conversion LHV efficiency at full load (40.4 kW net) was 36.9% or 9263 Btu/kWhr HHV heat rate. The maximum thermal output occurred at 30.5 kW and was measured at 98,000 Btu/hr.

The peak current total harmonic distortion was measured at 18% @ 20 kW for grid-connected and 10% @ 11 kW for grid-isolated. The peak voltage total harmonic distortion was found to be about 1.3% over the load range for grid-connected and approximately 9% for grid-isolated.

The near unity power factor did not change for the grid-isolated fuel cell over the load range which is expected with a resistive load. However, the grid-connect load showed a degradation of power factor at lower loads. It ranged from .62 @ 9.7 kW to .99 @ full load. IFC has commented that this was the intended design.

ELECTRIC PROTECTION CHARACTERISTICS

The loss of phase test in the grid-isolated mode did not initiate a response by the fuel cell although a 2.9% voltage degradation occurred on the remaining active phases. In instances of long grid-isolated phase outages (2 hours or more), the Scott-T transformer in the inverter would trip out on high temperature. This feature was not tested.

In the grid-connect mode, a loss of phase is interpreted as a loss of grid. This protection feature is essential in preventing an inadvertent energizing of grid circuits during a power outage. A manual opening of a phase circuit, during the test resulted in the fuel cell cycling off the grid into a "disconnect" mode. The time interval to disconnect was measured from .1 to 5.07 seconds. At higher loads it took longer for the fuel cell to respond and cycle off. It was able to reestablish grid connection upon closing of the lost phase.

In the grid-isolated mode, complete power plant shutdowns resulted from all three single-phase to neutral fault tests. IFC was not able to explain the full plant trips with the limited information from the tests. The fuel cell is designed to disconnect from the load and cycle the inverter off in approximately 5 seconds. The inverter should then restart at zero net load in about 6 seconds.

Grounded phases in the grid-connected mode resulted in immediate disconnect from the grid and subsequent operation at zero net load. A current spike of 425 amp was detected during the test, but IFC has indicated that this is more than the peak commutable pole current. It is possible that the current spike was actually produced by the paralleled 24 kVa signal generator.

An overload condition was induced while the fuel cell was in the grid-isolated operating mode by increasing the load bank resistance in steps of 2 to 3 kW. At 58 kW, the fuel cell disconnected itself from the load and 4 seconds later the inverter shut down and did not restart. This is the predicted operation for grid-isolated overloads of this magnitude.

The voltage tolerance range for the grid-connected fuel cell was found to be 112 volts to 135 volts. When voltages outside this range were dialed into the signal generator the fuel cell disconnected itself from the simulated grid. The fuel cell was able to cycle back on the simulated grid once the out-of-limit voltages were returned to the proper 120 volt level.

The out-of-limit frequency test for the grid-connected operating mode was not completed because of problems synchronizing the fuel cell with the signal generator in the variable frequency mode.

ENVIRONMENTAL EMISSION TESTING

The fuel cell was found to have a constant sound level over the load range in both the grid-connected and grid-isolated operating modes. The loudest area of the fuel cell was found to be in front of the fans. At a distance of 4.5 feet the sound level was measured to be 81 dB within the enclosure.

The discharge water of the fuel cell was found to be cleaner than the referenced city water and no measurable EMI was found at selected locations around the power plant.

Stack exhaust emissions were found to be low except for CO. It was measured to be at 1400 PPM at full load; this is still lower than the most strict air emissions requirement set by the Southcoast Air Quality District in Los Angeles.

CONCLUSIONS

In general, the fuel cell thermal and electrical conversion efficiency were within 5 percent of IFC specifications. This is in light of the poor resolution of the fuel and water flow meters which were used (gas meter: 1 pulse=2 SCF, water meter: 1 pulse=1 gallon). Its full load electric conversion heat rate (9263 Btu/kWhr) is very good compared to other generating units of this size (<100 kW).

The intrinsic protection features of the fuel cell in general, were able to detect out-of-limit conditions and to initiate proper action to protect the fuel cell and the load. Some of the time intervals and set points did not match IFC specifications exactly, but many of these are adjustable.

The voltage THDs, at full load, are approximately .8 percentage points higher than IFC specifications. It does not appear to be a serious difference. However, the current THDs, 18% for grid-connect, appear very high. There is not an IFC specification for current THD.

Only CO measurements indicated a possible exhaust emission problem with the fuel cell. But even at these levels it is still lower than the most stringent air quality requirements. All other possible environmental perturbations (sound, discharge water EMI) by the fuel cell were found to be small or negligible.

40 KW FIELD TEST EXPERIENCE

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As part of the 40 KW Onsite Fuel Cell Field Test, The Dayton Power and Light Company installed a 40 KW fuel cell at a hotel in Dayton, Ohio in September 1984. Over the course of the field test the system provided electricity for use in the guest rooms of the hotel and supplemented the domestic water heating requirements of the facility. During the 14 month field test period, the fuel cell operated for 6,227 hours producing 189,000 KWh and 148 million BTU of usable heat. Overall power plant availability was 60% with several months during the test at 100% availability. Utility personnel performed the majority of operation and maintenance work required on the system.

Since this project was designated as a field test rather than a demonstration project, its main goal was to determine the operational feasibility of the fuel cell system while at the same time identifying areas for needed improvement. The operation of the fuel cell at DP&L along with those of other participants in the program helped to reveal specific subsystems requiring modification or design changes that need implementation prior to full scale commercialization. At the DP&L site, the following are examples of areas for improvement that were identified:

- * Cold weather operation; Several components experienced freeze damage both during unit operation as well as while the system was shut down.
- * Heat recovery; Local water supplies appear to have deposited scale on the fuel cell heat exchangers which reduced flowrates through the system and inhibited heat transfer.
- * Control logic; At times during the field test random, unexplained fuel cell shutdowns were experienced.

While there were numerous opportunities during the field test to perform maintenance on the system, the problems encountered were of the type which should not inhibit fuel cell development. The results of the field test indicate that fuel cell technology is capable of providing both electricity and heat energy according to specifications.

FIELD EXPERIENCE WITH 40 KW FUEL CELL POWER PLANTS AT MILITARY BASES

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Introduction

The U.S. Department of Energy (DOE), in cooperation with the Department of Defense (DoD), is sponsoring the field testing of four 40 kW fuel cell power plants at military bases in the United States. The purpose of the project is to gain experience with the operation and performance of onsite fuel cell power plants to demonstrate their viability for military bases. Science Applications International Corporation (SAIC) is responsible for the power plant/site design, installation, and performance data collection and analysis.

The fuel cell power plants were scheduled to operate for one year at each site providing electricity and heat for space heating, domestic hot water and process heat. A complete data acquisition system (DAS) was installed at each site to monitor the power plants' performance.

The installation of 40 kW fuel cells at four military bases is a separate, but parallel program to the Gas Research Institute's (GRI) and DOE's Onsite Fuel Cell Field Test Project. In the GRI/DOE Project, over forty 40 kW fuel cell power plants are being field tested by approximately thirty gas and/or electric utilities.

Site Characterizations

The first of the DoD fuel cell power plants was installed at the Wright-Patterson AFB near Dayton, Ohio in August 1984. The power plant was installed at the USAF Museum to supply electricity and space heat. Operation continued for over 2300 hours until a leak in an internal heat exchanger caused water to flow back through the reformer and into the cell stack washing out the electrolyte. Significant damage resulted, and it was decided to decommission this power plant early and concentrate the field test efforts on the other three power plants.

The second power plant was installed at Sheppard AFB near Wichita Falls, Texas in November 1984. It provided electricity to a dormitory as well as heat for domestic hot water. This power plant operated for a full year as planned, accumulating 5100 hours.

The third power plant was installed at Ft. Belvoir, Virginia in February 1985. It provides heat for domestic hot water for an Army dining hall. The electric output is provided to the

mess hall in a grid-connected mode as were the first two installations. However, the power plant is also electrically connected to serve an isolated lighting load. In the case of a grid power outage, the fuel cell can continue to operate and demonstrate its ability to serve an isolated load. This power plant has accumulated over 6200 hours of operation and is intended to go into extended testing beyond the one year (8000 hour) operation originally planned.

The last fuel cell was installed at Elmendorf AFB near Anchorage, Alaska in August 1985. It provides process heat for the boiler make up water at an adjacent base power plant. The power plant also is grid-connected and serves an isolated lighting load. The power plant has accumulated over 4600 hours and it also is expected to perform extended testing.

Power Plant/Site Data Collection

The purpose of the DAS was to collect data vital to the operation and maintenance of the power plant and analyze this data to determine performance characteristics.

Figure 1, a simplified block diagram of the DAS which was installed at the DoD sites, shows the flow of data from electrical sensors (select load panel) and thermal sensors (water and gas flowmeters, resistance temperature devices) to the datalogger and data recorder. The datalogger, which is capable of monitoring up to 75 data points, scans each data point every fifteen seconds. Average maximum and minimum values are recorded by the data recorder every half-hour on magnetic tape cassettes.

INSTRUMENTED SITE

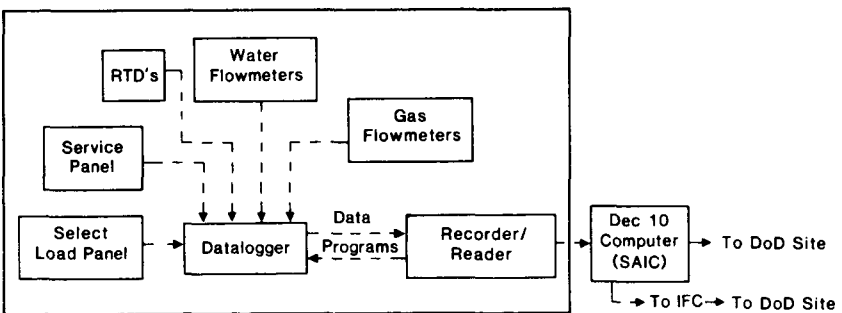


Figure 1. Data Acquisition System (DAS)

Every two weeks the DoD site personnel send a data tape to SAIC for initial analysis. SAIC's computer program analyzes the data, provides a statistical correlation of each parameter, calculates and provides power plant performance data, and summarizes the performance. A plot of the fuel cell electrical output and the total fuel utilization is also generated.

System Performance

All four of the fuel cell power plants normally operated in the grid-connected mode and were usually set to maximum capacity (40 kW). Tables 1 and 2 show a comparison of the performance characteristics of the four power plants as of June 1, 1986. The major reason the average kW power level was below 40 kW was that on many occasions operation and maintenance problems dictated operating at reduced power levels.

Table 1. Fuel Cell Power Plant Performance Characteristics

	Average Electric Capacity Factor (%)	Average Thermal Capacity Factor (%)	Cumulative Availability (%)	Operating Hours
WPAFB	70	45	46	2300
Sheppard AFB	73	67	61	5100
Ft. Belvoir	77	31	61	6200
Elmendorf AFB	72	54	78	4655

Table 2. Fuel Cell Power Plant Operating Characteristics

	Average Power Output (kW)	Average Heat Output Btu/hr x 1000	Average Electrical Efficiency (%)	Average Fuel Utilization (%)
WPAFB	28	68	37	60
Sheppard AFB	29	100	31	61
Ft. Belvoir	24	44	38	59
Elmendorf AFB	34	81	39	57

The expected efficiency for the power plants at the power levels indicated was 37-40 percent based on the lower heating value of the natural gas. The Elmendorf and Ft. Belvoir fuel cells equalled or exceeded the specification. The Sheppard power plant had lower efficiency because it operated at lower power levels for longer time periods as a result of operating problems.

The average electric capacity factors shown in Table 1, are calculated by dividing the actual kWhrs produced by the kWhrs that would have been produced if the fuel cell had operated at

40 kW for the entire operating period. These capacity factors correlate well with the other power plants in the GRI program. The availability is a measure of the percent of time that the power plant actually operated. This is a good indicator of the reliability of the power plant. However, it should be understood that due to the prototype nature of the 40 kW fuel cell and the R&D nature of the field tests, more maintenance problems and downtime to receive parts are expected when compared to commercial operation. The availabilities ranged from 46 percent to 78 percent. The Elmendorf power plant's availability of 78 percent was one of the highest in the GRI field test. The GRI/DOE program goal was to achieve availabilities of 55-65 percent. The actual program average is 63 percent.

The thermal output from the fuel cells ranged from 44,000 Btuh to 100,000 Btuh at Sheppard AFB. The design specification for heat output was approximately 150,000 Btuh based on 2.5 gpm flow, 160°F supply water temperature and 80°F return water temperature. The thermal output is more indicative of the site load than the performance of the power plant.

The thermal capacity factor is a measure of the actual heat produced and used by the site vs. the predicted heat production (150,000 Btuh) during average conditions at 40 kW electrical output. For the reasons already discussed, these ranged from 31 percent at Ft. Belvoir to 67 percent at Sheppard AFB.

The overall fuel utilization is calculated by dividing the actual energy produced (heat plus electricity) by the energy supplied (fuel). Based on the higher heating value of natural gas the predicted fuel utilization was approximately 73 percent. For the reasons previously discussed, all four power plants had lower fuel utilization, ranging from 57 percent to 61 percent.

Problems

Almost all of the problems encountered by the four DoD fuel cell power plants had also occurred with many of the other GRI/DOE 40 kW fuel cells. Most of these types of problems can be expected in a preproduction scale field test. The following is a list of the most significant problems.

- The cell stack coolant loop plugged as a result of dissimilar metals, small orifices, and inadequate condensate blowdown
- Unreliable logic cards
- Inadequate pumps
- Steam and water leaks
- Extremely sensitive grid-connect unit (GCU) tolerances
- Freeze-ups of coolant loop components

- Unreliable solenoid valves
- High-grade HEX water hammer
- Low-grade HEX undersizing

Successes

The major success was the reliable operation of the fuel cell stacks. Almost all of the problems encountered were with a conventional part of the fuel cell power plant and they will be rectified. In addition, the following successes were achieved.

- o The electrical efficiency met specifications
- o The inverter produced extremely good power quality
- o Very low levels of emissions were produced
- o The load following capabilities were proven

Conclusions

The four 40 kW fuel cell power plants field tested are compatible with conventional military base energy usage. Through this project, much experience has been gained with the operation and performance of developing phosphoric acid fuel cell power plants. Site personnel performed most of the maintenance and all of the operational aspects of the project. In particular, the personnel at Elmendorf AFB have performed all but the first fuel cell coolant loop chemical cleaning unassisted. Problems were encountered but were understood. The major challenges now facing military applications of fuel cell power plants is to improve the operating and performance characteristics, prove the reliable operation of a commercial power plant, reduce the capital costs and determine appropriate early applications for the military.

ON-SITE 40-kW FUEL CELL FIELD TEST

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During the period 1982 through 1986, a 40-kW fuel cell power plant was designed, fabricated, and field tested. The 40-kW program evaluation was both comprehensive and intense:

- 1) Forty-six plants were produced. A picture of one of the installed units is shown in Figure 1.

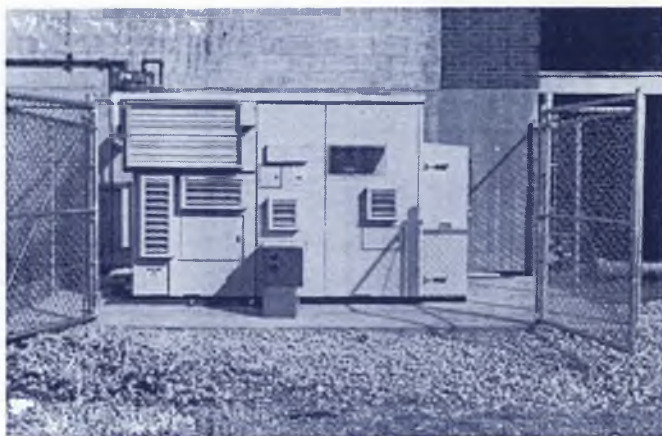


FIGURE 1. 40-kW FUEL CELL POWER PLANT

- 2) The 42 power plant sites in 21 states of the United State and two locations in Japan provided exposure to a broad range of environments. Figure 2 shows the installation locations.
- 3) The power plants operated both independent from and connected to the utility grid. Three installations involved two grid-independent power plants operating in parallel. The power plant heat was used to supply domestic hot water, space heating, pool heating, and low-temperature process loads.
- 4) Thirty-six organizations served as field test hosts performing power plant installation, operation, and maintenance.
- 5) The average power plant operated for over 6500 hours. Fourteen power plants exceeded 8000 hours of operation with the longest running unit operating for over 11,000 hours. Total operating experience exceeds 300,000 hours.

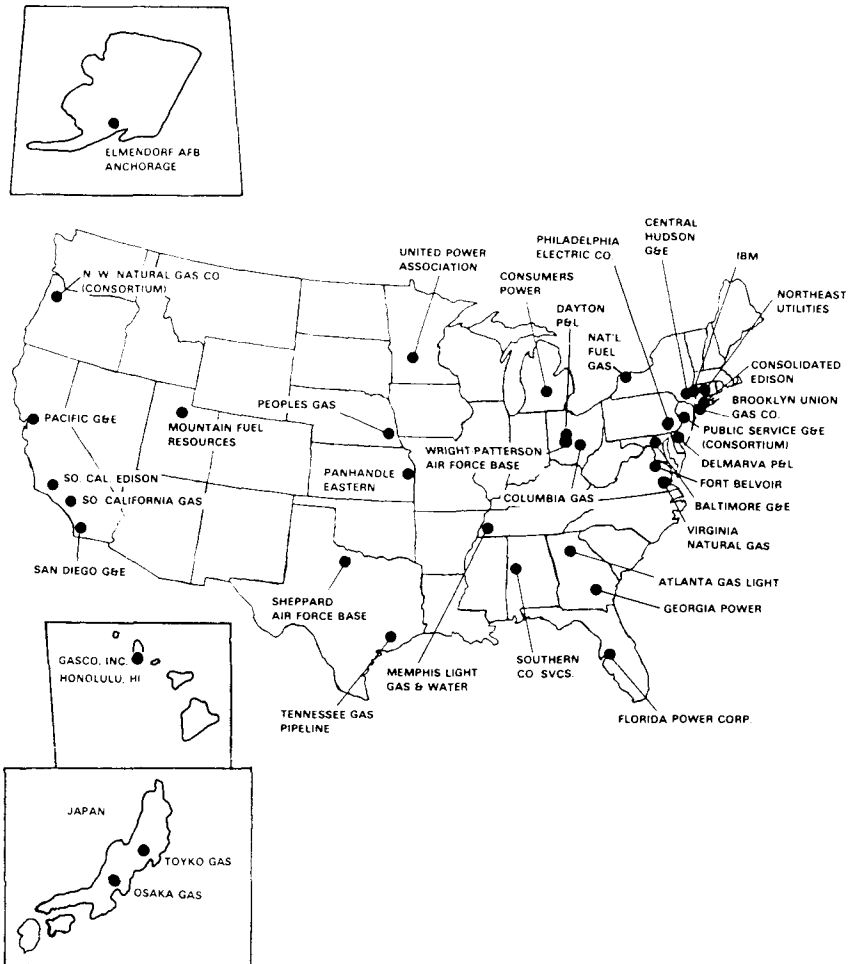


FIGURE 2. 40-kW FUEL CELL LOCATIONS

The field test was successful in demonstrating the performance features of on-site fuel cell power plants and the ability of the host utility organizations to install, operate, and maintain the equipment.

The power plants were produced in an experimental fabrication facility using process control, rather than component testing, as the quality control approach for the cell stack and reformer. The resulting power plant characteristics were as predicted and quite consistent throughout the fleet. The ability of a standard power plant design to meet the needs of a range of electrical and thermal loads was demonstrated.

The attractive fuel cell characteristics of high efficiency, low environmental intrusion, and rapid response were demonstrated repeatedly. The efficiency was quite stable over the operating period. Figure 3 is a typical plot of electrical efficiency and overall efficiency (including recovered heat) over a power plant operating period. At a few sites, air pollution emissions were measured; the measured values were lower than the most stringent U.S. Standards. Rapid load response was demonstrated in grid-independent sites. Figure 4 shows excellent load sharing and rapid response of two grid-independent units operating in parallel.

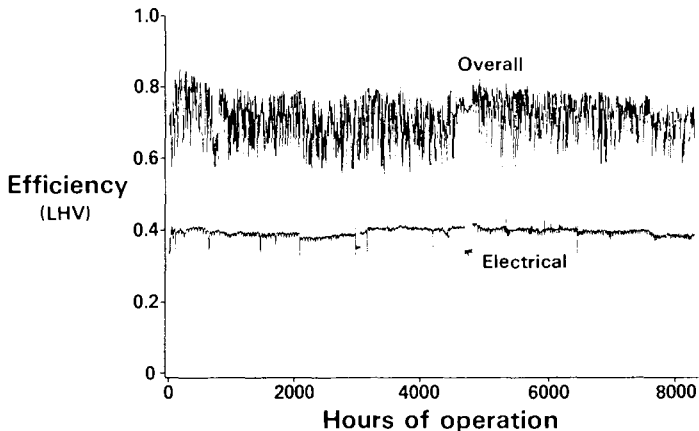


FIGURE 3. EFFICIENCY STABILITY FOR OPERATING PERIOD

The cell stack and reformer showed excellent operating integrity throughout the program. The program approach to ancillary components was to utilize available catalog items with limited evaluation testing. As a consequence, field test ancillary component operating integrity was deficient. Approaches to overcome these deficiencies have been identified and are being evaluated in the parallel technology development activity. In spite of this, the potential for long operating periods without maintenance was demonstrated. Most of the power plants had at least one continuous run of 1000 hours or more, with the longest being 2165 hours (3 months). One power plant operated for 4025 hours without a forced outage.

One hundred twenty-five individuals from host organizations attended the two-week training course of International Fuel Cells. This course and the power plant manuals provided attendees with the ability to install, operate, and maintain

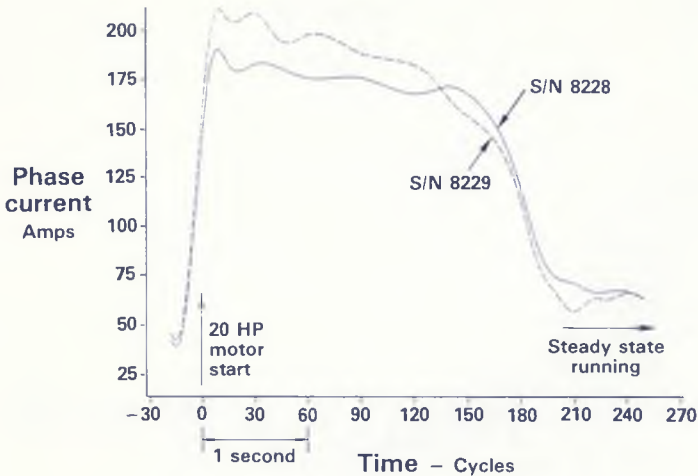


FIGURE 4. RESPONSE TO LOAD CHANGE FOR TWO PARALLELED POWER PLANTS

the power plant with a reasonable level of assistance from IFC. The level of support required declined as the host organizations gained experience. The major reason for requesting assistance was in diagnosis of the cause of shutdown. This area will be addressed with improved diagnostic information in future power plants.

Acknowledgements

The power plant fabrication and field test support activities were sponsored by the Gas Research Institute and the U.S. Department of Energy through the DOE Morgantown Energy Technology Center. NASA-Lewis served as project manager of the DOE-funded activity. The host organizations funded site activities. The efforts of a large number of personnel at the host utilities, the sponsoring organizations, and International Fuel Cells in achieving the results reported herein are gratefully acknowledged.

THE NATIONAL ECONOMIC MARKET OPPORTUNITY AND
COMMERCIALIZATION OF ON-SITE FUEL CELLS

STEVE KNABLE
GAS RESEARCH INSTITUTE

An abstract of this presentation was not available at press time. Copies will be provided to attendees at the Seminar.

OVERVIEW OF THE WESTINGHOUSE SOLID OXIDE FUEL CELL PROGRAM

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The Solid Oxide Technology Venture of the Westinghouse Electric Corporation located at the Research and Development Center in Pittsburgh is the organization with the dedicated objective of development and commercialization of Solid Oxide Fuel Cell technology.

Westinghouse conceived the solid oxide fuel cell in 1958 during the course of corporate sponsored fundamental research on oxygen ion conductivity of cubic phase zirconia. The present state of solid oxide fuel cell technology has grown out of this work, financially supported over the past 28 years by Westinghouse and several agencies of the U.S. Government -- Office of Coal Research of the Department of the Interior, Energy Research and Development Administration, and most recently the Department of Energy (DOE). The current DOE contract is under the direction of the Morgantown Energy Technology Center.

Prior to the initiation in 1980 of our present contract with DOE, Westinghouse devised both the tubular solid oxide fuel cell with axial interconnection strip and a seal-less generator concept that permits the interconnection of cells in an array with both series and parallel cell interconnection. These inventions promised the potential for practical, clean, efficient, and economic solid oxide fuel cell (SOFC) systems for cogeneration of useful heat and electric power as well as for all electric power applications.

Performance under this contract has thus far corroborated this potential. It has been demonstrated that hydrogen and carbon monoxide in any proportion are acceptable as elemental fuel gases. The focus of the DOE program has been on coal derived fuel gases, and the reference fuel is a synthetic reformat gas (67% hydrogen, 22% CO, and 11% water vapor). Individual cells (approximately 1.5 cm diameter by 30 cm length, i.e., approximately 110 cm² active cell surface area) have delivered a peak power of 22 watts using this simulated reformat fuel (85% utilization) and air oxidant (25% utilization). The contract goal for these conditions was 11 watts. Using the state-of-the-art materials and cell design, a three-cell stack was operated for over 9000 hours with no evidence to suggest that corrosion, phase change or component materials interdiffusion would limit life. A 24 cell, subscale generator module was operated for over 2000 hours, and verified the seal-less design concept. The test also demonstrated that this generator could operate in a thermally self-sustaining mode. Data showed that the efficiency

(i.e., the ratio of electric power output to the power equivalent of the high heating value of the methane fuel flow input) of this generator exceeded 45%, with no utilization of the high quality exhaust heat. This data was obtained with the standard fuel and air utilizations stated above, atmospheric pressure, and nominal 250 ma/cm² cell current density.

The culmination of the DOE program phase just completed was the designing, building, and testing of a 324 cell generator, called the 5 kW unit. Its purpose was to show that SOFC technology could be applied to a thermally self-sustaining generator encompassing key features of a large-scale power generating system. The cell arrangement was 108 cells in series and three cells in parallel. Under test at the standard conditions mentioned earlier the generator output initially was over 61 volts at 85 amps producing in excess of 5200 watts.

A modification to our contract with DOE has been negotiated which will provide \$15M of continued support for SOFC technology development through April 1989. With this latest modification, our DOE funded contract effort since 1980 will exceed \$28 million. Of this Westinghouse will have contributed \$6M as direct cost share. The effort planned for the continuing DOE program includes:

- Establishment of user requirements.
- Conceptual design and trade-off studies to delineate the performance and cost goals for cells and other components to be applied in early market entry units.
- Continued technology advancement of the fuel cell, fuel cell generator module, and process technologies directed toward developing the capability to meet performance and cost goals necessary for viability in a competitive marketplace.
- The manufacture and testing of numerous cells and the development, construction and test of two SOFC generator modules of roughly multi-kW electrical capacity in order to verify technological advances and provide the design for a generator module suitable for a 25 to 200 kW SOFC generation system.

During the course of the DOE contract, Westinghouse will commit approximately \$5M million in additional capital funds for the construction of a "miniplant" to increase the scale of our SOFC manufacturing capability. This plant will incorporate larger scale batch type processes including significant scale-up of the key film application process (EVD) and will focus on reducing the cost (i.e., mechanization) of the most labor intensive process steps while instituting a broad ranging quality assurance program. The "miniplant" will be operational in 1988.

Westinghouse has recently been awarded a contract with the Gas Research Institute for solid oxide fuel cell development. The ultimate objective of this program is the development of natural gas fueled cogeneration systems for application to the

commercial and industrial sectors. The first phase of this program is a 21 month effort funded at \$2.6 million by GRI.

The first phase objective of the GRI program is the development and proof of concept testing of an SOFC generator module that can be fueled by direct input of natural gas. In our DOE development programs, the fuel has been a simulated coal derivable reformat fuel gas that required no further processing. It can be shown thermodynamically that the direct reformation of methane on the anode surface should be possible at the normal SOFC operating temperature near 1000°C. The kinetics of the reforming reaction are very rapid, however, and provision of adequate heat transfer may be a limiting factor. This is a major issue which will be thoroughly investigated. Beyond heat transfer considerations, the most significant problem expected is the avoidance of carbon deposition, especially across the range of operating conditions and expected natural gas fuel compositions. We plan to verify the feasibility of insitu reformation of natural gas early in the GRI program using single cell tests. As an alternative technical strategy, we will develop means to integrate an SOFC exhaust gas heated reformer within the generator module. The direct use of natural gas will be demonstrated in the design, construction and test of a proof of concept SOFC generator module before the end of 1987.

The proposed second phase of the GRI program will yield a 100+kW class cogeneration system, and the development of several such systems as field experiments.

The proposed third phase includes the successful maintenance of the field test plus the development and test of a MW class cogeneration system at an industrial site as a field experiment.

Westinghouse has designed, built, tested, and delivered to the Tennessee Valley Authority a 400 watt SOFC generator module, very similar to our 24 cell unit tested on the DOE program, and installed it in a host test apparatus. Much more about the details of operation of this unit will be discussed in another paper. This unit was sold to TVA because we felt TVA testing the unit, corroborating generator performance, and gaining first hand experience with the technology was an important early step toward ultimate commercialization. Contracts have now been signed with large, overseas gas utilities for test units as the first phase of continued cooperative efforts between us to familiarize them with the technology and enable Westinghouse to benefit from their particular technical and market expertise.

We are presently addressing the questions:

- Do we have a market?
- Do we have a product?
- Can we be competitive?
- What is the proper strategy to implement?

We know many potentially different applications exist and cogeneration is one likely market entry application. We assert that learning curve theory applies to this product and that low cell cost will require high volume production. Initial cost of production will be high, much higher than that of competing technologies such as gas turbines and diesels. Our business approach then is to familiarize potential system partners with the technology, concentrating initially on those with a long-term view who have a valuable expertise to bring to the program. We have included in our consideration potential overseas demonstration plants.

Westinghouse will be the systems integrator for some applications but we believe a market approach by varied system integrators will be appropriate to broaden the SOFC market. We do intend to be a low cost, high quality cell and generator vendor.

We believe competitive commercial offerings can be made in the early 1990's and this puts solid oxide fuel cells on a competitive commercial timescale with other fuel cell technologies. SOFC's should no longer be considered an interesting technology for some time in the far distant future.

DEVELOPMENT STATUS OF MULTI-CELL SOLID OXIDE FUEL CELL GENERATORS

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INTRODUCTION

Solid oxide fuel cell technology has seen major advances over the past few years. Tubular cells, with a thin-film electrolyte, were found to be stable during tests which approached 9000 hours duration.⁽¹⁾ Cell fabrication techniques were developed which permit the production of the large cell quantities required for SOFC generators, and a 24 cell generator was built and tested.⁽²⁾ During the past year, testing of the 24 cell generator was continued and a 5 kW generator was fabricated and tested.

24 CELL GENERATOR DESIGN

The 24 cell generator was a major step in the development of practical large-scale SOFC power generation systems. It was the first successful operation of a self-heating SOFC generator. Cell temperatures were controlled through the air delivery system and not by enveloping heaters typical of laboratory experiments.

This generator consisted of two cell bundles, each containing twelve tubular cells in a three-parallel by four-series matrix. A series connection was made between the two bundles and power take-off leads were joined to the free end of each bundle. The terminal voltage was eight times and the current three times that of the individual cell.

Air was supplied through feed tubes suspended from a common supply plenum. Each air feed tube extended into the tubular cell to introduce air near the closed end of the cell. The air then passed along the air electrode in the cell bore and exited at the open end of the cell. The air flow provided cell temperature regulation and oxygen for cell function.

The cell stack was surrounded by a thin-walled inner canister which directed the gaseous fuel through the spaces between cell outer surfaces, and isolated the fuel from the surrounding insulation package.

24 CELL GENERATOR TEST RESULTS

The prescribed test plan for the 24 cell generator included a 750 hour endurance run followed by a series of five shutdown and start-up cycles designed to check out the thermal cycle ability of the design. A special experiment was then run during which the air supply to one of the cells was interrupted for several hours. This test checked the parallel interconnection current path of cells in this unit and demonstrated the current sharing ability of parallel cells. Finally, the unit was run again for a second endurance test

before being shut down and dismantled. In all, the unit ran for over 2000 hours.

Figure 1 presents two voltage versus current characteristics for this 24 cell generator, one at the beginning and one at the end of the tests. The unit satisfied most of its pre-test goals and encouraged us to proceed with the construction of the 324 cell unit. A problem in the sinter-bond to the peripheral cells was observed during the thermal cycle tests, but this was resolved through additional development efforts.

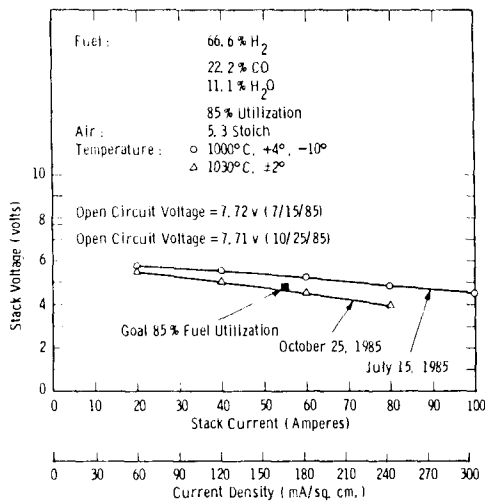


FIGURE 1

V VS. I CURVE FOR 24 CELL GENERATOR

5 KW GENERATOR DESIGN

The 5 kW generator incorporated proven design features of the 24 cell generator to the greatest possible extent. For example, the electrical power take-off and leads were almost identical to those of the smaller generator. Each pre-assembled 18 cell bundle was composed of a three-parallel, six-series cell matrix. Eighteen of these bundles were series-connected to form the 324 cell stack, which is shown in Figure 2 during assembly. As in the smaller generator each air supply plenum fed two adjacent bundles, but now 36 instead of 24 cells. The nine air plenums were joined to a single manifold by slip-joint tube couplings which accommodate thermal expansion and tolerances. Alumina-fiber blanket material was incorporated adjacent to the inner canister walls to accommodate the larger thermal growth for the 5 kW

generator. Fuel distribution was accomplished by flow channels cut into the insulation boards under the cell stack. The completed 5 kW generator is shown in Figure 3 during operation in the test installation.



FIGURE 2

5 kW GENERATOR CELL STACK

5 kW GENERATOR TEST RESULTS

The start-up procedure, test plan, and performance goals for the 324 cell generator were similar to those of the 24 cell unit. After successfully reaching full power operation, the initial endurance run of this unit was interrupted at around 200 hours by anomalous temperatures and low voltages in two of the bundles of cells. The unit was partially disassembled and two 18 cell bundles were replaced. The unit was successfully restarted and Figure 4 shows a power versus current plot which was measured during this second run. The extrapolation of the measured data indicated that the peak output of this unit could have been around 6 kW. Heat balance calculations were run which confirmed the integrity of the test instrumentation and verified both our thermal and electrical prediction for the performance of this unit. A total operating time of 400 hours at full power (greater than 5 kW) has been accomplished.



FIGURE 3
5 KW GENERATOR
AND TEST FACILITY

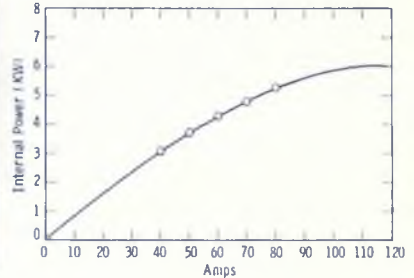


FIGURE 4
5 kW (324 CELL) GENERATOR
POWER-CURRENT TEST RESULTS

CONCLUSIONS

1. The SOFC generator design features were proven to be sound.
2. Electrical performance of the generator can be predicted on the basis of single-cell performance.
3. The generator design permits access for service and individual cell bundles can be replaced.

ACKNOWLEDGMENTS

This work was supported by both the U.S. Department of Energy under the direction of Morgantown Energy Technology Center and Westinghouse Electric Corporation. The contributions of both sponsors and the other Westinghouse personnel involved in this work are gratefully acknowledged.

REFERENCES

1. A.O. Isenberg, "Performance and Life Test of a Solid Oxide Fuel Cell Stack," National Fuel Cell Seminar Abstracts, May 19-22, 1985, pp. 102-106.
2. G.W. Zymboly, P. Reichner, and J.M. Makiel, "Cell Fabrication, Design, and Operation of a Solid Oxide Fuel Cell Generator," National Fuel Cell Seminar Abstracts, May 19-22, 1985, pp. 95-101.

TVA TEST OF SOFC SUBSCALE GENERATOR

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I. Introduction and Objectives

The Tennessee Valley Authority (TVA) has purchased a laboratory prototype 400-Watt Westinghouse Solid Oxide Fuel Cell (SOFC) generator module installed in a host test apparatus for the purposes of demonstrating the capabilities of the technology, providing independent corroboration of overall performance and reliability, and gaining familiarity with the technology. TVA is the first organization outside of a research and development laboratory to initiate a program to explore the systems aspects of this technology. The test apparatus is housed in a special TVA facility located in Chattanooga, Tennessee.

This 400 Watt SOFC testing program is envisaged as the initial phase in a potentially long-term TVA program which has as its ultimate goal the development of a fuel cell technology for dispersed, cogenerating electrical power generators that operate on coal-derived fuels. SOFC technology has the high temperature heat and the potential for fuel flexibility that are required for this application. The Westinghouse solid oxide fuel cell generator has certain inherent features which may be advantageous. These features include:

- Cooling with process air.
- By-product heat available in the gaseous exhaust stream at temperatures in excess of 600°C (1086°F), temperatures sufficiently high to support virtually any cogeneration application.
- The demonstrated ability to utilize hydrogen and carbon monoxide, the principle constituents of all coal derived fuel gases, as electrochemically consumed fuel.
- The formation of water at the fuel electrode, at cell operating temperature of 1000°C, a feature which promises the capability to reform natural gas, within the fuel cell generator, without the need for external fuel processing equipment such as reformers and shift converters.
- All solid state construction with demonstrated material compatibility, stability, and freedom from corrosion.
- A limited tolerance for sulfur in the fuel gas.
- A stack design that requires no gas tight seals.
- An exhaust effluent that should be free of NO_x.

The test apparatus designed and built by Westinghouse is capable of exercising the SOFC generator module with variations in the parameters perceived to be of interest for potential applications.

II. Generator & Test Apparatus Description

The TVA SOFC generator module utilizes 24 state-of-the-art tubular cells arranged in two series connected bundles, each bundle

consists of a two-dimensional cell array with four cells in series and three in parallel. The generator has a power output of nominally 400 Watts. In order to facilitate steady operation, the thermal enclosure is equipped with electrically powered guard heaters.

The test apparatus consists of fuel and air flow modulation means, an electrically powered air preheater, fuel humidification means, an external electrically heated natural gas reformer, an electrical load, an inert gas purge system, and a control system. The fuel system is configured to permit fuel cell operation on either a hydrogen plus carbon monoxide mixture or on reformer output. The inert gas purge system is used at startup and during both programmed and unprogrammed shutdowns.

The dc output from the fuel cell generator module can be routed through an inverter system to produce 120 volt ac, with the ac output absorbed in a servo controlled rheostat, or the dc can be absorbed in an FET electronic load for operation at constant current.

The control system is designed to permit unattended automatic operation at set point values for generator temperature, fuel utilization, and air utilization for arbitrary values of electrical load. In automatic mode, the fuel gas can be either a fixed reference mixture of hydrogen and CO ($H_2/CO = 3$) or reformer output, with the moisture content determined by the set point value for the bubbler temperature. The fuel flow rate will automatically adjust in response to the delivered current in order to maintain the set point value for fuel utilization as the electrical load is varied. The air flow rate is automatically adjusted similarly. In manual mode, the flow rates of the fuel gases are adjusted individually to set point values, and load follow operation at constant utilization is not automatic. Switchover from hydrogen and carbon monoxide to natural gas fuel is accomplished in automatic mode by throwing a switch. The control system also includes a programmable logic controller which monitors the value of important parameters and takes appropriate action (such as an automatic, unattended shutdown) when the permitted operating envelope is violated.

The test apparatus is housed in two structural steel cabinets. The assembly occupies a space roughly 36 inches deep, 96 inches long, and 80 inches high.

In addition to the sensors coupled to the control system and the associated digital displays, there are 27 thermocouples and 20 voltage channels connected to the TVA supplied data logging system. There are 9 thermocouples installed inside the generator module, as well as a voltage probe for each quadrant of the cell bundle. Data recorded includes internal generator temperatures and voltages, feed and effluent gas temperatures, feed gas pressures, feed gas mass flow rates, and generator current, terminal voltage, and power.

III. Test Program Description

The initial experimental design consists of two overlapping fractional factorial designs with the range of parameter values shown in Table 1.

TABLE 1 TEST MATRIX VARIABLES

Current, Amperes	95	90	80	60	30
Fuel Utilization, %		55	70	80	85
Mean Temperature, °C		800	900	1000	1050
Air Stoichs	3	4	5	6	7
Fuel type	preformed		reformed		

After startup, the generator is to be moved to a new set of experimental conditions every other day, thus, allowing time for the change of conditions and achievement of equilibrium, there will be roughly 40 hours of steady operation accumulated at each condition in the matrix. Assuming that the matrix is repeated three times, the duration of the initial test program will be about six months.

Upon completion of the test matrix, the generator voltage will be statistically fitted to a full second order functional model containing linear, quadratic, and cross-product terms in the five independent variables (current, fuel utilization, temperature, air stoichs, and duration of operation) for the two fuels. Note that if the natural gas were methane, and the reforming accomplished with 1.5 moles of water per mole of methane, then the reformer supplied fuel would be the reference preformed fuel (67% H₂, 22% CO, 11% H₂O).

Following this initial phase of testing, TVA expects to operate the device aggressively, demonstrating various aspects of transient operation, reformer operation across a range of water to carbon ratios, and direct operation of the unit on natural gas without the external reformer.

IV. Results & Conclusions

Prior to shipment, the apparatus was exercised to demonstrate operation and to familiarize TVA personnel with its operation. Among the operating conditions established were the following:

1. Steady operation at nominally 1000°C on hydrogen plus CO fuel gas, 5 stoichs of air flow, nominally 82.3% fuel utilization, 90 Amperes, 4.47 Volts, 402 Watts DC output.
2. Steady operation on hydrogen fuel.
3. Steady operation in both manual and automatic control modes.
4. Steady operation in automatic mode with hydrogen plus CO fuel across the range of fuel utilizations between 55% and 85%, air stoichs between 3 and 7 stoichs, and loads between 30 and 100 amperes.

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5. Rapid traversing across the load range.
6. Sudden loss of electrical load.
7. Operation of the AC inverter system.
8. Loss of electrical supply power for 20 seconds.
9. Switchover operation between the reformer and preformed fuel.
10. System response to a trip condition calling for shutdown followed by manual reset and resumption of operation.

The apparatus was shipped to Chattanooga as a complete assembly in a cushioned crate using a dedicated commercial moving van, and was put into place within the TVA facility on the day it arrived. During initial startup, the unit was deficient in output and evidenced characteristics of a cracked cell. Subsequent disassembly of the generator module revealed one badly cracked cell, attributed to a defect in manufacturing. After the generator is repaired, it will be reinstalled and the test matrix will be executed.

Conclusions to date:

1. The test apparatus meets its design requirements for automatic unattended operation, and operation at set point conditions for load follow.
2. Loss of electrical load is without deleterious consequences.
3. There was no shipping damage to either generator or test apparatus.

V. Acknowledgment

The development of SOFC technology has been supported by Westinghouse and the United States Department of Energy under a cost shared contract currently managed by the Morgantown Energy Technology Center (METC).

VI. Legal Notice

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MONOLITHIC FUEL CELL DEVELOPMENT

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A new fuel cell design, called the "monolithic fuel cell," is being developed at Argonne National Laboratory. The monolithic design employs the same thin ceramic components used in other oxide fuel cells in a strong, lightweight honeycomb structure of small cells, and thus can achieve very high power per unit mass or volume. The light weight and low volume, as well as the efficiency and reliability of electrical systems, are advantageous in space and terrestrial systems.

In the monolithic concept, fuel and oxidant are combined electrochemically in a ceramic cell at an operating temperature of 1100 to 1300 K. Cell components are fabricated as one piece, much like a block of corrugated paper-board, as shown in Fig. 1. Fuel and oxidant are conducted through alternating passages in the stack. These passages are formed from thin (0.025 to 0.100 mm) layers of the active cell components: electrolyte (yttria stabilized zirconia), cathode (strontium doped lanthanum manganite), anode (nickel-zirconia cermet), and the interconnection material (magnesium-doped lanthanum chromite) that connects cells in electrical series (bipolar plate). The corrugations also form the gas seal at the edges of the structure. Advantage is taken of the ability to fabricate the solid electrolyte and other solid cell components into shapes that cannot be achieved in liquid electrolyte systems. In liquid electrolyte systems, much of the mass and volume goes into building the inert container for the liquid. Eliminating this unnecessary material gives the monolithic fuel cell a significant advantage in performance.

The potential for the high power density of the monolithic fuel cell results from the small cell size. Cells 1 to 2 mm in diameter or smaller are achievable when the inert container for electrolyte and the inert support for the thin active layers are eliminated. The small cell size increases the active surface area per unit volume of the cell. More importantly, the small cell size in the monolithic design reduces the voltage losses due to internal electrical resistance(1). This reduction is a significant consideration, because internal resistance is the principal dissipative loss for the ceramic materials and temperatures of interest. Decreasing the cell size decreases the current path length because current is carried in-plane by the electrodes in the monolithic design.

FABRICATION

The principal challenge for the development of the monolithic fuel cell is fabrication of the intricate structures. Well developed ceramic fabrication techniques are being employed. Tape casting methodology is being optimized to fabricate thin, high density layers of electrolyte and interconnection material. Tape casting is used to form thin, high-density layers in the ceramic capacitor industry. Tape casting is also being used to form the thin porous layers of anode and cathode. Alternate thin layer fabrication techniques, such as spraying, curtain coating, and hot roll milling, are also being considered.

The fabrication effort focuses on the critical three-layer composites: cathode-electrolyte-anode and cathode-interconnection-anode. These are the fundamental building blocks of the array. Considerable attention is given to achieving adequate bonding between the layers. In addition, methods

have been developed to produce the desired corrugated structure. Thermo-setting resins are employed which make the structure sufficiently rigid so that the corrugated tapes may be stacked in the green state.

All layers of the array are co-fired in air under the same conditions. The principal challenge for co-firing is to match the shrinkage rates of all four materials by tailoring the particle size and the binder content in each layer. Gas manifolding is added after the array is fired. The present effort employs cross-flow gas passages to reduce the complexity of manifolding.

PRESENT STATUS

CELLS - Cells of the monolithic design have been fabricated and operated. The cells were three layer composites of cathode/electrolyte/anode with an active area of 3 cm^2 . The cell tests required a configuration different from that of a monolithic array. The cell geometry was flat in order to simplify gas manifolding. The unsupported three-layer composite was sealed to the end of a tube. The seal was made with a commercial zirconia/silica cement. For the cell test, air was supplied to one side of the cell and hydrogen to the other side. The electrical contacts applied to the cell for test purposes were a platinum paste and platinum screen. The cell and test apparatus were maintained in an isothermal zone.

Cell performance has been improved. The fabrication methodology has been upgraded so that cell performance more closely approaches the materials resistance, as shown in Fig. 2 (for tests at 1000°C with hydrogen as fuel and air as oxidant). The principal increase in cell performance arises from reducing the resistance at electrode/electrolyte interfaces. In particular, tailoring the distribution of nickel at the fuel electrode/-electrolyte interface is important to reducing interfacial resistance.

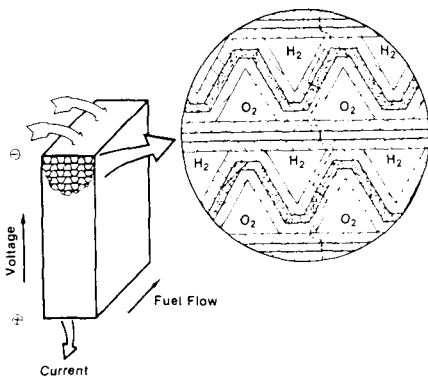


Fig. 1. Monolithic Fuel Cell.

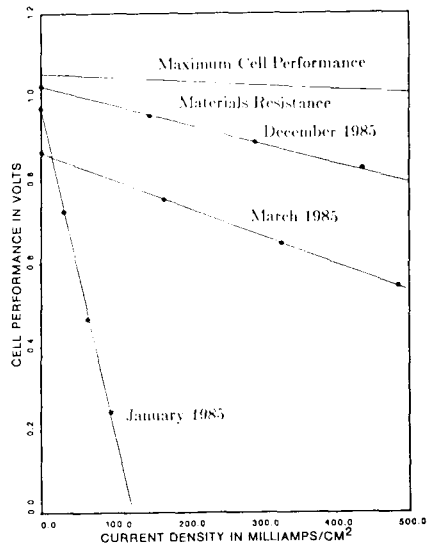


Fig. 2. Performance of Single Cells.

High current densities have been achieved. Cells of the monolithic design have been operated at 2.2 A/cm^2 with hydrogen as fuel and air as oxidant. This current density is about a factor of two higher than previously achieved with these conditions and materials(2). The high current density results directly from the low internal resistance of the monolithic cells. Further, the high current density clearly exceeds the monolith design goal of 0.6 A/cm^2 . More importantly, the data indicate that there is no fundamental limitation to achieving high current densities with solid oxide fuel cell materials.

ARRAYS - Arrays of the monolithic design have also been fabricated and operated. An array has been operated for more than 650 hours, as shown in Fig. 3. The array was two cells in electrical series; each with an active area of 9 cm^2 . The operating conditions were 1000°C , 50 mA/cm^2 , hydrogen as fuel, and air as oxidant. The performance demonstrates the feasibility of the monolithic fuel cell concept.

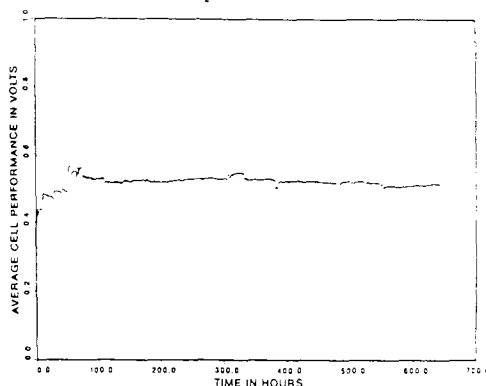


Fig. 3. Performance of Monolithic Fuel Cell Array.

Operation on hydrocarbon fuels was also demonstrated. The hydrocarbons were mixed with steam and introduced directly into the array. The fuels include methane, propane, octane, ethanol, and natural gas. The array performance was similar to operation on hydrogen. The natural gas contained about 5 ppm sulfur in the form of an odor producing mercaptan. So operation with a sulfur containing fuel has also been demonstrated.

The array incorporated a cross-flow pattern of gas channels. The electrochemically active region was a three layer composite of cathode/electrolyte/anode, as shown in Fig. 4 for an array of four cells in electrical series. A corrugated anode layer formed the fuel gas channels on one side of the three layer composite. Similarly, a corrugated cathode layer formed the oxidant gas channels on the other side of the three layer composite. The oxidant channels in the cathode are at right angles to the fuel channels in the anode, as shown by a cut at 45 degrees through an array in Fig. 5. Consequently, the corrugations in the cathode do not show in the photograph of the anode face of the array in Fig. 4. An interconnection layer separated the fuel and oxidant channels and linked the layers in electrical series.

The performance of the first monolithic arrays is similar to the performance of the first monolithic fuel cells. The array performance is expected to improve with time in much the same manner as the cell perfor-

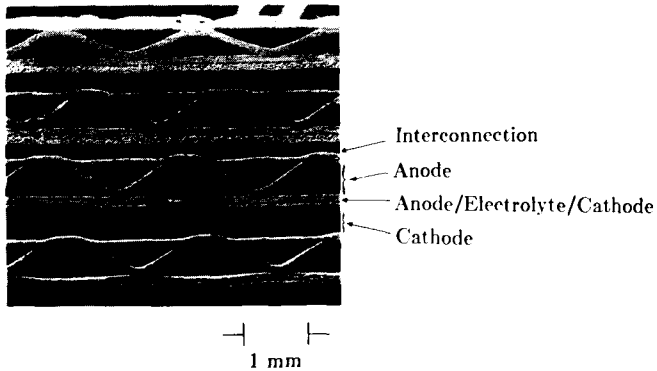


Fig. 4. Four-cell Monolithic Fuel Cell Array.

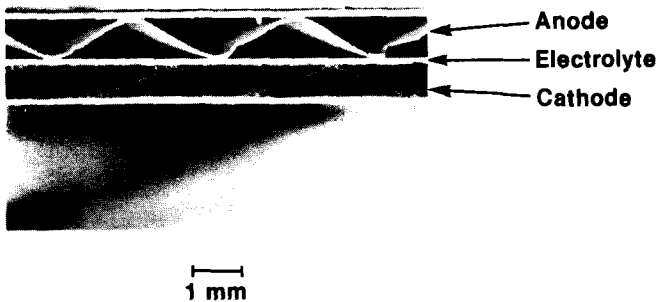


Fig. 5. Cut-away View Showing Cross-flow Gas Channels.

mance, as shown in Fig. 2. In addition, a slight improvement is desired in matching the firing shrinkage in order to reduce the incidence of cracks in the electrolyte and interconnection layers, as shown in Fig. 5. The cracks allow fuel and oxidant gas to mix. The mixing is the principal limitation on open circuit performance of the array. The internal resistance of the array is similar to the first cells tested.

ACKNOWLEDGEMENT: Work supported by the U.S. Department of Defense under Defense Advanced Research Projects Agency.

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REFERENCES

1. D. C. Fee, R. K. Steunenberg, T. D. Claar, R. B. Poeppel, and J. P. Ackerman, "Monolithic Fuel Cells," 1983 National Fuel Cell Seminar Abstracts, Courtesy Associates, (1983) p. 74.
2. S. Nagata, Y. Ohno, Y. Kasuga and H. Sato, "Development of High Temperature Solid Electrolyte Fuel Cell at Electrotechnical Laboratory," 1983 National Fuel Cell Seminar Abstracts, Courtesy Associates, (1983) p. 165.

FABRICATION OF A SOLID OXIDE FUEL CELL MONOLITHIC STRUCTURE*

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The monolithic fuel cell structure is a honeycomb-like structure with gas-flow passages built into the fuel and oxidant electrodes. The structure is comprised of the four solid-oxide fuel cell materials: electrolyte, anode, cathode, and interconnection. The gas channels in the electrodes have characteristic dimensions on the order of 1 to 2 mm.

The Mod 1 design⁽¹⁾ consists of alternating layers of anode/electrolyte/cathode composite, which is corrugated, and cathode/interconnection/anode composite which is flat. Fuel and oxidant flow in alternate sections of the corrugation on opposite sides of the anode/electrolyte/cathode composite. This design provides a high power density because it has high electrolyte surface area per unit volume; however, the manifold arrangement for this design is relatively complex. The Mod 0 design⁽¹⁾ consists of alternate flat layers of anode/electrolyte/cathode composites and cathode/interconnection/anode composites separated by corrugated anode and cathode layers to provide the fuel and oxidant flow passages. The anode and cathode corrugations are oriented at 90° apart to allow simple fuel and oxidant manifold design. The objective of this work is to develop the processes for fabrication of the Mod 0 Monolithic Fuel Cell, and to fabricate the first working fuel cells of this design.

Description of Design

In the design of the Mod 0 Monolithic Solid Oxide Fuel Cell, the electrolyte layer is fabricated as an anode/electrolyte/cathode composite tape, and the interconnection layer is nominally fabricated as a cathode/interconnection/anode composite tape. The early models of the monolithic fuel cell have been fabricated using a single tape of interconnection rather than the cathode/interconnection/anode composite. The electrode tapes are corrugated to provide gas flow passages, and these corrugations are oriented 90° apart to allow manifolding. The gas manifolds may be applied in a simple manner by placing the fuel inlet and outlet manifolds on opposite sides of the monolithic structure. Likewise, the air inlet and outlet manifolds are located on opposite sides of the structure and rotated 90° from the fuel manifolds. This simple arrangement allows rapid testing of the first generation of monolithic fuel cells and results in a small sacrifice in performance from the Mod 1 design.

Description of Fabrication Process

All of the fuel-cell components are fabricated by tape casting⁽²⁾. Tape casting has been used for many years to form thin, uniform ceramic sections, particularly in the electronics industry. Products including ceramic capacitors, solid state chip substrates, etc, have been successfully fabricated using this technology. Tape casting is a process

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which uses a doctor blade to distribute a dispersed ceramic slip uniformly over a casting surface such as glass. The solvents in the slip are evaporated and the ceramic particles and binder remain in a thin, coherent layer called a tape. The slip is formulated to allow the tape to be easily stripped from the casting surface and to remain flexible for ease of handling. After stripping, the tape is stored either as a roll with a separator to prevent the tape from sticking to itself or it is stored flat between sheets of paper or other suitable separator. When composite tapes such as the anode/electrolyte/cathode tapes are made, they may be cast either by making sequential passes over the same casting surface using the three materials, or a special doctor blade may be used having three or more compartments for the separate slips and three or more separate blades to distribute the slips in sequence. Other fabrication methods include various combinations of spray coats and tape-cast layers. The composite tapes that have been used to make the monolithic fuel cells have been cast in sequential passes over the same substrate with drying time between passes and by combinations of spraying and tape casting.

The anode and cathode tapes are corrugated using a mold that was designed to provide the desired corrugation pitch and amplitude. The tape is laid on the bottom half of the mold, and the top half is moved stepwise from one end of the tape to form the corrugated shape. After the electrode tapes are corrugated and all tapes are cut to size, they are stacked with alternating interconnection and electrolyte layers in the proper sequence and with the proper orientation to form the fuel-cell stack. Figure 1 shows this stacking process in exploded view. The electrode tapes are shown off to the sides in their flat condition prior to corrugation. One repeating unit is shown with the interconnection tape on the bottom, then the corrugated anode, the anode/electrolyte/cathode composite, and the corrugated cathode on top. This unit is repeated as many times as desired to form the fuel-cell stack. The top of the stack is finished off by adding another interconnection tape as a termination.

After the stack has been assembled, it is heated, under restraint, through the firing process. The binder burn-out step is critical, and care is taken to assure that the binder is removed from the tapes very slowly. Excessive binder burn-out rate is likely to cause delamination of the composites, formation of blisters in the tapes, etc. After the binder burn-out stage, the stack is heated rapidly to the sintering conditions, then cooled to room temperature. Figure 2 shows an example of a four-cell stack that was fabricated with this procedure. The structure is flat, well bonded, and free of visible cracks. The corrugations appear open and well formed, and the edges are relatively free of curling and other distortions.

Structural Examination

After fabrication, the stacks are examined by several methods including visual, radiography, and ceramography. In some cases, in order to facilitate manifolding, the edges of the stacks are cut off using a slow speed diamond saw and ethanol lubricant. These edge trim pieces are examined microscopically to determine the number and severity of defects. Figure 3 is an example of such a trim piece. In this case, the cut was made parallel to the air electrode and perpendicular to the fuel electrode corrugations. The corrugations that are visible are the fuel electrode

while the air electrode appears as a single, straight section. In general, this fuel cell has a good appearance. The corrugations are well formed, the interfaces are well bonded, and few cracks are present in the structure. This structure is typical of the monolithic fuel cell structures currently being fabricated. While the structure is not defect free, the number and severity of the defects allows the fuel-cell stack to perform at a level above the current performance goals.

An important evaluation tool used to examine the fuel-cell stacks for integrity is x-ray radiography⁽³⁾. The stacks are radiographed using a very low energy x-ray to match the low-energy k-absorption edge of zirconia. Figure 4 is a photograph of an x-ray negative from a typical stack. The checkerboard pattern results from the crossed corrugation pattern. As the x-rays penetrate the corrugated structure vertically, the path length through solid material is longer in the sloping sides of the corrugations than through the peaks and valleys. Thus, a sort of sine-wave variation in intensity occurs in the x-ray negative. These sine-wave variations are oriented at 90°, thus forming the checkerboard pattern.

The radiograph appears defect free at this magnification because the defects which are present are very small. Examination of these radiographs at 40x magnification allows detection of very small cracks of the order of 5 to 10 μm . To minimize or eliminate these cracks, it is necessary to closely match the sintering shrinkage of the four materials, to match the thermal expansions of the four materials as nearly as possible, and to design the structure to be flexible enough to accommodate some mismatch.

Conclusions

A process has been developed to fabricate solid oxide fuel cells in a monolithic structure with cross-flow design. The process uses tape-casting to form the fuel-cell components, and the gas flow channels are formed by corrugation of the electrode tapes. This fabrication process has been shown to be effective in producing relatively defect-free structures that have exceeded the performance goals. Ceramographic and radiographic methods have been used to examine the fuel cells to determine the number and severity of defects. These examination methods have been successful in detecting very small defects and have been used to screen those fuel cells which should be tested.

References

1. D. C. Fee, et al, "Monolithic Fuel Cells", National Fuel Cell Seminar Abstracts, pg 74, November 13-16, 1983.
2. G. Y. Onoda, Jr., "Ceramic Processing Before Firing," John Wiley & Sons, New York, pp 411-448, 1978.
3. W. A. Ellingson, R. A. Roberts, E. Segal, and B. Van Pelt, "Non-Destructive Evaluation Methods Applied to Solid Oxide Fuel Cells", This Conference, Poster Session, October 27, 1986.

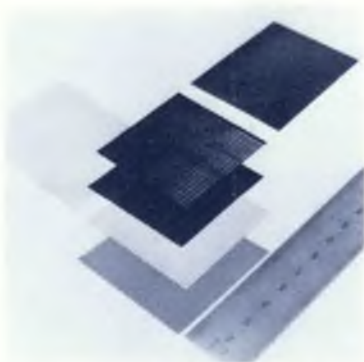


Figure 1. Exploded view of Solid Oxide Fuel Cell assembly. Electrodes shown before and after corrugation.



Figure 2. Sintered four-cell stack. Flat, well bonded structure free from visible cracks.

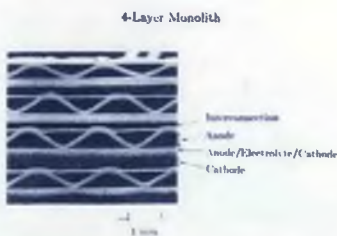


Figure 3. Edge section of four-cell stack cut across fuel electrode corrugations and parallel to air electrode corrugations.

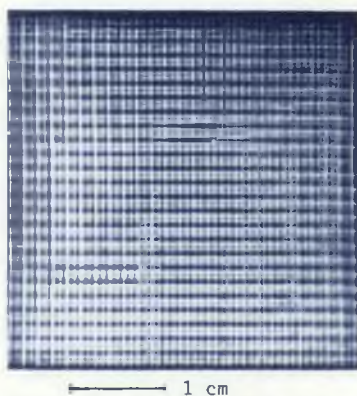


Figure 4. Radiograph of typical two-cell stack. Bright spots are alundum particles.

OXIDE ELECTRODES FOR SOLID OXIDE FUEL CELLS

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State of the art solid oxide fuel cells (SOFC) use different materials metals as electrodes, electrolytes and current interconnections, i.e. chromites, manganites, zirconates, metal-composites and nickel. These materials exhibit different properties unless modified, may require different, multiple-step fabrication process conditions and are susceptible to degrading chemical and electrochemical interactions.

High-temperature oxides materials based on rare-earth (RE_xO_y) stabilized ZrO_2 (or HfO_2) are being studied as advanced SOFC electrode and interconnection materials. The objective is to develop high-electronically conducting oxide materials with thermal and fabrication characteristics similar to the solid electrolyte. Ionically conducting Y_2O_3 or RE_xO_y stabilized ZrO_2 (HfO_2) solid electrolytes are made electronically conducting with additions of other oxides, e.g., In_2O_3 , with structures similar to the fcc electrolyte. These related structures may provide: 1) thermal expansion match with the electrolyte, 2) simultaneous fabrication of electrode/electrolyte as integral cell component, 3) compositions which minimize material interactions between SOFC components, and 4) improved electrode/electrolyte reaction rates. These same materials may also be used as current connections for similar reasons.

This paper describes the research and development of materials based on the ZrO_2 - PrO_2 (RE_xO_y)- In_2O_3 system as electrodes and current interconnections for SOFC. The electrical transport and thermal properties are described in relationship to structure, phase equilibria and composition. Some compositions containing HfO_2 which are isomorphous with the ZrO_2 systems are also discussed.

Fabrication - The mixed oxides were prepared by coprecipitation and air sintered at 1823K. Composite discs of dense Y_2O_3 (RE_xO_y) stabilized ZrO_2 (HfO_2) solid electrolyte sandwiched between porous electrode materials were fabricated for electrochemical testing.

Phase Equilibria - A phase diagram for the ZrO_2 - PrO_2 - In_2O_3 at 1823K in air was developed as a base for electrical transport, thermal and electrochemical property studies, Figure 1 (1). (PrO_2 is used for actual $\text{PrO}_{1.83}$ in this report for convenience.) The two and three component phase fields containing the bcc In_2O_3 solid solution (B) with 10% PrO_2 + ZrO_2 , the $\text{Pr}_2\text{Zr}_2\text{O}_7$ pyrochlore (P) and the fcc In_2O_3 stabilized ZrO_2 (F) (all percentages are in mole%) are considered most important since these compositions and structures represent the best match of thermal, electrical and structural properties with the Y_2O_3 stabilized ZrO_2 electrolyte. A similar phase diagram was

**$\text{In}_2\text{O}_3\text{-PrO}_2\text{-ZrO}_2$ Phase
Diagram (1823K)**

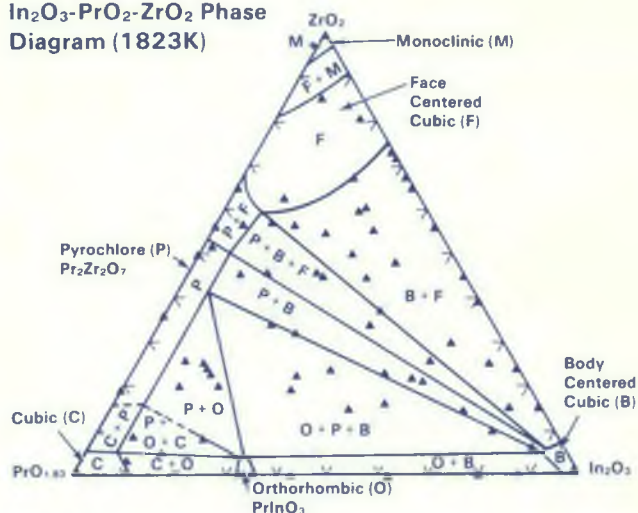


Figure 1. $\text{ZrO}_2\text{-PrO}_{1.83}\text{-In}_2\text{O}_3$ Phase Diagram (1823K)

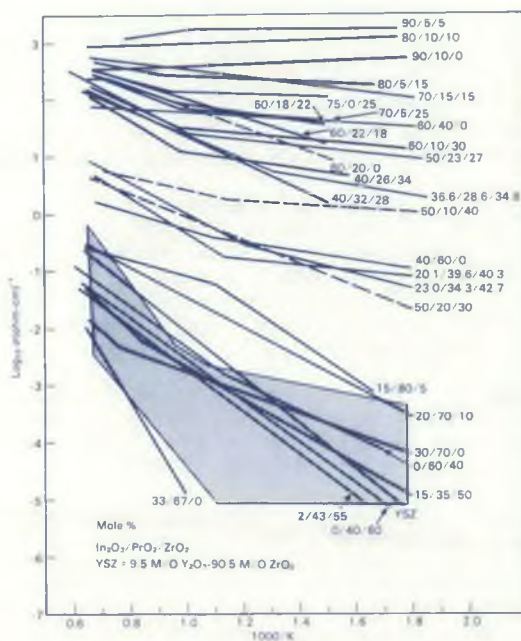


Figure 2. Electrical Conductivity of $\text{In}_2\text{O}_3\text{-PrO}_{1.83}\text{-ZrO}_2$

developed for the isomorphous $\text{ZrO}_2\text{-PrO}_2\text{-In}_2\text{O}_3$ system, the only significant difference being the formation of an $\text{In}_2\text{Hf}_2\text{O}_7$ rhombohedral phase on the $\text{HfO}_2\text{-In}_2\text{O}_3$ binary (2).

Electrical Conductivity - The dc electrical conductivities (σ) in air to 1583K $\text{ZrO}_2\text{-PrO}_2\text{-In}_2\text{O}_3$ vary significantly and are directly related to the oxide composition, structure and phases, Figure 2. The highest electrical conduction is associated with the bcc In_2O_3 solid solution. The σ decreases with decreasing bcc phase in the fcc-bcc, bcc-P and fcc-bcc-P phase fields, Figure 3. The fcc-bcc compositions exhibit the highest σ with the lowest bcc concentration. The σ are near those for the $\text{La}(\text{Sr})\text{MnO}_3$ and $\text{La}(\text{Sr})\text{CrO}_3$, Figure 3. The electrical conductivity of some compositions can also be increased by 2 to 5 times with the small additions of another RE_xO_y , such as Yb_2O_3 , especially for isomorphous bcc-fcc HfO_2 structures (2).

Seebeck Coefficients - The Seebeck coefficients in air for the fcc-bcc compositions high in bcc are negative indicating an n-type semiconductor. As the fcc phase increases, an n- to p-type transition occurs near 800-900K which is consistent with increasing ionic conduction by oxygen ion vacancies similar to Y_2O_3 stabilized ZrO_2 .

Transference Numbers - The ionic transference number (t_i) were determined for some fcc-bcc compositions to 1275K in high oxygen pressures. Conduction in fcc $\text{In}_2\text{O}_3\text{+PrO}_2$ stabilized ZrO_2 is >99% ionic. As the bcc phase increases to 30 and 60%, t_i decreased to 0.9 and 0.0003 with σ at 1273K of 3 and 250 (ohm-cm)⁻¹, respectively. For $0.21\text{In}_2\text{O}_3\text{-}0.39\text{PrO}_2\text{-}0.39\text{HfO}_2\text{-}0.01\text{Yb}_2\text{O}_3$ between 1073 and 1223K, t_i was <0.01 with σ at 1223K of 0.16 (ohm-cm)⁻¹. In the $\text{ZrO}_2\text{-PrO}_2\text{-In}_2\text{O}_3$ system, the t_i can be varied with composition until a substantial ionic transport exists, potentially improving oxygen adsorption and charge transfer rates at the electrode/electrolyte interfaces.

Thermal Expansion - The thermal expansion in air for the bcc-P and bcc-fcc compositions are close to 10 (in $10^{-6}/\text{K}$) reported for stabilized ZrO_2 . The coefficient of thermal expansion of the bcc phase is 9.2 and increases with increasing fcc or pyrochlore structures. The bcc-P phases increase to 9.6 for a 50% composition. The fcc-bcc compositions increase linearly from 9.3 to 10.2 for 20 and 69% fcc phase, respectively.

Thermal Stability - The bcc-B and bcc-fcc compositions are stable at 1473K in air at atmosphere pressure. Weight losses are within experimental error (0.01%). The bcc phase is not stable at 1273K in a reducing atmosphere of 4% hydrogen-96% argon.

Electrochemical Testing - The interactions between $\text{ZrO}_2\text{-PrO}_2\text{-In}_2\text{O}_3$ and Y_2O_3 stabilized ZrO_2 were determined during electrochemical testing using a sintered electrode/electrolyte sandwich. For example, a cell with a fcc-bcc porous $0.3\text{In}_2\text{O}_3\text{-}0.3\text{PrO}_2\text{-}0.35\text{ZrO}_2$ cathode operated in air and 5% H_2 for 96 hours at 1273K without materials interaction. The cell produced 10 mA with a density near

Conclusions

o Highly electronically conducting oxides based on $\text{ZrO}_2(\text{HfO}_2)\text{-RE}_{x-y}\text{-In}_2\text{O}_3$ have been developed as cathodes and possibly current interconnections and can be fabricated integrally with Y_2O_3 stabilized ZrO_2 electrolyte.

o The $\text{ZrO}_2\text{-Pr}_{0.83}\text{-In}_2\text{O}_3$ phase diagram at 1823K was developed and the electrical transport and thermal transport properties were related to the compositions and structures of this diagram. The bcc In_2O_3 solid solution is the major conducting phase.

o Electrical conductivities as high as those for the lanthanum manganites and chromites now used in SOFC can be achieved.

o The two phase fcc-bcc compositions provide the best electrical, thermal and electrochemical properties as SOFC cathodes with sufficient electrical conductivity, good thermal expansion match with electrolyte, and significant ionic conductivity for improved electrode/electrolyte reactions.

References:

1. J. Lambert Bates and Curtis W. Griffin, "Oxide Electrodes for High-Temperature Fuel Cells", Fossil Energy Materials Program, Quarterly Progress Report, December 31, 1985, ORNL/FMP-86-1, (1986) pp. 105-124.
2. J. Lambert Bates and David D. Marchant. *Ibid*, December 31, 1983, ORNL/FMP-84-1 (1984), pp 483-500.

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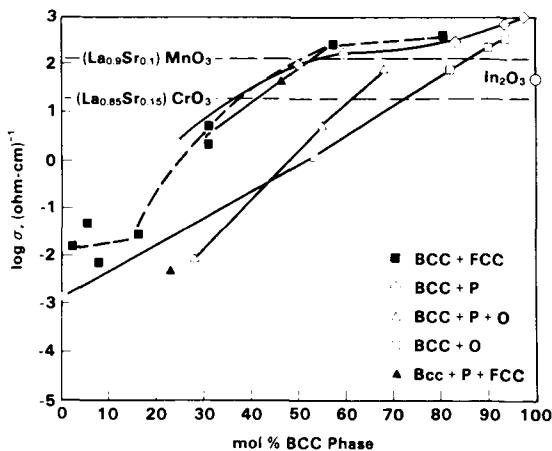


Figure 3. Electrical Conductivity at 1273K

NONDESTRUCTIVE EVALUATION METHODS APPLIED TO SOLID OXIDE FUEL CELLS*

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Introduction

The ANL solid oxide fuel cell (SOFC) design yields a rather complex structure after assembly. Therefore, for the greatest reliability, non-destructive evaluation (NDE) inspection should be conducted on individual laminates or subassemblies (e.g., 3-4 stacked cells). As with multilayer ceramic capacitors, detection of both delaminations and cracks is important, and NDE methods must be able to yield information as a function of depth into the SOFC as well as plan view information. "Conventional" radiography yields X-ray shadowgrams of an object and does not provide any information on the location of a defect relative to the thickness (z-axis) of the sample. Computed tomographic imaging, on the other hand, yields information on the z-axis location of defects, but presently not at a high spatial resolution.

Other NDE methods, such as acoustic emission, are being studied in order to help determine desirable firing schedules (temperature range rates, hold times, etc.) for best reliability. This paper presents recent results on the application of several NDE methods that are being developed as part of the ANL SOFC program.

Inspection of Laminated Tapes: Low-kV Radiography

The primary low-kV radiographic methods being developed for inspection of three-layer composite tapes are contact, projection, and real-time radiography with both standard and microfocus (<20- μ m focal spot) X-ray heads. Both green and sintered composite tapes have been studied.

Figure 1 is an example of a low-kV contact radiograph of a green three-layer composite. The image was obtained by use of a molybdenum anode X-ray head with an aluminum window and 10- μ m focal spot. The accelerating voltage was 20 kV and the filament current was 4.2 mA. The space between the X-ray head and the object was filled with helium. Both voids and nearby features that appear to be fissures are detected. As noted earlier, conventional contact (or projection) radiographs give no information on the z-axis location of defects. In order to establish the plane of the voids, a scanning electron micrograph (SEM) was taken of a cross section through the green ceramic composite of Fig. 1. The resulting SEM image (Fig. 2) shows that the voids are at the cathode-electrolyte interface. In addition, the voids appear to be reasonably large, i.e., 50-100 μ m in diameter.

Figure 3 is a low-kV radiographic image of a sintered composite, obtained under the same conditions as for Fig. 1. Extensive porosity was again detected. Destructive analysis at an oblique angle (see Fig. 4) shows that the porosity again occurs at the cathode-electrolyte interface, with void sizes of $\sim$ 50-100 μ m.

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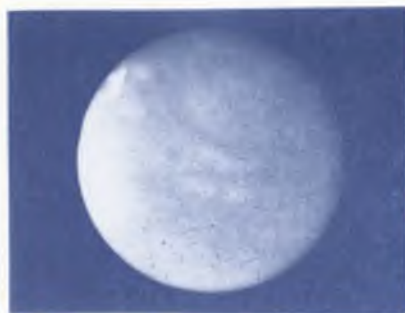


Fig. 1. Low-kV Radiographic Image of Green Anode-Electrolyte-Cathode Composite.

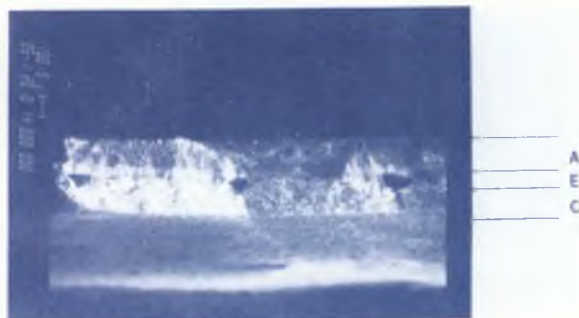


Fig. 2. SEM Image of Cross Section Through Composite of Fig. 1.



Fig. 3. Low-kV Radiographic Image of Sintered Composite.

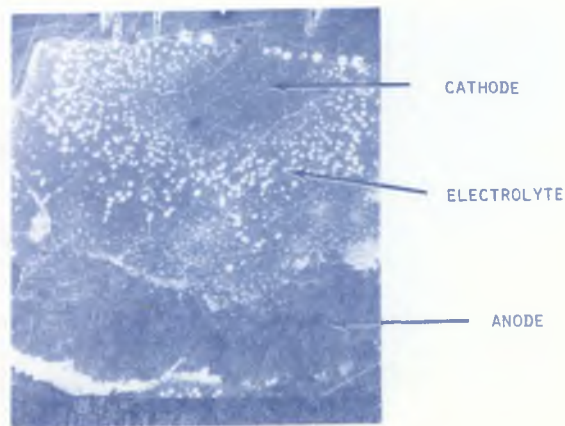


Fig. 4. SEM Image of Tapered Cross Section Through Sintered Composite of Fig. 3.

Inspection of Complete Subassembly: Computed Tomographic Imaging

Unlike the radiographic imaging methods described above, computed tomographic (CT) imaging¹ provides cross-sectional images, and thus information on the z-axis location of defects. CT imaging studies have been conducted on a two-cell (four-layer) configuration. The CT scanner used in these studies was a first-generation device with a radioactive source ¹⁹²Ir in this case. A CsF scintillator, hermetically sealed to a photomultiplier tube, was used as the detector. The fuel cell was placed on a turntable mounted on translatable stage. The turntable and stage were driven by individual stepper motors with absolute positions continuously monitored by shaft angle encoders. Tomographic image reconstruction was executed on an LSI-11/23 with the assistance of an array processor. After reconstruction, images were displayed on a graphics screen, and photographed off the screen.

Figure 5 shows a schematic diagram of the two-cell configuration used in this exploratory test and one of the CT images obtained. The image was reconstructed from 360 projections taken over 180°. A 256x256 matrix with a pixel size of 100 μ m was used. Unbonded areas, lack of adequate channel definition, lack of uniform channel size, and apparent differences in material density are clearly seen. The potential of CT imaging for visualization of a variety of defects in fuel cell subassemblies is thus demonstrated.

Detection of Crack Formation During Firing

If radiographic imaging or visual inspection reveals cracks in the fuel cell stack, it is of interest to know when these cracks developed in the final sintering process, e.g., during heat-up or cool-down. Heat-up and cool-down schedules could then be modified to minimize cracking. Acoustic emission² (AE) is a passive monitoring method well suited to the detection of incipient cracking in inaccessible locations such as the inside of a furnace. Our program has included efforts towards implementing AE methods to detect cracking during sintering of fuel cell arrays. A schematic of the experimental arrangement used for AE monitoring is shown in Fig. 6.

Figure 7 shows a heat-up and cool-down schedule and the accompanying AE activity. The AE activity was detected in only three temperature regions. The relative strength of the detected emissions can be assessed by using amplitude distribution analysis. The amplitude distributions obtained at the ten points shown in Fig. 7 are presented in Fig. 8. The data, as presented, show the changes in distributions from the previous measurement. The amplitude distribution plots show a high level of AE activity at points 8, 9, and 10. The relative strength of the pulses increases near point 10. These initial findings suggest that AE holds potential for tracking crack formation during fuel cell fabrication.

1. G. T. Hermann, Image Reconstruction from Projections, Academic Press, New York (1980).
2. A. A. Pollock, "Acoustic Emission Amplitudes," J. Nondestr. Test. 10, 264-269 (1973).

Poor Channel Definition and
Nonuniform Channel Size

Crack

Apparent Differences in
Average Material Density
for These Layers

Delamination

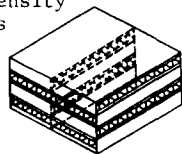


Fig. 5. Schematic Diagram of Four-Layer Fuel Cell
Used for Initial Gamma-Ray (^{192}Ir) CT Scan
Test and Resulting Reconstructed Image.

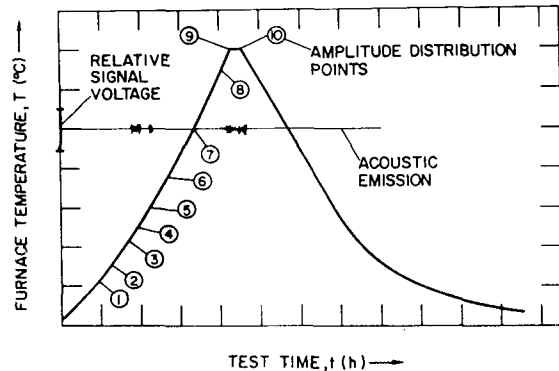


Fig. 7. Acoustic Emission Activity during
Heat-Up and Cool-Down of the Fuel
Cell Stack.

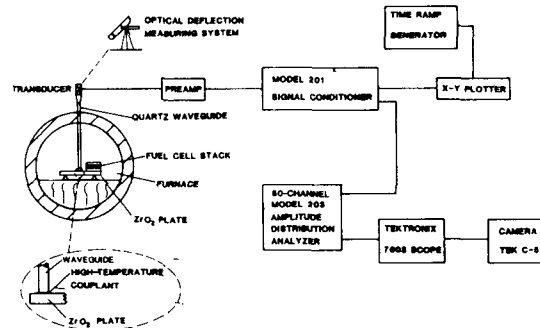


Fig. 6. Schematic Diagram of Acoustic
Emission and Deflection
Detection System.

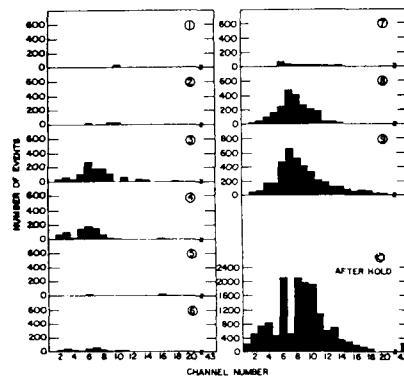


Fig. 8. Acoustic Emission Amplitude
Distributions Measured at Indicated
Points on Time-Temperature Plot
of Fig. 7.

CHARACTERIZATION OF MONOLITHIC FUEL CELL COMPONENTS

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Electrochemical characterization of materials and components is an important part of the monolithic fuel cell development effort. The high power density of the monolith depends on achieving low dissipative losses in the bulk materials and at interfaces between materials.

The bulk electrical/ionic conductivity of all cell materials has been determined over the range of temperatures (800-1000°C) and oxygen pressures (0.2 to 10^{-18} atm). Complex impedance methodology was utilized to determine the conductivity of the four fuel cell components as a function of temperature, which is given in Fig. 1. All measurements were taken with the components in the same environment as it sees in the fuel cell during operation. All components were fabricated by the same methods used in the development of the monolithic fuel cell.

A series of AC impedance studies has been performed on various three-layer (anode/electrolyte/cathode) composite samples. The studies were performed using a special vessel designed and built in this laboratory. The manifold in the vessel allowed for separate atmospheres to be established on each side of the composite. The fuel environment on the anode side was a mixture of H_2 and H_2O ($H_2/H_2O=97/3$) which produced a partial pressure of oxygen equal to 0.4×10^{-11} at 1000°C. The oxidant on the cathode side was air. Platinum screen current collectors were attached to the samples with platinum paste.

A complex impedance diagram for one of the composites is given in Fig. 2. The size of the circular arc (approximately 0.7 ohms on the graph) when compared to its high frequency intercept of the real component axis (approximately 0.1 ohms on the graph) indicates that the sum of the interfacial resistances is relatively large when compared to the bulk resistance of the materials in the fuel cell. It was found that the sum of the interfacial resistances for the fuel cell could be varied more than two orders of magnitude (0.238-33.6 ohm cm^2) by varying the particle size distribution in the electrodes next to the interfaces. The size of the individual interfacial resistances has been determined through the use of a reference electrode in the test system. Measurements indicate that the anode/electrolyte and cathode/electrolyte interfacial resistances are of the same order of magnitude.

Both a "contact resistance" at the interface and kinetic effects can give rise to an interfacial resistance. The two are connected in that an improvement in one will improve the other. Linear I-V curves over a wide range of current densities were obtained in recent DC polarization studies on the fuel cells. This indicates that kinetic effects are not significant.

Cell tests show that diffusional effects in the electrodes are unimportant as long as their porosity is greater than 10%. This has been confirmed through AC impedance studies and DC polarization studies. Theoretical

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- 2 -

calculations also indicate this for the 25 to 50 micrometer thick electrodes. A typical cross-section of a three-layer composite is given in Fig. 3. The porosity of the anode and cathode is well above the 10% minimum. Generally the electrode porosity is between 20% and 50%.

While current densities up to 2.2 amps/cm^2 have been observed, further improvements are possible through reductions in the interfacial resistances.

ACKNOWLEDGEMENT

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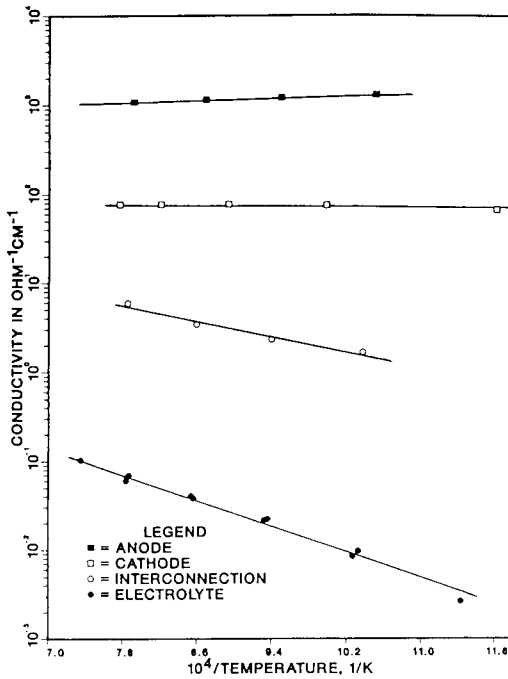


Fig. 1. Conductivity of Individual Solid Oxide Fuel Cell Components.

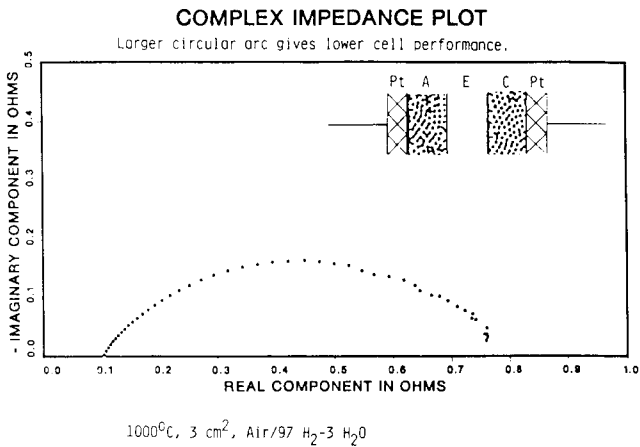


Fig. 2. Complex Impedance Plot of Solid Oxide Fuel Cell.

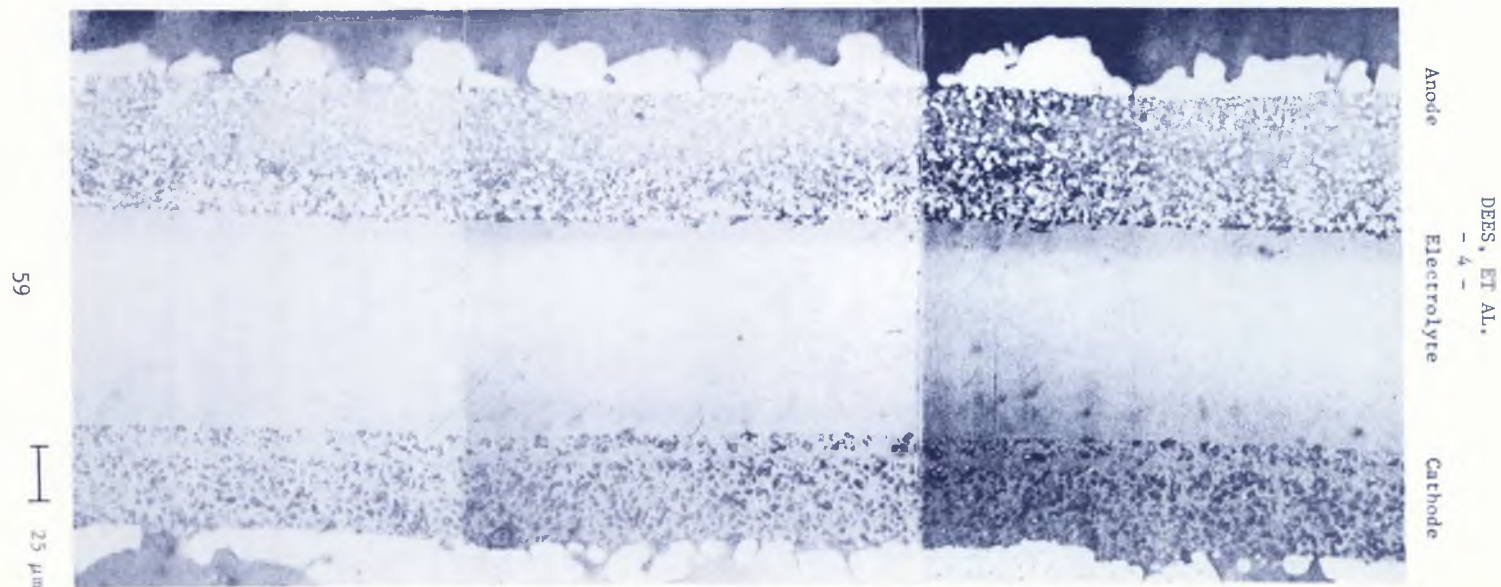


Fig. 3. Typical Cross-section of a Solid Oxide Fuel Cell.

STRESS AND FRACTURE BEHAVIOR OF MONOLITHIC FUEL CELL TAPES

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The design of a solid oxide monolithic fuel cell employs thin ceramic components in a honeycomb structure. The technical challenge is to fabricate a ceramic honeycomb from repeating thin layers of four components - anode, electrolyte, cathode, and interconnection under the same condition. The cathode consists of a porous layer of lanthanum manganite, the electrolyte consists of a dense layer of yttria stabilized (fully) zirconia, the anode consists of a porous layer of fully stabilized zirconia containing nickel (NiO in the green state), and the interconnection consists of a dense layer of lanthanum chromite. During sintering of individual layers the total linear shrinkage strains are approximately equal ($\sim 30\%$). However, when three or more layers are fabricated as a composite, the total shrinkage strain during sintering is found to be considerably less ($\sim 20-25\%$). On closer examination, the shrinkage strain history of the interconnection was found to be significantly different from that of the rest. Similarly, although the coefficients of thermal expansion of the cathode and the electrolyte are closely matched, the anode containing NiO has a slightly higher coefficient of thermal expansion, depending on the NiO content. During the early phase of the program at ANL, cracking was experienced during cooldown after firing if the NiO content in the anode layer exceeded about 30%. The present study was undertaken to analyze the stress and creep behaviors of a three-layer tape due to differential shrinkage strain rates during sintering, and the fracture behavior of a three-layer tape due to thermal stresses generated during cooldown after sintering.

Shrinkage Stress and Strain: For simplicity, consider a three-layer symmetrical tape with the outer layers of thicknesses h_1 and the middle layer of thickness h_2 . The shrinkage strain rates of the outer and the middle layers are denoted by $\dot{\epsilon}_{s1}$ and $\dot{\epsilon}_{s2}$ respectively. Although the shrinkage strain rates can be different, the total shrinkage strains of all the layers are assumed to be equal to $\Delta\epsilon_s$. It is difficult to calculate absolute values of stresses during sintering because, the mechanical properties of the various layers change with time and are unknown at the present. However, the relative values of shrinkage strains and stresses can be calculated using simple thin plate theory if it is assumed that the ratios of mechanical properties of the layers remain approximately constant during sintering. To simulate the sintering of a dense interconnection layer sandwiched between two porous electrodes, it is assumed that the ratio of the modulus of elasticity between the layers $E_2/E_1 = 2$. The creep strain rate of each layer is expressed as a power function of stress with coefficients A_i ($i = 1, 2$) and exponent equal to 1, in keeping with the assumption that the dominant mechanism for creep during sintering is diffusional creep. Figure 1 shows the variation of the composite shrinkage strain as a fraction of the individual layer shrinkage strain for a value of relative shrinkage strain rate equal to 5 (assumed greater than 1 to reflect the higher shrinkage rates observed in the interconnection) as a function of the non-dimensional quantity α_1 defined as

$$\alpha_1 = E_1 A_1 \Delta\epsilon_s / (1 - \nu) \dot{\epsilon}_{s1}$$

where ν is the Poisson's ratio. Note that if the composite shrinkage is to be less than the individual layer shrinkage, then the ratio between the coefficients of the creep equation, A_2/A_1 , has to be less than 0.5 (i.e.,

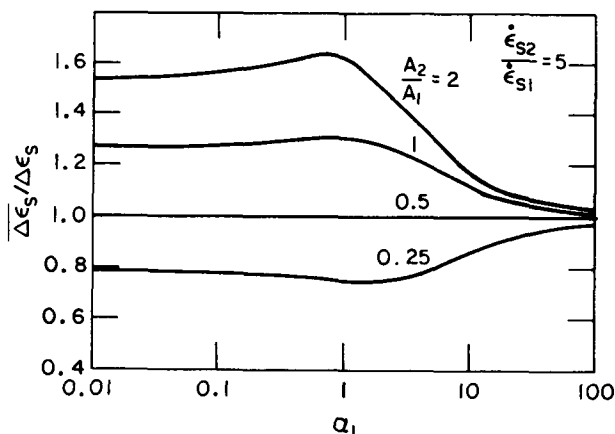


FIGURE 1

Variation of ratio between composite ($\overline{\Delta\epsilon_s}$) and individual layer ($\Delta\epsilon_s$) linear shrinkage strain with α_1 for various values of A_2/A_1 .

the interconnection should be more resistant to creep deformation than either of the electrodes), and α_1 cannot be significantly greater than 10.

Figure 2 shows the effects of thickness ratio on the maximum nondimensional tensile and compressive stresses of the various layers for a given set of values of material parameters, and for a case where the shrinkage rate of the middle layer is 10 times that of the outer layers. Note that both the maximum tensile and compressive stresses in the middle layer can be reduced by increasing its relative thickness. However, such an increase in thickness also increases the maximum stresses in the outer layers.

Experimental data needed to verify these predictions are not currently available, but will be conducted later on in the program.

Thermal Stress and Fracture: The model consists of a three-layer circular disk, with each layer potentially having different thermal and elastic properties. The plate is assumed to be flat and free of stress at the firing temperature at the beginning of cooldown. Stresses are generated in the externally unconstrained plate during cooldown, reaching a maximum at the end of cooldown when the plate is at a uniform temperature (200°C). Stress and fracture analyses of the plate are carried out using small displacement linear elastic theory of plate, and linear elastic fracture mechanics [1]. Fracture toughness properties of the various thin ceramic components are not currently available. A fracture toughness value (1.25 MPa/m) of the electrolyte was deduced by correlating the fracture behavior of symmetrical A/E/A tapes of thicknesses 51 μm with the calculated maximum stress intensity factor. The predictions of the model are compared with experiments on symmetrical (A/E/A) and unsymmetrical (C/E/A) tapes in Fig. 3. The coefficient of thermal expansion of the anode in the experi-

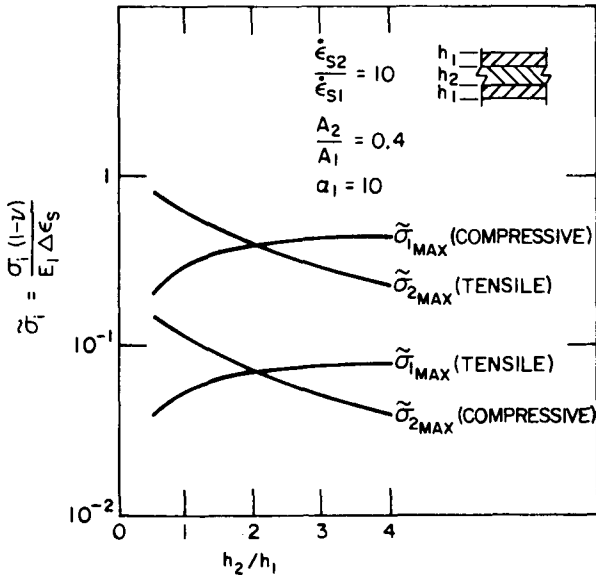


FIGURE 2

Variation of maximum nondimensional tensile and compressive shrinkage stresses in a symmetrical three-layer composite as a function of thickness ratio.

mental tapes were $12 \times 10^{-6}/^{\circ}\text{C}$ in all cases. As is evident from the figures, the predictions are in good agreement with experimental results.

The model also predicts that for a set of given thicknesses of the layers, fracture during cooldown can be avoided by either tailoring the NiO distribution or by increasing the porosity of the anode, as shown in Fig. 4.

Conclusions: A shrinkage stress analysis has shown that a possible explanation for the relatively low linear shrinkage of a composite as compared to that of its components may be the occurrence of creep strains that help relax the stresses generated by differential shrinkage strain rates during sintering.

A model has been developed for the analyses of thermal stress and fracture of a three-layer composite during cooldown after sintering. The experimental results are in good agreement with the predictions of the model. The model also predicts that the fracture behavior of three-layer composites can be improved by tailoring the NiO distribution and increasing the porosity of the anode.

Reference

1. Saurin Majumdar, Terry Claar, and Brian Flandermeyer, "Stress and Fracture Behavior of Monolithic Fuel Cell Tapes," to appear in J. Am. Ceramic Soc.

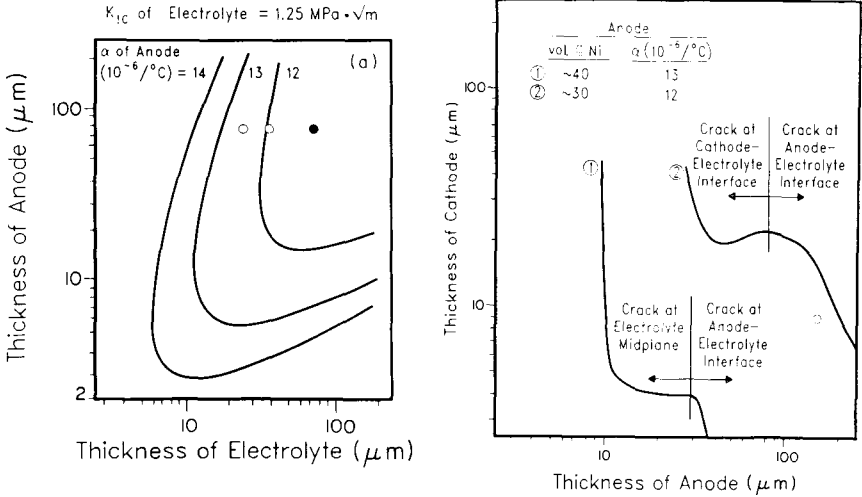


FIGURE 3

Maximum permissible thicknesses of electrodes and electrolyte to avoid cracking of symmetrical anode/electrolyte/anode (left) and unsymmetrical anode/electrolyte/cathode (right) tapes with an electrolyte thickness of $38 \mu\text{m}$. Open symbols represent actual fabricated composites that survived a cooldown after sintering and the filled symbol represents one that cracked.

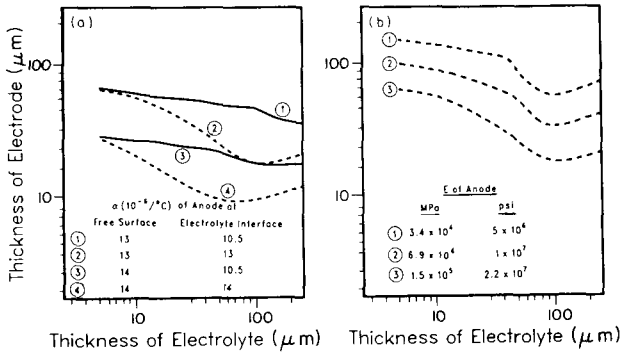


FIGURE 4

Effects of a linear distribution of NiO (i.e., coefficient of thermal expansion) and porosity (i.e., reduced elastic modulus) in the anode on the maximum permissible thicknesses of electrodes and electrolyte to avoid cracking of a composite during cooldown. In the left figure, the interface of the anode with the electrolyte is assumed to contain zero NiO. Dashed lines represent composites with a uniform NiO distribution.

TAPE CASTING HIGH-DENSITY ELECTROLYTE FOR SOLID OXIDE FUEL CELLS*

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Yttria-stabilized zirconia (YSZ) has many applications in high-temperature electrochemistry because of its relatively high oxygen-ion conductivity, good stability, and fabricability. Its use as the oxygen-ion conductor in the monolithic solid-oxide fuel cell depends on its fabricability into high density structures which are very thin yet impermeable to the fuel-cell gases. The objective of this work was to develop a process for fabricating thin, high-density, gas-impermeable YSZ structures. More specifically, the fabrication process must be capable of producing structures on the order of 25 to 100 μm thick with densities greater than 94% of theoretical density, firing shrinkage as low as possible, and room-temperature gas permeabilities less than 10^{-7} cm^2/s . The processes considered for this application included hot rolling, tape casting, and curtain coating. Tape casting was selected on the bases of its advanced state of development and extensive use in other technical areas such as the electronic industry, and its relative simplicity.

Prior studies with alumina⁽¹⁾ and with barium titanate⁽²⁾ have shown that the most important parameters for development of a good tape casting process include the powder characteristics, the dispersant composition and amount, the solvent/binder system, and other process variables. This study was, therefore concentrated on developing the optimum combination of these variables to meet the above performance requirements.

Powders from several suppliers of YSZ were tested to determine the most suitable, and two were selected for further study: 1) Zircar type ZYP, fully stabilized, and 2) Toyo Soda, TZ-8Y. The Zircar powder has a specific surface area in the range of 50 to 65 m^2/g and an ultimate crystallite size of 0.02 to 0.03 μm . The Toyo Soda powder specific surface area is in the range of 20 to 25 m^2/g with ultimate crystallite size of the order 0.1 μm . The agglomerate sizes of these powders were measured after ultrasonically dispersing the powders in distilled water. The Zircar powder had a narrow particle size distribution from 0.1 to 2.5 μm with the peak at 1 μm diameter. The Toyo Soda particle size distribution was broader, ranging from 0.1 to 20 μm with two peaks at 1 and 5 μm .

Good dispersion of the powder in the tape-casting slip is the most important variable for successful tape casting. Several solvent/binder/dispersant combinations were tried during the course of this study. In general, those systems studied included acrylic binders from various suppliers with a variety of organic solvents. Effective dispersants must be soluble in the solvent while forming a strong bond with the YSZ particles. One end of the dispersant molecule normally attaches firmly to the particle while the tail end of the molecule extends into the surrounding solvent. Interaction of the tails from separate particles causes a local increase in energy, thus the driving force is toward separation or dispersion of the individual particles.⁽²⁾ As illustrated in Figure 1, it is important to add

*Work sponsored by the Defense Advanced Research Projects Agency (DOD), under ARPA Order No. 4850.

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a sufficient quantity of dispersant to effectively form the steric hindrance to separate the particles. Suspensions of Zircar powder in solvent were prepared using various quantities of dispersant. These suspensions were vibratory milled for 2 hours, then allowed to settle. The height of the interface between the clear solvent and the suspension was measured as a function of time to determine the settling rate of the smaller suspended particles. For quantities of dispersant below about 40 mg/g YSZ, the settling rate was quite high, while above that level, the dispersion appears adequate.

Sintering aids are often used to improve the fired densities of ceramic bodies. Prior work⁽³⁾ has shown that alumina can act as an effective sintering aid for YSZ, and the mechanism has been proposed to be scavenging of impurity silica from the YSZ and precipitating it in the grain boundaries thus inhibiting grain growth and promoting sintering. A series of tape casting slips were prepared containing increasing additions of alumina (added in the form of aluminum isopropoxide). These slips were processed in the normal fashion, tape cast, sampled and fired. The resulting fired densities and firing shrinkages were measured and plotted in Figure 2 as a function of weight percent alumina. It was found that increasing concentrations of alumina resulted in increased fired density up to a maximum at 0.6 wt%. Further additions resulted in a slight decrease in fired density. The firing shrinkages of the samples increased along with the increasing densities, indicating that the sintering process was improved by improved mass transfer rather than by improved particle packing.

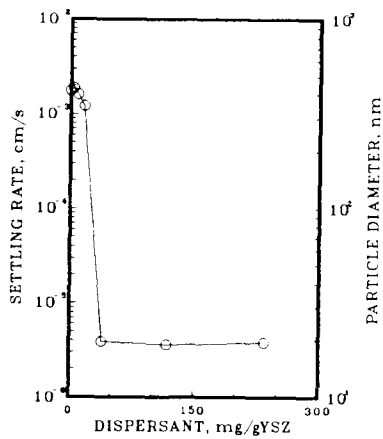


Fig. 1 Effect of dispersant concentration on dispersion in terms of particle settling rates.

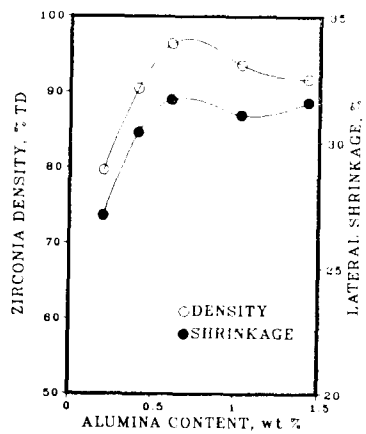


Fig. 2 Effect of alumina as sintering aid on density and shrinkage of YSZ.

One of the objectives of this work was to minimize the firing shrinkage of the YSZ so that distortions of the monolithic structure during firing could be minimized. The approach to this objective was to improve particle packing in the green body. One method to improve particle packing is to use a graded particle size distribution. The Toyo Soda powder can be considered a "coarse" powder with a fairly wide particle size distribution relative to the Zircar powder which has a narrow particle size distribution and is a relatively "fine" powder. These powders were mixed in various proportions and several slips were prepared with increasing total solids loading. The total ceramic content of the slips was increased to the maximum that could be achieved while maintaining a reasonably workable viscosity. Tapes were cast from these slips, samples were fired, and the fired densities and shrinkages were determined. Figure 3 shows the effect of solids loading on the densities and shrinkages that were achieved. Solids loading is expressed here as the ratio of the fired sample weight to the weight lost during firing. All of the samples in this series had fired densities greater than 98% of theoretical density, and the density seems to be a maximum at medium solids loadings. Very high solids loadings may inhibit good particle packing because of the higher viscosity under these conditions. As expected, the shrinkage is an almost linear decreasing function of solids loading. The more closely packed the particles in the green body, the less shrinkage is necessary to achieve theoretical density.

In the solid oxide fuel cell environment, it is important that the YSZ electrolyte layer is impermeable to the fuel and oxidant gases. The requirement of permeability less than 10^{-7} cm²/s is a cross-leakage equivalent to a current loss of 1 mA/cm². A vacuum apparatus was used to measure permeation rates of room temperature air through fired samples of YSZ tapes. The samples were attached to the end of a copper tube with epoxy. The permeability of the epoxy had been previously measured to assure that it was negligible relative to the permeabilities being measured. The vacuum pressure was reduced to about 400 to 500 torr (50 to 65 KPa), the system was isolated, and the rate of pressure rise was measured. The permeability of the membrane was then calculated from the rate of rise. It was found that for YSZ samples having greater than about 92 to 93% of theoretical density, the rate of rise was too small to be measured over a period of 7 to 10 days. Based on the uncertainties of each instrument involved (pressure gauge, barometer, thermometer, standard volume, etc), the smallest permeability measurable was about 1×10^{-8} cm²/s. The porosity in YSZ samples having densities >94% of theoretical is apparently not connected porosity. Samples having densities less than 90% exhibited permeabilities which were easily measurable and were > 10^{-7} cm²/s.

The tape cast YSZ structure was examined both as fracture surfaces and as polished and thermally etched surfaces using the Scanning Electron Microscope (SEM). Figure 4 shows a fracture surface on the left of a YSZ sample which has a density of 94% of theoretical. The photograph on the right is a polished sample which was thermally etched at 1300°C for 30 min. These photographs illustrate the fine-grain, uniform structure that was achieved by this tape casting process. The porosity is isolated, somewhat spherical, and not interconnected as inferred from the permeability data.

Conclusions

This work has shown that high-density, impermeable, thin YSZ structures can be produced by tape casting. The most important parameters in developing the tape casting process were found to be the YSZ powder characteristics, the binder/solvent system, the dispersant which must be compatible with the solvent/binder system, adequate milling to assist dispersion, and the proper solids loading to minimize firing shrinkage.

References

1. G. Y. Onoda, Jr and L. L. Hench, "Ceramic Processing Before Firing", John Wiley & Sons, New York, 1978.
2. Kurt Mikeska and W. Roger Cannon, "Forming of Ceramics", Advances in Ceramics - Vol 9, American Ceramic Society, Columbus, OH, pg 164, (1984)
3. K. C. Radford and R. J. Bratton, Zirconia electrolyte cells, Part 1, Sintering studies, J. Mat'l Sci., 14(1979)59-65.

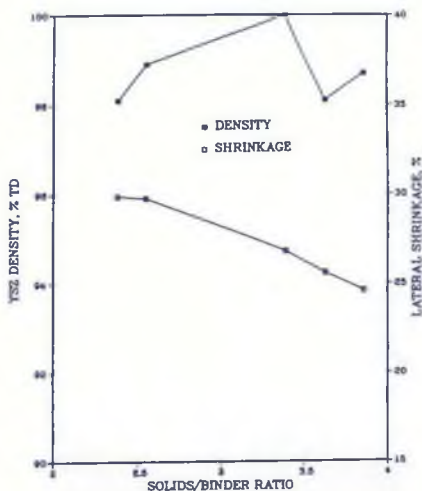
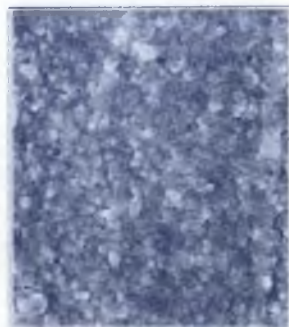


Fig. 3 Effect of solids loading on YSZ fired density and shrinkage during firing.



1 μ m



1 μ m

Fig. 4 Fracture surface (left) of 94% dense tape cast YSZ, and thermally etched surface (right) of 97% dense tape cast YSZ.

INTERCONNECTION DEVELOPMENT FOR MONOLITHIC
SOLID OXIDE FUEL CELLS

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The development of an interconnection layer for the monolithic solid oxide fuel cell (MSOFC) has posed a significant materials development challenge because of the particularly demanding set of electrical, mechanical, and chemical requirements that this material must meet. Previous researchers had identified LaCrO_3 acceptor doped with Mg or Sr as a material that would satisfy these conditions except for the fact that it, like all Cr oxides, will not sinter to high densities in air. The challenge with these materials is that the predominant method of mass transport during firing is an evaporation-condensation mechanism which leads to coarsening of the original particles without densification. To obtain high densities, it has been found necessary to fire LaCrO_3 to temperatures in excess of 1650°C in a hydrogen atmosphere. However, these conditions are unacceptable for fabrication of the other cell components for two reasons. One is that interdiffusion of the cell components will become significant at such high temperatures and the other is that the LaMnO_3 cathode will decompose to La_2O_3 and MnO in the hydrogen atmosphere. Given the favorable properties of LaCrO_3 (thermal expansion characteristics, electrical conductivity, and chemical stability under reduction), efforts were concentrated on developing some method of sintering it at $<1600^\circ\text{C}$ in a relatively oxidizing atmosphere ($\text{P}_{\text{O}_2} > 10^{-5}$ atm) rather than developing a new material.

A survey of the literature implied that the most promising approach to enhancing the sinterability of LaCrO_3 was to substitute transition metal cations (i.e., Mn, Fe, Ni) for Cr. A possible alternative would be to find a second-phase addition that would promote liquid phase sintering. Accordingly, the initial approach was to perform a survey of potential dopants by preparing a series of LaCrO_3 's doped with the desired cations and then to use high-temperature dilatometry to directly measure the firing shrinkage vs. temperature. Any promising sintering aids found by this survey would then need to be tested for their effect on the other required characteristics, such as electrical conductivity and stability under reducing conditions.

Samples were prepared by a "liquid mix" technique (1). Nitrate solutions of the desired cations were prepared and mixed with ethylene glycol-citric acid. This solution was then slowly evaporated down to a solid and the oxide was formed by a low-temperature calcination at about 800°C . The function of the ethylene glycol-citric acid is to maintain homogenous mixing through the evaporation process and ensure a uniformly doped final oxide. After calcination, these powders were vibratory milled for 16 h, mixed with 2-3 wt % binder,

and then spray dried to reduce agglomeration and obtain a fine powder suitable for dry pressing. Small sample pellets approximately 1.5 cm long by 0.7 cm in diameter were pressed and their shrinkage as a function of temperature measured in a high-temperature (1550°C) differential pushrod dilatometer (supplied by Theta, Inc.).

Figure 1 shows some typical firing shrinkage results; the data are displayed as theoretical density vs. temperature, which was increased at a constant rate of 200°C/h. As can be seen from this plot, the substitutional doping of transition metal cations (Mn substituted for the Cr in this case) does indeed increase densification, but not sufficiently for the purpose of fabricating an interconnection for the proposed monolithic fuel cell.

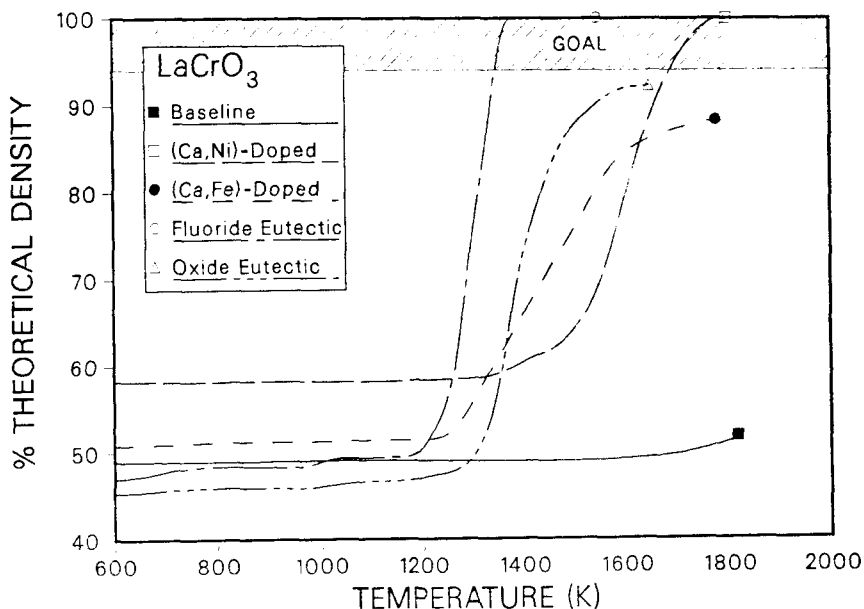


FIGURE 1

Plot of theoretical density vs. temperature for various doped LaCrO_3 's compared to the baseline $\text{LaCr}_{0.9}\text{Mg}_{0.1}\text{O}_3$. Density is required to be >94% of theoretical.

Accordingly, attention was turned to alternative methods of enhancing densification by using deliberately added second phases which could be separately formulated and added to the

base $\text{La}(\text{Cr},\text{Mg})\text{O}_3$ in low quantities. Although the selection of such a second phase is almost an empirical process because of the wide variety of factors concerned (i.e., wetting phenomena, chemical reactions, solubilities, etc.), two general approaches were employed, both of which used the premise that the additives should be as chemically similar to the basic LaCrO_3 as possible. One approach involved searching the literature for a low-melting ($1000\text{--}1200^\circ\text{C}$) oxide compound or eutectic that could be added to LaCrO_3 . The other approach involved an attempt to find a more unconventional sintering aid, such as a carbonate precursor that would melt to promote densification and then decompose to form LaCrO_3 or a benign second phase. Of the many candidates that were considered, two additives proved especially interesting as shown in Fig. 1. One is a low-melting oxide eutectic whose components are stable under the expected oxygen potential gradient. The second approach was to add 8-10 wt % of a (La or Y)-Mg fluoride mixture to the basic LaCrO_3 . As shown in Fig. 1, remarkable improvement in densification is found with either of these additives. Within the limits of x-ray diffraction, the fluoride second-phase additions do not remain after firing.

Initial attempts to use these approaches to fabricate an acceptable three-layer anode/interconnection/cathode composite have been successful. It was noted that these sintering aids do affect the adjoining electrode layers by generally increasing the density and grain size. This effect produces unexpectedly large firing shrinkages for the electrodes in the composite, which can cause warping, curling, or cracking. Considerable work has been done to optimize the quantities of sintering aids present, the particle size distributions, and the fabrication techniques so as to control the dimensional stability of these composites.

As noted earlier, just increasing the sinterability of these materials may not be sufficient; the thermal expansion, stability, and electrical conductivity of the new materials must still be acceptable. Figure 2 displays the results of thermal expansivity testing for the two new proposed materials as compared to the baseline LaCrO_3 ; clearly, this property is not significantly affected by the sintering aids. Although space does not permit a complete discussion of the TGA or electrical conductivity results, initial work has revealed no immediate problems in these areas.

In summary, although the use of such sintering aids in the MSOFC application has only just begun to be thoroughly investigated, initial results are very encouraging in terms of improved sinterability, apparent stability under reduction, and electrical conductivity. An operating fuel cell array has been fabricated from these materials. Issues remaining include optimization of the three-layer composites, long-term testing to ensure that degradation effects are not significant, and dimensional and shape control during firing.

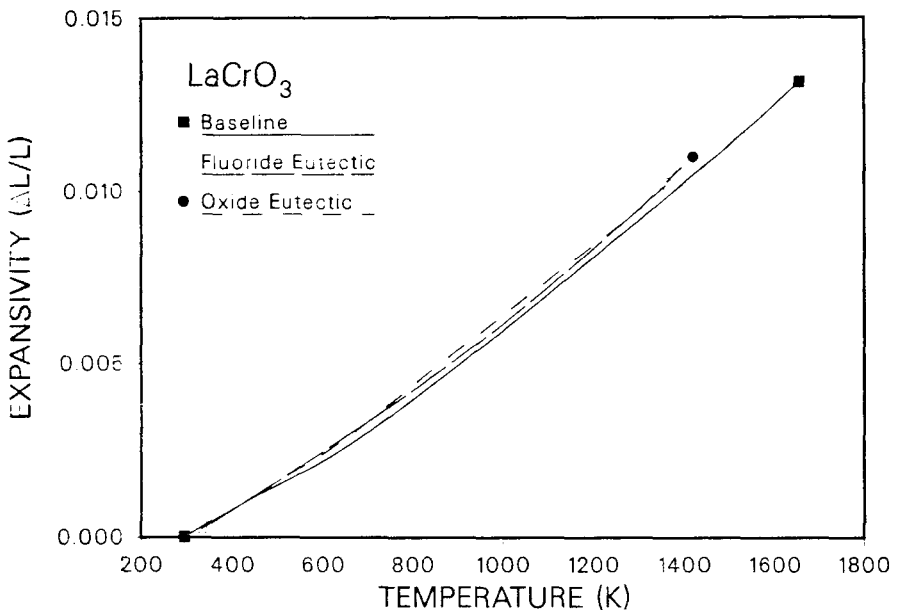


FIGURE 2

Plot of expansion vs. temperature for LaCrO_3 doped with two types of sintering aids as compared to that of the baseline material.

This work was sponsored by the Defense Advanced Research Projects Agency.

REFERENCE

1. M. Pechini, U. S. Patent No. 3,330,697, July 11, 1967.

ELECTRODE DEVELOPMENT FOR MONOLITHIC FUEL CELLS

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The methodology for producing electrodes for monolithic solid oxide fuel cells has been developed. Ceramic powder particle size distributions and solvent/binder systems have been tailored to yield the desired electrode porosity levels (20-50%), while matching the firing shrinkages of other cell components. Electrodes have been fabricated with thicknesses of 25-125 μm . Careful control of the stoichiometry and powder characteristics of the cathode material (strontium-doped lanthanum manganite) is necessary for the production of acceptable layers. In the two-phase nickel/zirconia anode, the nickel content is a key variable. Lower nickel contents reduce the thermal expansion mismatch among the cell components; however, the anode conductivity becomes insufficient at nickel contents below about 35 vol. %.

CATHODE DEVELOPMENT

The cathode, or air electrode, is strontium-doped lanthanum manganite ($\text{La}_{0.9}\text{Sr}_{0.1}\text{MnO}_3$). The cathode must be stable in an oxidizing environment and must be an electronic conductor with a minimum conductivity of $30 \text{ ohm}^{-1} \text{ cm}^{-1}$ at 1000°C . The composition described here has a conductivity of approximately $80 \text{ ohm}^{-1} \text{ cm}^{-1}$ at 1000°C . The material must be fabricated with a porosity level of 20-50% to allow for gas flow through the layer, and to provide sufficient surface area at the cathode/electrolyte (zirconia) interface for the electrochemical reduction of oxygen to take place. Close matching of the firing shrinkage and the thermal expansion coefficient to those of the other cell components is also an important consideration. Tape casting has been chosen as the fabrication technique for forming the thin layers of cathode material, which must be less than 10 mils (0.01 in.) thick.

The most satisfactory results are obtained when two lanthanum manganite powders of differing sinterability are combined. One powder is fabricated by a solid-state reaction process in which a solution of nitrates of the cations is spray dried to produce a powder which is subsequently calcined. This powder is relatively coarse and of lower sinterability. The second powder is produced by an organic synthesis method which yields a relatively fine-grained and more sinterable powder. The characteristics of these powders are shown in Fig. 1. Since the degree of densification of the cathode must be carefully controlled, various combinations of these powders can be used to attain desired density (and porosity) levels, and to adjust the firing shrinkage of the layers. Additional flexibility is afforded by the incorporation of pore formers which burn out during firing to

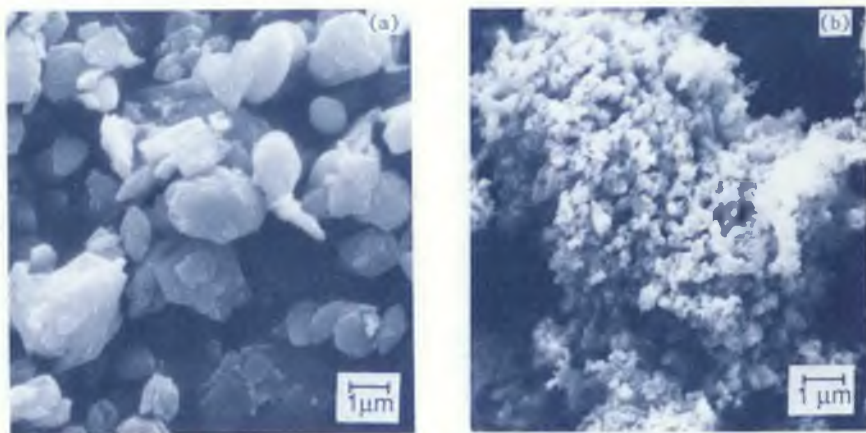


FIGURE 1

Strontium-doped lanthanum manganite powder prepared by (a) solid-state reaction process and (b) organic synthesis method.

produce more porosity. The relationship of porosity to firing shrinkage as a function of the two powder contents is shown in Fig. 2.

ANODE DEVELOPMENT

The anode or fuel electrode is a nickel/zirconia cermet. The yttria-stabilized zirconia serves as a porous substrate which supports the nickel phase. The metallic nickel conducts electrons across the circuit between the electrolyte and interconnect layers and serves as a catalyst for the electrochemical oxidation of the fuel. The anode layer must be stable in a reducing environment and must have a minimum electronic conductivity of $120 \text{ ohm}^{-1} \text{ cm}^{-1}$ at 1000°C . As for the cathode layers described above, the anode must be fabricated with a porosity of 20-50%, and must have a firing shrinkage and coefficient of thermal expansion closely matching those of the other fuel cell components. Tape casting has been used successfully to fabricate thin ($<0.01 \text{ in.}$) layers of anode material.

The principal challenge during anode fabrication has been the degree of thermal expansion mismatch with the other components. Since it is convenient to carry out the final sintering of the constructed fuel cell array in air in order to maintain the composition of the cathode material, the nickel phase in the anode is introduced as nickel oxide and subsequently reduced to nickel metal by the fuel during operation. The thermal expansion of the nickel oxide is sufficiently different from the other components to cause

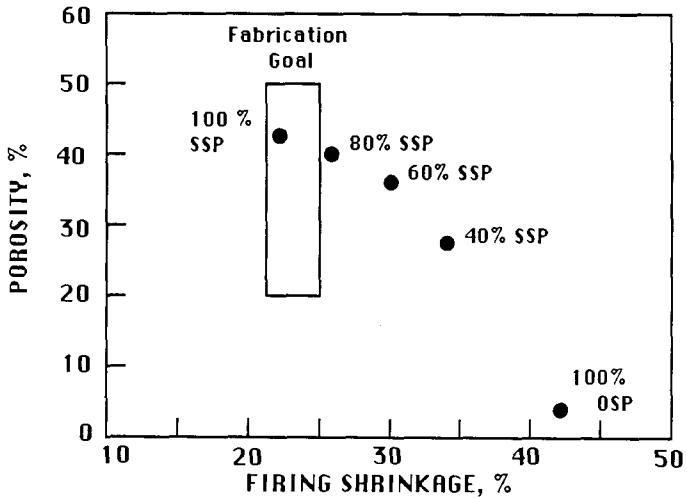


FIGURE 2

Effects of relative percentages of solid-state reaction powder (SSP) and organic synthesis powder (OSP) on porosity and firing shrinkage of cathode.

development of stresses in the array. As the nickel oxide content is increased, the thermal expansion mismatch becomes larger, as illustrated in Fig. 3. The thermal expansion of the zirconia electrolyte layer is approximately $10.5 \times 10^{-6}/^{\circ}\text{C}$, and it has been determined that deviations of $\pm 2 \times 10^{-6}/^{\circ}\text{C}$ from this value by the other components could result in unacceptable stresses within the arrays. Since the electronic conductivity of the anode is dependent on the amount of nickel present, some thermal expansion mismatch must be accommodated. However, as illustrated in Fig. 4, the volume of nickel needed to maintain the required level of conductivity is known. The minimum amount of nickel required can therefore be incorporated in the anode layers to reduce the degree of thermal expansion mismatch. It has been found that changing the microstructure of the porous zirconia substrate also reduces the amount of nickel that is required. A coarse-grained zirconia substrate will result in a continuous nickel phase at lower nickel contents because of the lower surface area that must be covered. Alternative methods of introducing the metallic nickel are also being investigated.

This work was sponsored by the Defense Advanced Research Projects Agency.

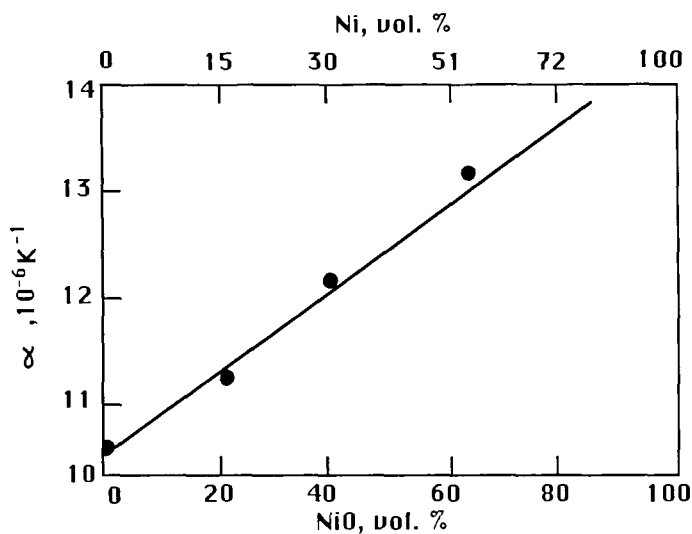


FIGURE 3

Thermal expansion of NiO/Y₂O₃-stabilized ZrO₂ anode.

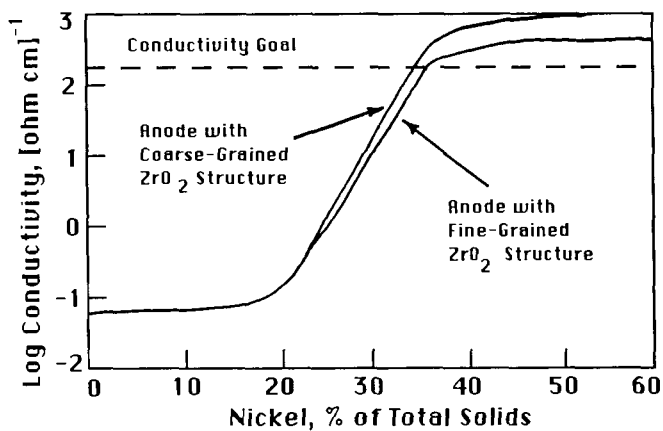


FIGURE 4

Conductivity of anode as a function of nickel content.

EXPERIMENTAL INVESTIGATION OF RESISTIVITY, THERMAL EXPANSION AND
OXYGEN PERMEATION OF LANTHANUM CHROMITE FILMS SIMILAR TO THOSE
IN THE WESTINGHOUSE SOLID OXIDE FUEL CELL

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The design of the Westinghouse solid oxide electrolyte fuel cell incorporates an interconnection layer of magnesium-doped lanthanum chromite made by the electrochemical vapor deposition technique (EVD). Measurements of properties of this layer, such as thermal expansion, electrical resistivity, stability to oxygen loss at high temperatures and oxygen permeability are difficult to measure when the film is incorporated in the cell due to interference of other cell components. To avoid such interference we have grown by EVD, similar lanthanum chromite layers on a porous calcia-stabilized support tube. These layers were used either directly for oxygen permeation experiments, or the layer was stripped off to give a free standing layer for thermal expansion and electrical resistivity measurements.

The electrical resistivity of a thin layer of $\text{LaCr}_{0.988}\text{Mg}_{0.012}\text{O}_3$ was measured and analyzed in terms of a solid state defect model. The resistivity values of the (EVD) layer in the temperature range of 800 to 1100°C and oxygen partial pressure range of 0.2 to about 1×10^{-18} atm were found to vary between 0.5 to 1.55 ohm-cm. The resistivity values (ρ) of this oxide and several bulk lanthanum chromite samples doped with Mg, Ca and Sr are shown Figure 1 as a function of temperature and have been found to approximately agree with the following relations for adiabatic hopping of the p-type charge carriers,

$$\sigma T = ne(f_{u.s.} e d^2 H_p / k) \exp(-E_h / kT) = C \exp(-E_h / kT)$$

where σ is the conductivity in $\text{ohm}^{-1}\text{cm}^{-1}$, n is the number of charge carriers/ cm^3 (equivalent to the number of Mg^{++} doping ions/ cm^3), e is the charge on the electron (1.6×10^{-19} coulomb), $f_{u.s.}$ is the fraction of unoccupied hopping sites, d is the distance in cm between hopping sites (i.e., nearest neighbor chromium ions), H_p is the polaron hop rate, k is the Boltzman constant (1.38×10^{-16} erg K^{-1}), E_h is the hopping activation energy and T is the temperature in K.

The loss of oxygen from $\text{LaCr}_{1-y}\text{Mg}_y\text{O}_{3-x}$ at 1000°C and different oxygen partial pressures has been determined using thermogravimetric measurements in a flowing gas atmosphere. The results at 1000°C and oxygen pressures ranging from that in air to about 1×10^{-17} atm agree well with those calculated from the equation:

$$\log P_{\text{O}_2} = 4 \log [(y-2x)/x] - \log K^2$$

where K is the equilibrium constant for the oxygen loss reaction which assumes an equilibrium of oxygen in the flowing gas atmosphere with ions, positive hole charge carriers and associated oxygen site vacancies in the lattice structure of the material. The oxygen loss below about 1×10^{-17} atm oxygen pressure exceeded that predicted from this equation. Data are shown in Figure 2.

Thermal expansion of EVD magnesium-doped lanthanum chromite was found to be almost identical to pure lanthanum chromite as shown in Figure 3. However, it is about 12 to 14% lower than the thermal expansion of the calcia-stabilized zirconia support tube of the solid oxide fuel cell. Modification of the chemical composition with other alkaline earth components can provide a better thermal expansion match among all the fuel cell components.

The permeation of oxygen through electrochemically vapor deposited thin films of magnesium-doped lanthanum chromite has been studied under UHV conditions using a mass spectrometer. Oxygen permeation through the interconnection material has been found to be extremely low. At 1000°C , with 1 atm oxygen pressure on one side and vacuum on the other side of the interconnection film, the oxygen permeation rate was less than 9.6×10^{-13} moles/cm²-sec. With air on one side and an $\text{H}_2\text{O}/\text{H}_2$ mixture (ratio=2) on the other, the permeation rate of oxygen through the interconnection film was found to be 1.9×10^{-11} moles/cm²-sec. This rate is over four orders of magnitude less than the rate of oxygen consumption due to current flow of 300 mA/cm² in the solid oxide fuel cell. Oxygen permeation through the interconnection layer is thus insignificant in the solid oxide fuel cell operation.

Acknowledgements

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The authors acknowledge valuable assistance of M. Stratis, R. Burlan and J. Fraino in obtaining experimental data.

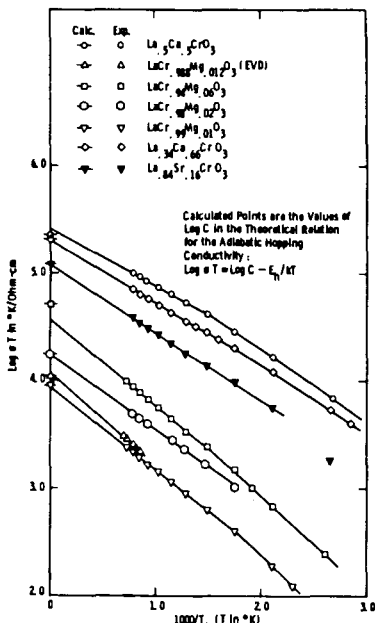


Figure 1. Conductivity data for lanthanum chromite doped with alkaline earth ions from 25 to 1100°C.

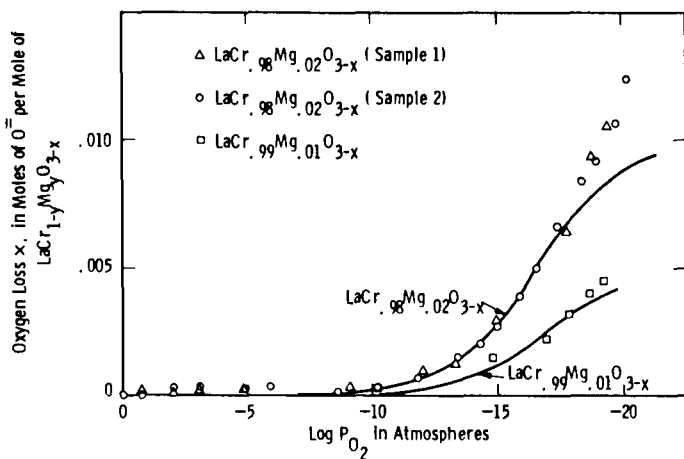


Figure 2. Oxygen loss from $\text{LaCr}_{1-y}\text{Mg}_y\text{O}_{3-x}$ as a function of oxygen partial pressure at 1000°C.

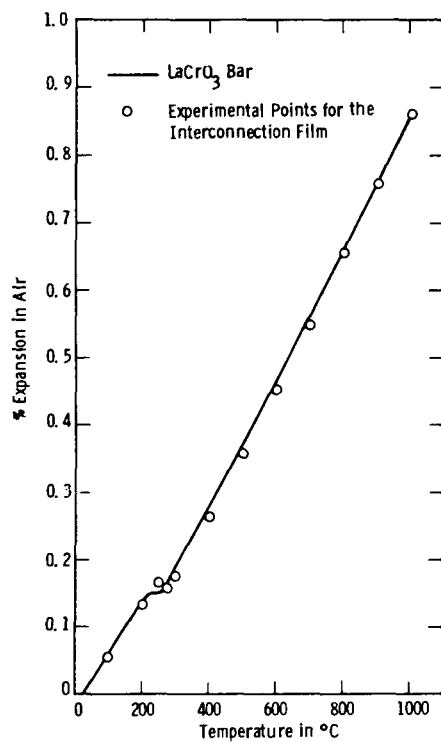


Figure 3. Comparison of thermal expansions of the LaCrO_3 bar and the $\text{LaCr}_{.988}\text{Mg}_{.012}\text{O}_3$ interconnection film.

FUEL CELL PRODUCTION PROCESS CONTROL AND QUALIFICATION OF FINISHED CELLS

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INTRODUCTION

Qualifying the processes by which solid oxide fuel cells are produced is an important objective of the Westinghouse-Department of Energy Solid Oxide Fuel Cell (SOFC) Power Generation System project. Reaching this objective requires, among other process control actions, that both product requirements and their measurements of compliance (quality measures) be established. At the present time SOFC technology is still emerging from the research phase of its existence, and consequently these requirements and quality measures need as much development as the processes themselves. To accelerate that development, a set of tentative product requirements and quality measures were developed along with the evolution of the processes employed to produce 324 cells for the first 5 kW generator produced on the project. Thus this first production experience provides the framework to define the process limits and refine both the process and product requirements accordingly.

FUEL CELL CONFIGURATION AND PRODUCTION METHODS

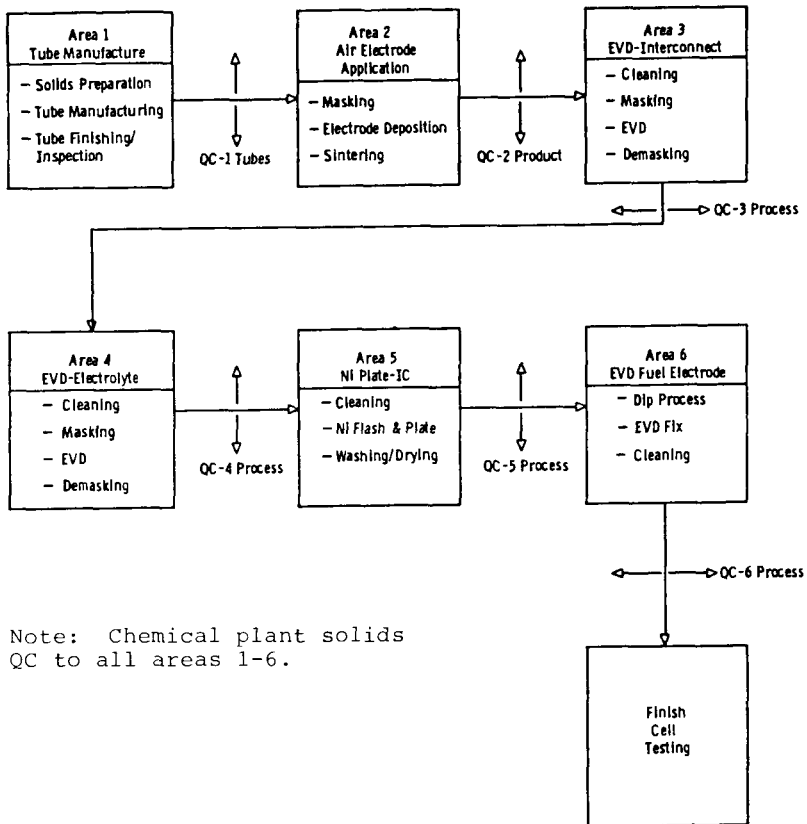
The solid oxide fuel cell used for the 5 kW generator is built upon a cylindrical porous support tube of calcia-stabilized zirconia which is 12.8 mm in diameter and closed at one end. The active fuel cell length for most of the cells used in the 5 kW generator is 303.5 mm; the overall length of the tube is 457.2 mm, and wall thickness is 2 mm. These tubes are produced by extruding an open cylinder, inserting a plug to close one end, sintering, and cutting and grinding to final dimensions and shape.

Cell components built up on the support tube include an air electrode, an electrical interconnection, an electrolyte, and the fuel electrode. These components are placed in successive steps as follows:

- The lanthanum manganite air electrode (~1 mm thick) is deposited as a slurry and then sintered.
- The lanthanum chromite interconnection (~40 μm thick) is deposited by electrochemical vapor deposition (EVD).
- The yttrium doped zirconia electrolyte (~30 μm) is deposited by EVD.
- The nickel cermet fuel electrode (~100 μm) is deposited by slurry and fixed by EVD.

The overall diameter of the cell is essentially determined by the diameter of the support tube and the thickness of the air electrode.

Production of cells is organized by areas that follow the progression of cell construction (Figure 1), starting with support tube manufacture and ending with fuel electrode fixing. Quality controls conducted before and after the process areas are shown.



Note: Chemical plant solids
QC to all areas 1-6.

FIGURE 1

FLOW SHEET - SOFC GENERATOR MANUFACTURING PROCESS

GENERAL QUALITY ASSURANCE PRACTICES

To ensure that process control and qualification can be pursued, management must first ensure a general environment of control. Properties of input materials must be controlled, process equipment must be capable of performing the desired operations, and people must be able to consistently exercise the process.

Cell production used material specifications derived from processing experience and knowledge that specifications could be met by material suppliers or by in-house processing. Five major groups of raw materials were used:

1. Calcia-stabilized zirconia powder for support tubes.
2. Lanthanum manganite powder for air electrodes.
3. Lanthanum chromite powder to mask cells for EVD process.
4. Various chlorides for thin films via EVD.
5. Nickel powder for fuel electrodes.

In each case, appropriate chemical and physical properties were specified, the specifications were sent to vendors known to produce the desired powder, and the received powders were inspected.

Before producing the 5 kW generator, the production equipment, and procedures were audited. Results were the adoption of standard operating procedures, training of technicians, preparing the process equipment, and instituting practices such as travelers, operator checklists, and production flow organization. Quality control measures were also chosen.

People for the production team were carefully chosen and trained by the technical leaders who developed the processes and production equipment. Documentation of the processes, checklists included, were part of the communication of process requirements that took place during this training. Also, several managers followed the combined experimentation and production to consistently resolve resource and schedule problems.

CELL PRODUCTION PROCESS QUALITY MEASURES

Process quality measures were established for each of the production areas (Figure 1) to begin a quantitative evaluation of conformance of the product to requirements specified. Product requirements and quantitative quality measures are described for the tube support production area (Area 1) which serves as an example for the remaining Areas 2-6; high temperature electrical performance (finish cell) tests are also described:

Support Tube Specification

SOFC support tubes consist of extruded, sintered, 15 mole % calcia-stabilized zirconia ceramic. Tubes are 457.20 mm long, 12.8 ± 0.13 mm OD with a straightness tolerance of 0.64 mm and an 8.80 ± 0.20 mm ID with concentricity of 0.15 mm T.I.R. Tubes are closed at one end with co-sintered plugs which have a 6.5 ± 0.10 mm radius, and are 3.6 ± 0.40 mm thick. Physical property specifications were tentatively set at 34-35% porosity, permeability of 0.02 Darcy minimum and uniform along the tube length to within $\pm 15\%$ of normal values, 34.5 MPa (5,000 psi) minimum hoop strength, 65.5 GPa (9.5×10^6 psi) maximum elastic modulus, and no cracks as determined by a candling technique.

Quality Measures

Zirconia powder was the major raw material requiring inspection. Chemical analysis and x-ray structural parameter measurements were used to establish powder chemistry and phase content; a pilot run was made for the powder batch to set process parameters and establish final requirements for powder acceptance. Quality measures for finished support tubes consist of defect identification, dimensions, and physical and mechanical properties. For the 5 kW generator project, the tube production process did not always yield tubes which met tentatively specified requirements (Table 1). Since the process produced tubes which functioned acceptably, the specifications will be revised.

TABLE 1

ZIRCONIA SUPPORT TUBE QUALITY MEASURES

<u>Quality Measure</u>	<u>Specification</u>	<u>Process Meets Specification</u>
Porosity	34-35%	No
Permeability	.02 Darcy min. & ±15% along length	Yes
Burst Strength	5,000 psi min.	No
Elastic Modulus	9.5×10^8 psi max.	Yes
Defects (as determined by candling process)	No light transmission	Yes
Dimensions	12.8 mm ± 0.13 O.D.	No
	8.80 mm ± 0.20 I.D.	Yes
	457.2 mm length	Yes
	0.64 mm straightness	Yes

High Temperature Electrical Performance Test Specification

Selected finished cells from each production run are electrically tested at high temperature. Cell output greater than 0.6 volts at 200 mA/cm² for 200 hours is required with simulated coal derived fuel, 85% fuel utilization and 25% air utilization. This cell output was met for 12 of 13 cells tested for the 5 kW generator; only the populations represented by the 12 conforming cells were used in the generator.

ACKNOWLEDGMENTS

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Other Westinghouse personnel who contributed to this paper are: J.E. Bauerle, J.G. Cleary, W.A. English, R.R. Jensen, P.R. Mulik, W. Pollack, and G.E. Zymboly.

ZIRCONIA FUEL CELL POWER SYSTEM PLANAR STACK DEVELOPMENT

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INTRODUCTION

For practical power generation or cogeneration applications, the zirconia fuel cell systems are required to be compact in assembly, competitive in cost, and capable of handling high electrical and thermal energies. To meet these criteria, a planar cell stack design utilizing a "composite structure" technique has been under development. The methods of fabrication, stack assembly and power system scale-up have been established.

PLANAR CELL STACK

The zirconia fuel cell which has been developed by Ztek is constructed of thin plates of zirconia electrolyte alternately arranged with interconnector plates. The electrolyte plates are made of thin zirconia membrane and electrode coatings. The interconnector plates are fabricated from corrosion-resistant conducting materials.

Internal gas passages through the plates provide the air and fuel supplies, and permit spent gases to exhaust. The distribution of gases to the surface of the electrode occurs along grooved networks formed in interconnectors. Gas seals and electrical contact between plates are obtained by pressing the interconnector plates against the surface of the electrolyte plates.

The interconnector plates also serve as thermal conductors to facilitate the heat transfer, thus reducing the thermal gradient in the electrolyte plates. The distinctive features that make this cell stack suitable for practical power system applications are:

- High power density
- Structural ruggedness
- Concealed electrodes
- Ease of heat removal
- Low stress assembly

Table 1 summarizes the estimated performance and power capability of the planar cell assembly.

M. Hsu

- 2 -

Ztek has developed a process which promises to be economical for the fabrication of thin plates of yttria stabilized zirconia (YSZ). YSZ plates up to 4-inches in diameter and 0.01-inch thick with better than 0.001-inch flatness have been fabricated successfully. Serious curling encountered by isostatic forming or the green-tape method has not occurred in this approach. No fundamental limitation is foreseen in fabrication of plates larger than a 4-inch diameter. Due to the heat rejection design consideration in the cell stacks, 4-inch-diameter plates are considered to be optimum for either near-term devices of multi-kW-level modules or future MW-level plants.

The material cost for the planar cell stack design is estimated to be below \$160/kW.

One major technical difficulty encountered with the zirconia electrolyte is its brittleness in tension. The ceramic electrolyte has a low tensile strength which is only 20 percent of its compressive strength. This property is not unlike concrete. The use of the concrete became widespread only after a reinforcing rod was introduced. Ztek's cell stack design utilizes a similar proven composite structure technique, in which the components have dissimilar though complementary properties. Recognizing the fabrication, assembly and performance constraints associated with the zirconia electrolyte, Ztek selected materials for the interconnector which emphasized practical requirements of ease of fabrication, mechanical reliability and good electrical conductivity. The thermal-expansion mismatch which exists between the electrolyte and the interconnector is utilized to favorably pre-stress the ceramic electrolyte in compression.

The above design approach can be accomplished with components that allow low cost and high volume production. The electrolyte plate and the interconnector plate are fabricated separately and assembled into the composite stack. The stack, serving as building block for the fuel cells systems, possesses excellent thermal/structural integrity. In addition, gas sealing is obtained in the assembly process of the stack.

TECHNICAL STATUS

A series of tests on a single-cell as well as a multiple-cell stack of 2-inch-diameter plates has been conducted. The results are summarized:

1. A single cell and a two-cell stack have demonstrated up to 0.12 W/cm^2 area power density. With system optimization of electrolyte thickness, electrode pore size, and gas distribution network, further improvement in power density can be anticipated.
2. The two-cell stack can withstand thermal cycling. No noticeable performance change or detectable physical damage occurred after five cycles.
3. A five-cell stack has been tested for quick thermal transient capability: 100°C/min. of temperature rise rate. The highly thermal-conductive interconnectors contribute to this desirable capability.
4. The porous electrode coatings, compacted under pressure, have simultaneously provided good electrical contacts between adjacent plates and good gas seals along the edges of the plates.

The fuel cell stack integrated with a gas/electric dual-mode furnace was tested, demonstrating operational safety, and startup and shut-down procedures.

Self-reforming of a lightweight hydrocarbon fuel has been demonstrated by continuously operating for several hours without carbon deposition.

DEVELOPMENT ACTIVITIES

Ztek Corporation is devoted to the development of the zirconia fuel cells. The activities will proceed according to three phases which represent a logical progression from a Phase I bench size 1-kW "stack", through a Phase II multi-kilowatt "prototype", to a Phase III full-up "pilot plant" system. The system will aim at utility power generation, industrial/commercial cogeneration applications, and space power sources.

Presently, Ztek and the Electric Power Research Institute are jointly funding an effort to evaluate the stability of the interconnector material and to assess the impact of unit cell failure to the assembly stack. These activities will be followed by the development of fuel cell modules and systems. Ztek's technology has also been selected by the Department of Defense to be developed for lightweight power systems in space applications.

TABLE I ENGINEERING SPECIFICATIONS OF PLANAR CELL STACK

	<u>English Units</u>		<u>Metric Units</u>	
Current density	300	Amp/ft ²	3000	Amp/m ²
Voltage per cell	0.7	Volts	0.7	Volts
Cell diameter	4	inches	10	cm
Cell height	1/16	inch	1.6	mm
Cell planar area (80%)	0.07	ft ²	0.007	m ²
Cell number/unit length	192	/ft	600	/m
Total current	21	Amp	21	Amp
Voltage per unit length	135	V/ft	420	V/m
Power per unit length	2.8	kW/ft	8.8	kW/m
Power density (70% pack)	28	kW/ft ³	880	kW/m ³

THE EFFECT OF S-POISONING ON THE ANODIC
OXIDATION OF HYDROGEN IN A SOFC

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Performance loss in the anodic oxidation of hydrocarbons caused by the presence of H_2S , even at a few ppm level, is a major problem for low- and medium-temperature fuel cells using platinum or nickel as electrodes since H_2S is known to chemisorb very strongly on these metals (1,2). In this study, the effect of H_2S chemisorption on the anodic oxidation of H_2 in a yttria-stabilized zirconia (YSZ) fuel cell is being investigated. The electrolyte is 10 mole % YSZ in the form of discs 25 mm in diameter and 2 mm thick. Porous electrodes of gold, platinum and nickel are made by suitably painting inks of these metals on the electrolyte surfaces. The inks are supplied by Engelhard Industries. The fuels used in this study are pure H_2 as well as hydrogen gas containing 69 ppm H_2S supplied by the Matheson Corporation. The temperature range studied was from 750 °C to 900 °C. The reactor is shown schematically in Fig. 1 and details on construction and experimental conditions have been previously described (3,4). To avoid contamination by H_2S of the pure H_2 influx stream, separate feed-lines including the alumina feed-tubes were used for the pure H_2 gas and the $\text{H}_2\text{S}/\text{H}_2$ mixture.

Typical current-overpotential curves for the porous gold, platinum and nickel electrodes are shown in Figs. 2,3 and 4 respectively. The surprising result displayed by these curves is that the H_2S does not appear to have any significant effect on the electrode kinetics of the H_2 anodic oxidation. This behavior is in sharp contrast to the behavior in non-electrochemical systems, where the chemisorbed H_2S acts as a strong poison. Since the oxidation of H_2S to SO_2 is thermodynamically favorable, and in fact H_2S burns in air and can be utilized as a fuel (5), a possible interpretation of these data is that the chemisorbed H_2S is being continuously electro-oxidized to SO_2 which is then desorbed. Even if the kinetics of the H_2S electro-oxidation is very different from that of H_2 , the net effect on the overall kinetics would be small because of the low H_2S concentration.

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University of Malaya, Kuala Lumpur, Malaysia.

In keeping with previous work ^(3,4), there is an alternative interpretation that can be made, and that is that the electrolyte itself is playing a major role in determining the electrode kinetics. In these earlier works, it has been assumed that F-centers (oxygen vacancies with trapped electrons) represent the electrocatalytically active sites. Since sulfur cannot enter into these vacancies to destroy them, the presence of sulfur in low concentrations in the fuel gas should not appreciably affect the overall anodic kinetics. The concentration of these F-centers and thus the rate of the anodic oxidation can be greatly increased by "current-blackening", i.e., by imposing on the electrolyte a voltage of 3.0 to 3.5 volts, which is sufficient to cause electrolysis. The upper curve in Fig. 4 for the nickel anode shows the enhanced effect after one minute of "current-blackening" treatment of the electrolyte. A brief electrolysis treatment such as this does not actually lead to appreciable darkening of the electrolyte, although prolonged treatment at high current densities of several amps/cm² will produce a black, highly oxygen-deficient electrolyte which may become brittle. Similar enhancements in electro-oxidation rates for the gold and platinum electrodes have been previously reported and discussed ^(3,4). The porosity and morphology of the electrode determine the relative area of the electrode/electrolyte/gas tri-phase boundary available for charge transfer and thus account for the differences in current densities with different electrodes on the same electrolyte. The nickel anode made from the ink used in this work is seen to perform poorly when compared to the gold and platinum electrodes. Scanning electron micrographs show that the nickel electrode has a very different morphology from that of the gold and platinum electrodes, the nickel electrode consisting of individual rounded particles whereas the gold and platinum electrodes consisted of particles which form continuous web-like structures.

Westinghouse ⁽⁶⁾ has reported long term (700 hours) sulfidation studies at 1000 °C on nickel anodes using lean fuel mixtures of H₂ and CO containing up to 50 ppm H₂S. A five percent drop in cell voltage was found to occur. It was also found that sulfidation will not occur for H₂S concentrations below 100 ppm. In this present work, only short-term chemisorption effects were studied. Typically, data for pure H₂ and the H₂S/H₂ mixture were taken within a 24-hour period in order to avoid variations caused by electrode morphology changes as the metal particles gradually sinter at the elevated temperatures.

ACKNOWLEDGMENTS

The grant of sabbatical leave by the University of Malaya to B.G.Ong is gratefully acknowledged. Acknowledgment is also made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for partial support of this research.

REFERENCES

1. J. Oudar, "Sulfur Adsorption and Poisoning of Metallic Catalysts" Catal.Rev.-Sci.Eng. 22(2), pp171-195(1980)
2. Ib Alstrup, Jens R. Rostrup-Nielsen and Stig Roen, "High Temperature Hydrogen Sulfide Chemisorption of Nickel Catalysts" Applied Catalysis, 1, pp303-314(1981)
3. B.G.Ong, C.C.Chiang and D.M.Mason, "Electrocatalytic Role of Stabilized Zirconia on the Anodic Current-Overpotential Behavior of Hydrocarbon Fuel Cells", Solid State Ionics, 3/4, pp447-452 (1981)
4. B.C.Nguyen and D.M.Mason, "Electrocatalytic Reactivity of Hydrocarbons on a Zirconia Electrolyte Surface", to be published in J. Electrochem. Soc., September 1986
5. Mitsui Engineering and Shipping Co Ltd, "Successful Power Generation Using Hydrogen Sulfide as Fuel", Chemical Economy and Engineering Review, 11(12), p53(Dec 1979)
6. Westinghouse Electric Corporation, "High-Temperature, Solid Oxide Electrolyte Fuel Cell Power Generation System", Quarterly Report Sept 1-Nov 30, 1980, DOE/ET/17089-3 (DE84015927)

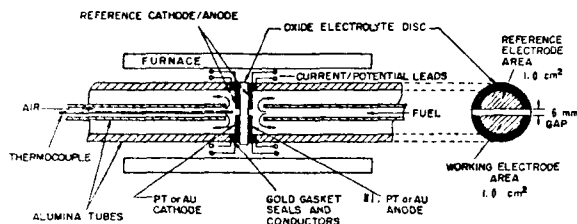


FIGURE 1 Schematic Diagram of SOFC Reactor

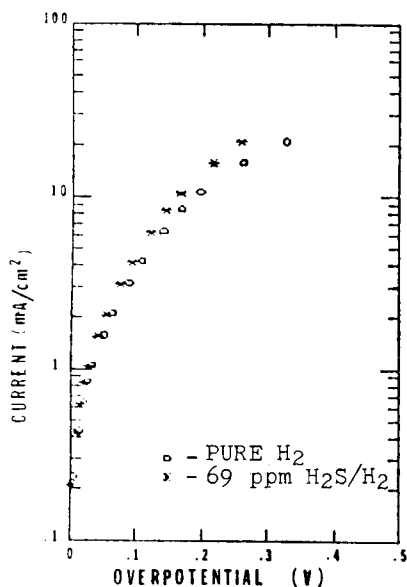


FIGURE 2 Current-Overpotential Curves for Gold Anode at 850 °C

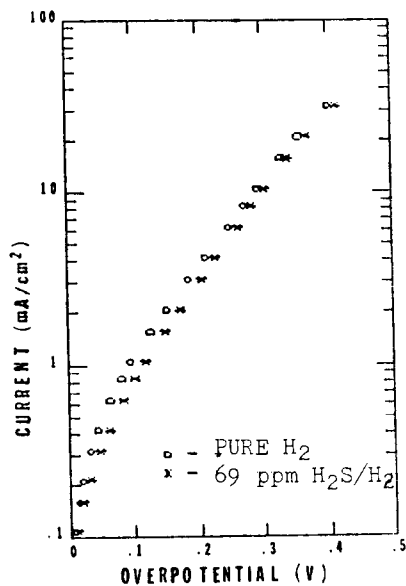
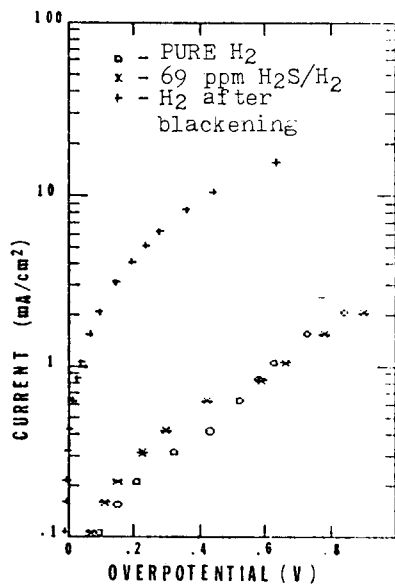


FIGURE 3 Current-Overpotential Curves for Pt Anode at 850 °C

FIGURE 4
Current-Overpotential Curves for Nickel Anode at 850 °C



STUDY ON PERFORMANCE OF AIR COOLED PAFC

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Introduction

Sanyo Electric Company has been developing R&D of air cooled PAFC technologies. In 1984, 50kw air cooled PAFC system (type 2) was developed and tested by the actual load (1). The verification test of on-site 200kw air cooled PAFC system is planned in cooperation with Tokyo Electric Power Company.

For the commercialization, the certification of the lifetime is one of the most important factors. The target of the PAFC lifetime is 40,000hrs, and now its test is continued. This cell has the acid in the thin porous matrix. The amount of the acid is so little that acid management such as acid-adding is important for achieving the high performance and high durability.

Cell construction

Figure 1 and Figure 2 show the construction of unit cell and stack, respectively. Unit cell consists of air electrode, fuel electrode and electrolyte matrix.

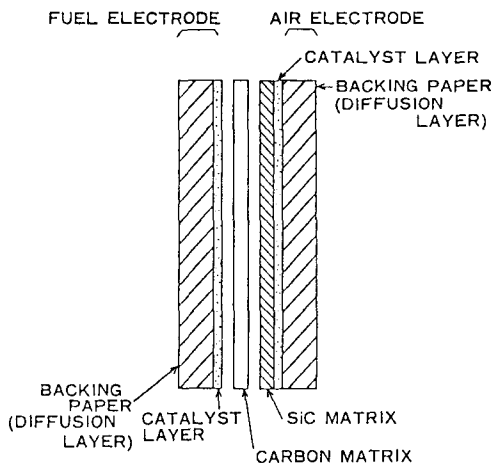


Figure 1. Cell construction

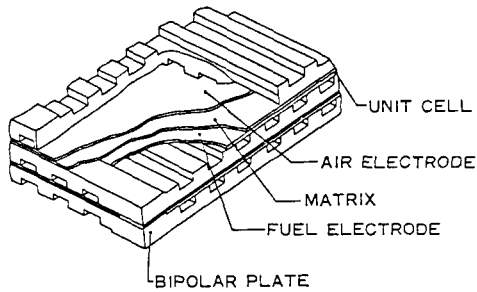


Figure 2. Cell stack construction

Both electrodes have double layer structure, gas diffusion layer and catalyst layer, which are wet-proofed. Electrolyte matrix consists of SiC and carbon layers impregnated by phosphoric acid.

The amount of the acid in the cell decreases with cell operation. When it becomes below 75% (Initial;100%), the cell resistance sharply increases (Figure 3).

Figure 4 shows the relation between the amount of the acid in SiC matrix and the cell resistance. Figure 4 shows the same tendency as Figure 3. So, it seems that the amount of the acid in SiC matrix dominates the cell resistance.

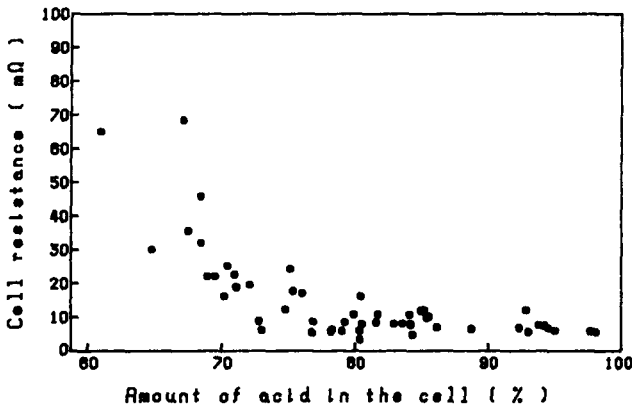


Figure 3. Relation between cell resistance and amount of acid in the cell

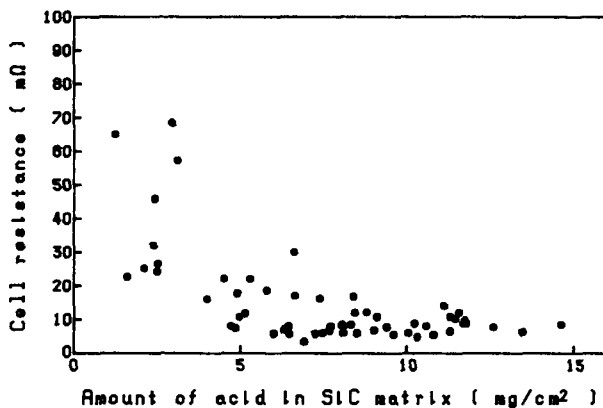


Figure 4. Relation between cell resistance and amount of acid in SiC matrix

Acid Management

Acid management, such as acid-adding, storage condition and so on, is one of the important technologies for achieving long life.

Figure 5 shows the result of accelerated life test without acid-adding at various storage conditions. The cells which are stored at high temperature show the sharp decay of cell voltage. The volume of the acid changes with thermal cycles. It seems that the volume change of the acid has an effect on the durability performance. It is expected that the stable performance is obtained by decreasing the acid volume change at thermal cycle.

Figure 6 shows the life test result of 5 cells stack with acid-adding (cell effective area: 1000cm²). The operating temperature is 180°C and the operating current density is 100mA/cm².

The target of the lifetime is 40,000hrs. Now this life test exceeds successfully 38,000hrs and continued further more.

Reference

1. T. Sakai et al., "Air Cooled Phosphoric Acid Fuel Cell Power Plant," Abstracts, Fuel Cell Seminar, 1985.

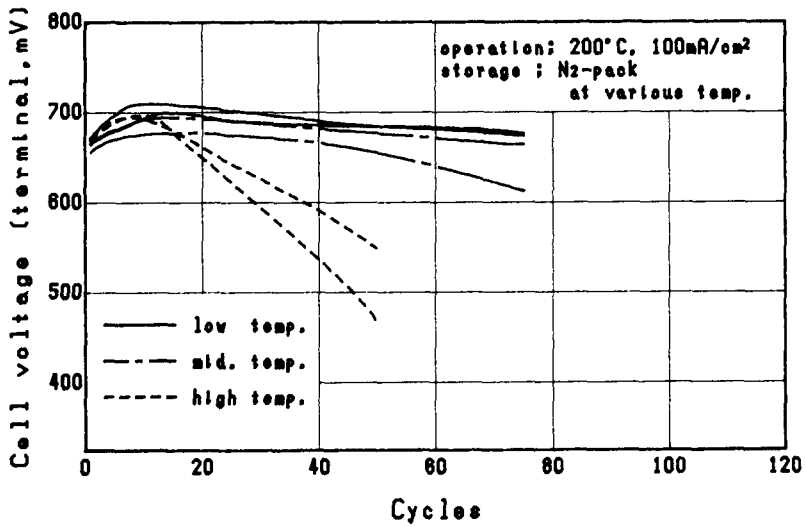


Figure 5. Accelerated life test

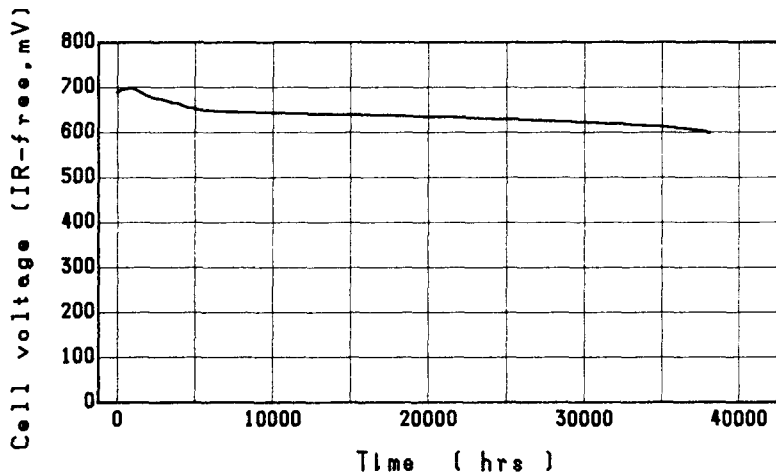


Figure 6. Short stack life test

FIRST HEAVY-DUTY QUALIFICATION OF A kW-SIZE PAFC
STACK SYSTEM IN ITALY

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Extended abstract of a poster paper
to be presented at the Tenth Fuel Cell Seminar
(Tucson, Arizona, October 26-29, 1986)

An ERC^{*}-made, air-cooled 2.5 kW PAFC stack, equipped with methanol reformer and dc-ac inverter, has been in operation for over 3 years in Segrate (Lombardy, Italy), undergoing hundreds of start-ups and shut-downs⁽¹⁾.

Maintenance operations of the reformer and of the stack were optimized to adjust them to the humid climate of the Lombard Region and to severely intermittent use of the system⁽²⁾.

Steady-state and transient electric characteristics of the stack were widely studied⁽³⁾. The efficiency of the catalytic beds through time was followed checking the chemical composition of the reformer output by both gaschromatographic sampling and on-line i.r. monitoring of CO concentration.

Repetition of the electric characteristics of the stack and of the entire system at regular time intervals gives us a useful insight into the behaviour of this fuel-to-electricity energy converter through its life⁽⁴⁾.

Recent determinations yielded an objective criterion to decide rewicking of phosphoric-acid electrolyte in the matrices.

Electrical characteristics of Fig.1 show the long-run worsening of the stack during its utilization, very likely due both to electrolyte losses at the operating temperature and to duty cycles (supercooling of concentrated H_3PO_4 during shut-downs). No particular degradation was noticed in³ about six months of stack in activity, except for the maximum current (53A and 53,8A at 44V) which is limited by the low stack voltage on the ballast resistor of the load.

It turns out that, at low current values, the curves tend to the same voltage values, i.e. activation overvoltages did not vary in time. This indicates a substantial stability of the electrocatalysts during time.

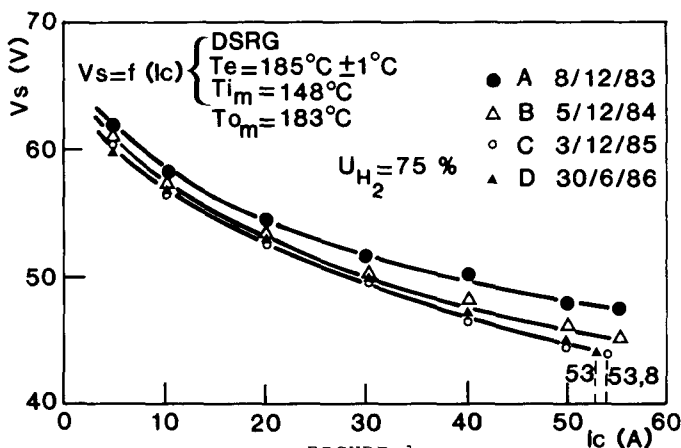


FIGURE 1

The electrical characteristics of the stack, repeated after each year of activity and after half year of inactivity

T_e = operation temperature

T_{im} = average inlet temperature

T_{om} = average outlet temperature

V_s = stack voltage

I_c = load current

DSRG = Dry Simulated Reformed Gas

U_{H_2} = hydrogen utilization factor

V_m = average ten-cell voltage (detected across twenty cells in the middle region of the stack)

Following this determination, the stack was rewicked on site with concentrated H_3PO_4 , with no particular precautions, except that the stack was kept at its regular operation temperature during wicking.

Further determinations of the electrical characteristics are now in progress to discriminate the wicking-reversible part of the degradation, due to electrolyte losses, from the permanent part, due to duty cycles. Preliminary results show that the permanent part is minor. Further, hopefully complete results will be shown in the poster.

The temperature coefficient of the stack voltage was determined at atmospheric pressure and at different loads (Fig.2). As an example, its value at the load $I_c = 40\text{A}$ was about $36\text{ mV}/^\circ\text{C}$.

Owing to temperature gradients along the stack, an averaged value of the temperature coefficient of the voltage, over the entire stack or over 10-cell groups, seems to be more significant

than a value measured on a single-cell. The values relevant to 10-cell groups were taken on groups in the central region of the stack (see also the caption of Fig.1), where temperature gradients are smaller. Average single-cell values were estimated on the basis of these measurements, and the average of all evaluations at the various loads gives about 0,23 mV/°C per cell.

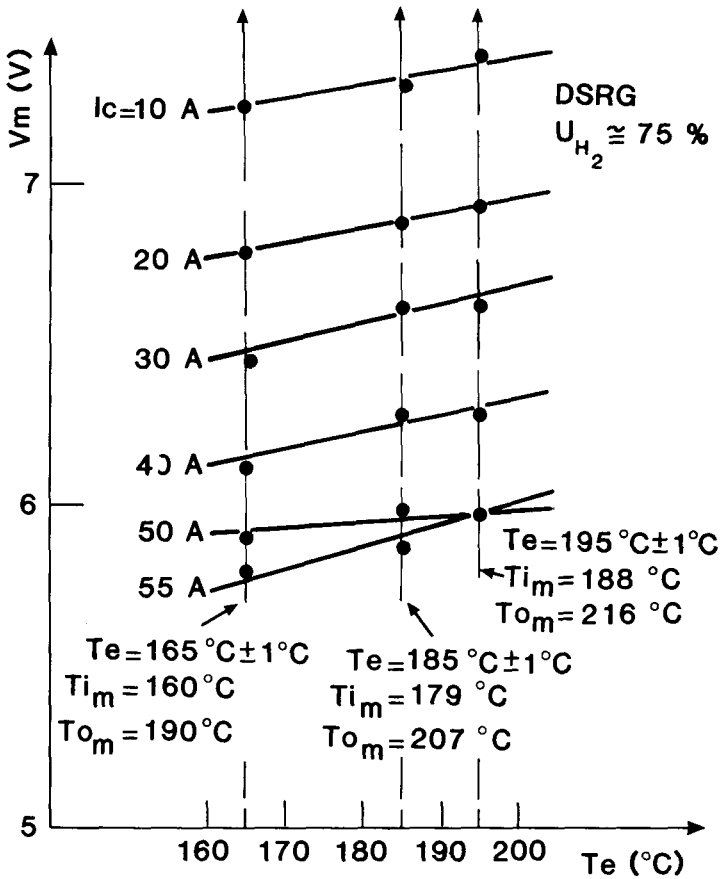


FIGURE 2

The average ten-cell voltage (see caption of Fig.1 for the symbols) as a function of temperature: the slope of the straights gives the temperature coefficient of the voltage, as mentioned in the text.

As a general conclusion, two further steps of experience were gained in the far-from-the-factory operation of portable kW-size air-cooled PAFC systems: 1) properly sealed, these systems can be shut-down for months in humid climates, with no measurable degradation effect; 2) on-site rewicking requires no more specialized training than does normal operation.

ACKNOWLEDGMENT

Thanks are due to Sandy Abens of ERC for assistance and fruitful discussion.

REFERENCES

- (*) Energy Research Corporation, Danbury, Connecticut.
- (1) A.Ascoli and G.Redaeli - Rendiconti della 84a Riunione Annuale dell'AEI - Cagliari, 2-5 ottobre 1983.
- (2) A.Ascoli and G.Redaeli - 1985 Fuel Cell Seminar Abstracts Tucson, Arizona, May 19-22, 1985.
- (3) A.Ascoli and G.Redaeli - Proceedings of the UNESCO Workshop on Fuel Cells: trends in research and applications Ravello, Italy, June 10-14, 1985.
- (4) A.Ascoli and G.Redaeli - Poster presented at the XX Congresso della Associazione Italiana di Chimica Fisica Torino, 21-24 ottobre 1985.

RECOMMENDATIONS FOR COMMERCIAL ONSITE FUEL CELL GRID-INTERCONNECT REQUIREMENTS

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INTRODUCTION

A program demonstrating experimental 40 kW fuel cell power plants in onsite applications is underway throughout the United States. The program is sponsored by individual utility companies; the Gas Research Institute (GRI), and the U.S. Department of Energy (DOE). The fuel cell power plants are fabricated by International Fuel Cells (IFC).

The power plants were originally designed to operate independent of the utility grid. The requirement for a grid-connected operating mode was added subsequent to the design and testing of the basic power plant. To accomplish this, a Grid-Connect Unit (GCU) was added to interface the grid-independent power plant to the utility grid. Twenty-eight of the 32 utility participants chose to operate 29 fuel cell power plants in the grid-connect mode.

OBJECTIVES

To resolve technical issues identified during the field test and assist in the development of future grid-connect features, a Grid-Connect Technical Committee comprised of utility participants was established to review the field test experience and establish grid-interface requirements for future power plants. The objectives of the Committee were to:

- o Review and summarize the 40 kW field test experiences related to grid-interconnections;
- o Outline and coordinate additional testing or grid monitoring activities, and
- o Review and define interconnect and other requirements for a commercial onsite fuel cell power plant.

To meet these objectives the major issues addressed by the Committee were: Protection Issues, Electrical Engineering Issues, and Grid-Interconnection Requirements. The Grid-Connect Technical Committee was divided into three Subcommittees to review Protection Issues, Electrical Engineering Issues, and Utility Grid-Interconnect Standards.

PROTECTION ISSUES

The task of the Subcommittee was to identify and emphasize what needs to be done to protect both the utility grid system and the fuel cell. The major emphasis of protection engineers was that at least two independent protection systems would be required, one to protect the power plant from the utility grid and one to protect the grid from the power plant. The Committee also recommended that the ability to test the operation responsiveness and accuracy of the fuel cell protection functions while the unit is in operation would be required prior to the acceptance of a protection system by the electric utility industry.

The intent of the System "A" protection system is to protect the fuel cell and customer whether they are connected to the grid or not. System "A" should trip the fuel cell and/or the grid-interconnect.

System "A": - Located in Fuel Cell Grid-Connect Unit

- Overfrequency (81-0)
- Underfrequency (81-U)
- Overvoltage (59)
- Undervoltage (27)
- Short circuit/overcurrent per phase (51)
- Ground fault (51N) or (59N)
- Phase voltage balance or current balance (60)
- Port for remote receive transfer trip (reconnect)
- Remote emergency shutdown switch

System "B" is to separate the fuel cell power plant from the grid when an abnormal situation exists either on the grid or the fuel cell/customer premises. System "B" should trip the grid-interconnection only.

System "B":

- Overfrequency (81-0)
- Underfrequency (81-U)
- Overvoltages (59)
- Undervoltages (27)
- Short circuit/overcurrent per phase (51)
- Ground fault (51N) or (59N)
- Phase voltage balance or current balance (60)

ELECTRIC ENGINEERING ISSUES

The topics addressed by the Subcommittee include power quality, harmonics, impedance, grounding, fuel cell operating features and switch gear.

Power Quality

Power quality is an important issue for utility-connected cogeneration systems and will become more important as large numbers of systems are connected to the electric grid. Power quality includes both power factor presented to the utility along with current and voltage harmonics. In designing static power converters (SPCs), it is essential to take into account AC voltage, the magnitude and frequency of voltage transients, voltage and current imbalances, surge currents, and harmonic tolerance of the electric distribution system.

Harmonics

Industry-wide, no standards exist for minimum harmonic levels that may be injected into the utility grid by dispersed storage and generation systems. For a commercial fuel cell power plant the Subcommittee reached a consensus regarding the setting of levels for allowable harmonic distortion. A total harmonic distortion (THD) of 2-3 percent for voltage and 4-5 percent for current, based on the full load rating of the SPC, should not be exceeded.

Impedance

The Subcommittee examined statistical data on feeder impedance to determine a typical range of distribution impedance which may be encountered at future fuel cell sites. The Subcommittee found that it is extremely difficult to provide typical impedance values for fuel cell applications due to the diversity of conditions on the various electrical systems. The Subcommittee recommended that the fuel cell be designed to meet harmonic distortion levels over the widest possible range of impedances consistent with economic power plant design, and that the impedance range used in the design should be specified.

Grounding

the output of the commercial fuel cell power plant should be wye connected with the neutral brought out, and should be capable of either grounded or undergrounded wye operation at the interconnected utility's option.

Switchgear

A manual, visible air gap disconnect means should be provided. A shunt-trip break will be needed to disconnect the fuel cell from the utility system. If current-limiting fuses are used in conjunction with the air-break switch, a standard molded-case breaker can be used rather than a hi-capacity breaker.

Operating Features

The 200 kW fuel cell should have emergency grid-independent capability and as an option include no-break capability. Another desirable feature would be for remote control and monitoring of the power plant. The monitoring should include: watt, var, volt, and temperature levels, diagnostic data from the power plant and alarm conditions.

SURVEY OF ELECTRIC UTILITY GRID-INTERCONNECT STANDARDS

Participants in the Onsite 40 kW Fuel Cell Field Test Project were asked to obtain published standards and policies pertaining to the interconnection of dispersed generation systems to their local electric utility grids. Utility requirements for interconnecting dispersed generation to the electric utility grid vary by the size of the system. The typical sizing breakdown is as follows:

- less than 100 kW
- 100 kW - 1,000 kW
- greater than 1,000 kW

There are two major areas of dispersed generation system protection that are concerns of the interconnected utility:

- protection during faults
- protection during normal conditions

Each of these in turn can be further broken down into two general areas:

- protecting the utility from the interconnected dispersed generation or storage system
- protecting the dispersed generation or storage system from the utility.

The survey consensus is that the interconnected utility will not assume responsibility for the protection of the fuel cell equipment from faults or other disturbances on the grid. The information contained in the utility grid-connect standards refers to the minimum protection required to protect the utility grid from the fuel cell or cogeneration system.

CONCLUSIONS

The widespread and significant use of grid-connected fuel cells and other dispersed generation systems give rise to technical issues and concerns of utility system interconnection not encountered extensively prior to the Public Utility Regulatory Policies Act of 1978 (PURPA). Major areas of electric utility concern are:

1. System Protection
2. System Stability
3. System Unbalance
4. System Impedance
5. Voltage Regulation and Reactive Power Requirements
6. Harmonics
7. Utility Operations
8. Metering
9. Distribution System Planning and Design
10. Personal Safety

The efforts of the Committee report defined the major technical issues and requirements associated with the interconnection of fuel cell power plants (and other cogenerators) to electric utility systems. The findings point to some unresolved technical issues and recognize that few standards, specifications, or guidelines currently exist in certain areas of utility concern. However, the Committee did identify general utility requirements necessary for safe and reliable interconnection of fuel cell power plants and dispersed generation systems to utility grids.

Contributing Utilities

Brooklyn Union Gas Company
Consolidated Edison of New York
Consumers Power
Georgia Power
Public Service Electric and Gas
San Diego Gas & Electric
Southern California Gas Company
Tennessee Gas Pipeline
Virginia Power

REMOTE MONITORING AND DISPLAY OF ON-SITE FUEL
CELL SYSTEM PERFORMANCE

THE BROOKLYN UNION GAS COMPANY
AND
SCIENCE APPLICATIONS INTERNATIONAL CORPORATION

An abstract of this presentation was unavailable at press time.

ASSESSMENT OF FUEL CELL APPLICATIONS FOR REMOTE AIR FORCE SITES IN ALASKA

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The objective of the Air Force Remote Site Fuel Cell Development Program is to demonstrate logistic fueled fuel cell power plants at a remote site in Alaska in the early 1990's.

SITE ENERGY SYSTEM DESCRIPTIONS

During 1984 and 1985, remote radar sites in Alaska were undergoing transition from Long Range Radar Stations (LRRS) built in the early 1950s to the Minimally Attended Radar (MAR) facilities which incorporate system consolidation and modernization using less manpower, less energy and having reduced operational requirements.

There are a total of twelve MAR sites, four Phase I, four Phase IIA, and four Phase IIB. The four Phase I sites were constructed from identical designs. The energy system consists of four 175 kW diesel engines used in a cogeneration mode to supply electricity and heat in addition to two 1.4 MMBtuh diesel fueled boilers sized to supply the entire thermal load in an emergency. The four Phase IIA MAR facilities are very similar in design concept. They have four 250 kW generators rather than 175 kW, and there are minor differences between the structures and energy systems at the four sites.

The four Phase IIB sites will no longer be remote sites but will be served by nearby electric grids.

REMOTE SITE ENERGY USE PATTERNS

The thermal and electric energy usage of the remote sites was obtained, summarized and analyzed for 1984 and 1985. The analysis includes comparisons of fuel consumption electricity production, operation parameters, costs and degree days. The data for the LRRS consist of gross monthly oil consumption and corresponding degree days. The annual total kWh usage and Btus consumed were also obtained. Data from the MAR facilities consists of total monthly oil consumption, degree days and kWhs generated. Heat consumption data was not available. The following table is a summary of the remote site energy data collected for 1984. Almost all of the data is based on LRRS facility energy systems.

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Energy Usage Characteristics at LRRS Facilities - 1984

Site	Electric and Thermal Usage		Electric and Thermal Capacity Factors		Thermal to Electric Ratio
	MWH	MBTU	% Electric	% Thermal	T/E
1) Indian Mountain	3,706	20,887	47.0	16.5	1.65
2) Fort Yukon	2,845	**	18.0	—	—
3) Tin City	2,731	23,730	31.2	20.7	2.54
4) Cape Lisburne	3,215	21,092	26.2	16.0	1.92
5) Cold Bay	3,233	**	30.8	—	—
6) Tatalina	3,050	19,436	34.8	52.7	1.87
7) Sparrevohn	3,860	10,583	24.5	13.6	.80
8) Murphy Dome	*	32,119	—	28.5	—
9) Kotzebue	2,573	**	32.6	—	—
10) Cape Newenham *	2,831	22,294	43.0	29.1	2.31
11) Cape Romanzof	3,055	23,210	34.9	24.2	2.22

* Purchased Power is wheeled through local Air Force Base

** Heat recovery equipment used exclusively at these sites

* Data for Cape Newenham is MAR Site Data from 2/84-12/84

Energy data reports were received from the MAR sites during 1985. Engine, boiler and combined fuel consumption for the Phase I and IIA sites were entered into a computer data base. Calculations based on this data and several assumptions provided operational performance parameters as summarized below.

	Average Monthly Degree Days	Average Monthly kWh Generation	Maximum Peak Demand (kW)	Power Plant Capacity Factor	Average Monthly Site Load Factor	Electrical Efficiency
<u>Phase I</u>						
Indian Mountain (MAR)	989	195151	---	.38	---	.34
Sparrevohn (MAR)	1019	167269	390	.33	.59	.34
Tatalina (MAR)	575	196197	---	.38	---	.36
Cape Romanzof (MAR)	980	240824	510	.47	.64	.37
<u>Phase IIA</u>						
Cape Newenham (MAR)	928	178740	350	.24	.70	.29
Ft. Yukon (MAR)	721	87498	240	.12	.45	.35
Ft. Yukon (LRRS)	1615	199603	465	.14	.60	.29
Cape Lisburne (LRRS)	1373	246028	612	.19	.55	.30
Tin City (LRRS)	1267	222271	443	.28	.69	.28

The power plant capacity factors were relatively low. This was expected because of the remoteness of the sites and the criticality of consistent power supply. The site electrical consumption patterns are all similar. Some variances exist due to different climatic conditions, site operating procedures and general site characteristics.

The site load factors show considerable variance from site to site. It is assumed that severe weather fluctuations caused the low load factors. The electrical efficiencies of the MAR site diesel generators was relatively high except for Cape Newenham which has Caterpillar diesel generators rather than Cummins.

DATA ACQUISITION SYSTEM (DAS) INSTALLATION

Fort Yukon was chosen as the preferred location for the installation of a remotely accessed DAS because it was accessible from Fairbanks, was a Phase IIA site and represented a severe north Alaskan climate. The DAS consists of sensors, datalogger and modem for data storage and remote telephone access.

The thermal portion of the instrumentation was installed to monitor the heat contribution to the MAR facility by the energy system. Clamp-on RTDs and nonintrusive ultrasonic flow meters were used to obtain data to calculate the thermal energy supplied to the site from the engines, boilers and electric booster heater. The fuel consumption of each of the four engines and the two boilers was measured with 1/2-inch flow meters. The electrical instrumentation consists of current transformers and watt transducers to measure the electrical consumption of the site.

Data from each sensor is transferred to the memory of the datalogger which is remotely accessed through the modem. The data is transmitted over a telephone line to a personal computer in SAIC's San Diego office where it is stored for further manipulation.

The information obtained at Fort Yukon will be used to determine the technical and economic feasibility of using onsite fuel cell power plants to meet the energy needs of the MAR facilities in place of diesel engines.

ENERGY SYSTEM LIFE CYCLE COST MODEL

An economic model was developed to evaluate the life cycle costs of remote site energy systems. It was developed specifically to analyze diesel engine systems and fuel cell power plants, but could be adapted to analyze other energy systems. The model was exercised to prove its validity with actual data from the remote site systems.

The model is written in FORTRAN and will run on an IBM compatible micro computer. It is menu driven to make it easy to use and it is programmed for maximum flexibility.

A sample run of the life cycle cost model was made based on the most accurate data available for a generic MAR site. Fifteen menu pages are used to input data to the program and three output pages show the results. The first page of the output is a summary of the inputs. The generic MAR site test case was based on the inputs shown below.

Life Cycle Cost Analysis Model Input Data

System Description

Prime mover(s)		Cummins Engine
Number of generators	4	Units
Electrical capacity	250	kW/unit
Boiler thermal capacity	2.8	MMBtu/hr
Boiler efficiency	80	%
Years of analysis	20	Years
Basic fuel cost	1.5	\$/gal
Basic oil cost	4.7	\$/gal
Installation cost	886000	\$
Construction start date		1/1986
On-Line date		1/1987

Inflation Rates

Consumer Prices	6	%
Fuel Prices	6	%
Electricity	6	%
Discount Rate	6	%

This work was conducted under a contract with the Belvoir Research, Development and Engineering Center.

EFFECT OF OPERATING CONDITIONS ON PERFORMANCE OF HIGH-PRESSURE TYPE PAFC

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Y. Nanba
Kokubu Works

Introduction

Hitachi Ltd. was involved in research and development of phosphoric acid fuel cell (PAFC) technologies under the Moonlight Project from 1981 to 1984.

In 1985, Hitachi Ltd. began construction of a 1 MW high pressure and high temperature type demonstration plant for concentrated power generation in cooperation with NEDO, Chubu-Electric Corp. and Toshiba Corp. Prior to the plant operation various simulation tests of operating conditions were performed to examine the stabilities of the cell performance using 100 cm² 5-cell stacks. This report summarizes results of these efforts.

Cell performance on rated operating conditions

Figure 1 shows cell performance at high pressure and high temperature conditions. Mean voltage loss from 1000 h to 10000 h was 5 mV/1000h and seemed to decrease with time.

Effect of differential pressure between anodes and cathodes

A relatively large transient differential pressure between anodes and cathodes of the stacks may occur when the plant assumes an emergency off operating mode.

Figure 2 shows the effect of differential pressure on the cell voltages. Simulated differential pressure up to 500 mmAq and 10 pulses, 10 seconds in duration did not have any effect on the cell voltages.

Effect of steam concentration

Steam concentration in the cell changes along the gas channels, as well as the cell inlet steam concentration and gas utilization. Therefore, cell performance must be stable for a wide range of steam concentrations.

Figure 3 shows cell performance which simulated one air inlet / fuel inlet position of a large size cell. In this position, the cell was operated at 10 % air utilization and 13 % fuel utilization.

Figure 4 shows the performance of another cell which simulated two other fuel outlet positions. In order to adjust gas compositions, another stack was connected in series to the upper stream of the test stack and exhaust gases from the former stack were supplied to the test stack.

Steam concentration up to 22 vol% corresponding to the air outlet position was tested and did not have any significant effect on the endurance.

Effect of air deficiency

Figure 5 shows the effect of a temporary air deficiency on cell voltages. Though the cell voltage decreased to almost 0 mV when air was in short supply, it recovered soon after more air was supplied.

Effect of fuel deficiency

Figure 6 shows the effect of a temporary fuel deficiency on cell voltages. When there was a fuel deficiency, cell voltage of one cell decreased to lower than -0.4 V while that of the other cell remained positive. Although the fuel was in short supply for only a few seconds, the former cell experienced an irreversible after effect on its performance.

These phenomena may be explained as electrolysis erosion on the fuel-deficient anode due to the electric potential of the relatively good cells connected electrically in series.

Acknowledgements

The authors wish to thank Mr.K.Joukou and Dr.K.Nozaki of the Agency of Industrial Science & Technology of MITI, Mr.K.Shirahama, Dr.N.Ito and Mr.M.Ito of NEDO for promoting the PAFC Research and Development of the Moonlight Project.

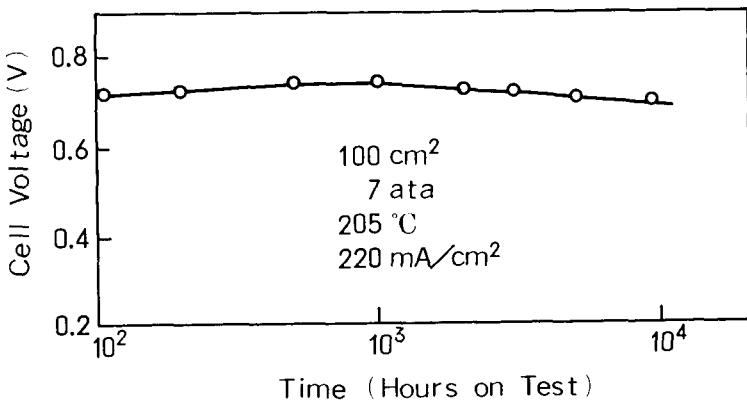


Figure 1 Endurance Test

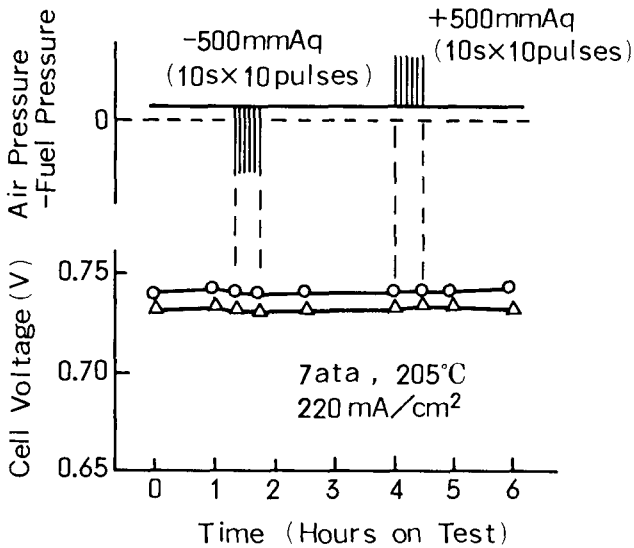


Figure 2 Effect of Differential Pressure on Cell Voltage

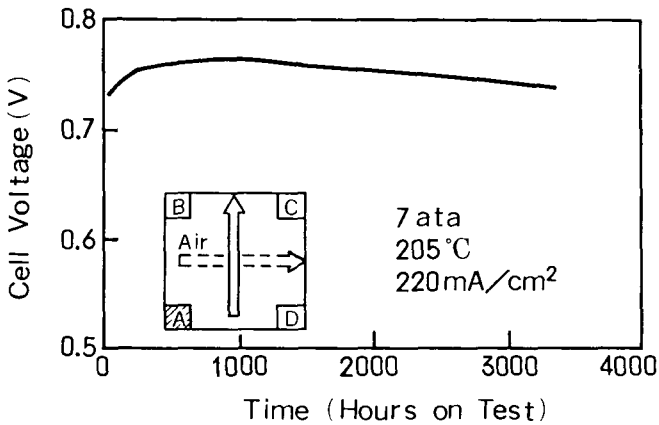


Figure 3 Cell Performance Corresponding to One Air inlet/Fuel inlet Position

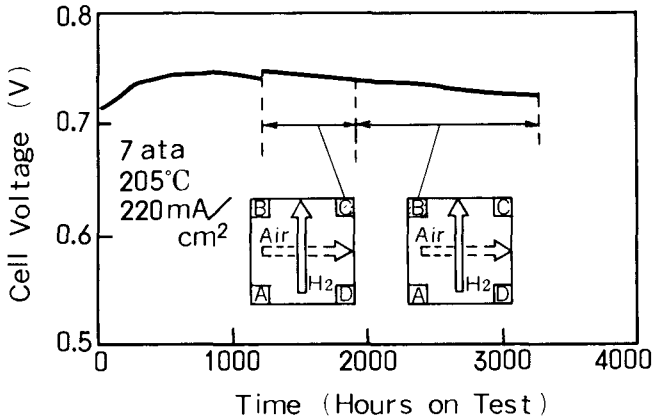


Figure 4 Cell Performance Corresponding to Two Different Positions

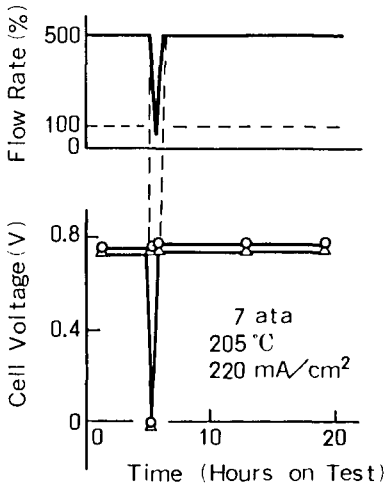


Figure 5 Effect of Air Deficiency on Cell Voltage

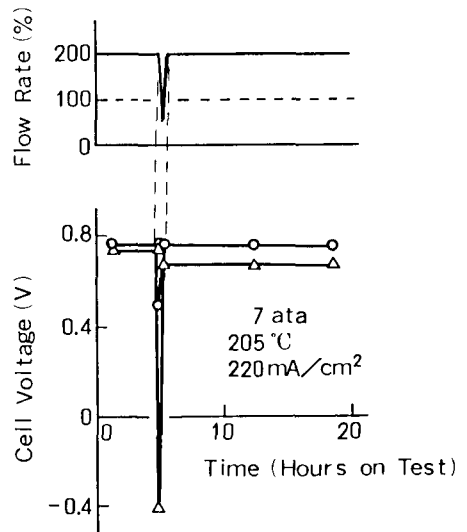


Figure 6 Effect of Fuel Deficiency on Cell Voltage

DYNAMIC RESPONSE OF FUEL CELL POWER PLANT TO LOAD REFERENCE

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INTRODUCTION

The Tokyo Electric Power Co., Inc. and Toshiba Corporation developed a dynamic simulator for a class of fuel cell power plant (FCPP) of commercial scale⁽¹⁾. The simulator is used for the study of dynamic characteristics and controllabilities of FCPP.

This report briefly describes the simulator and presents some results obtained by the simulation.

SIMULATOR CONFIGURATION

The FCPP dynamic simulator simulates the dynamic characteristics including the response to the load change. The simulator includes reformer, shift-converters, cell stack, turbo-compressor, inverter, cell stack cooling system and plant controller (see Fig.1).

The inputs to the simulator are the active power and reactive power which are required. The simulator has about 90 output variables (pressures, flow rates, temperatures, lifts of control valves and so on) and 70 state variables. The simulator is based on the non linear physical model. The language used to describe the simulator is FORTRAN-77.

The basic equations applied are listed in the following.

• Flow Rate	$F = \sqrt{\rho (P_h - P_l) / \eta} / W_m$	[1]
• Pressure	$dP/dt = nRT(F_i - F_o) / V$	[2]
• Temperature	$dT/dt = (Q_{cond} + Q_{conv} + Q_{reac}) / M_{cp}$	[3]
• Energy Transfer	$dh_o/dt = RTf(h_i - h_o) / (PV)$	[4]
• Gas Composition Transfer	$dx_o/dt = RTf(x_i - x_o) / (PV)$	[5]

where

F: Gas Flow Rate[kmol/hr] (i: inlet side o: outlet side)
P: Gas Pressure[kg/cm²] (h: higher side l: lower side)
 η : Flow Resistance[hr²/cm²/m²] W_m : Molecular Weight[kg/kmol]
n: Polytopic Constant R: Gas Constant[kgm/kmol^oK]
T: Temperature[^oC] V: Volume[m³]
 ρ : Gas Density[kg/m³] M_{cp} : Heat Capacity[kcal/^oC]
Q: Heat Flow Rate[kcal/hr] h: Gas Enthalpy[kcal/kmol]
(cond: conductivity conv: convection reac: reaction)
x: Gas Composition c_p : Specific Heat[kcal/kmol^oK]

A part of the simulator block diagram is presented in Fig.2. It represents the model structure of the fuel line which simulates the dynamic responses of reformer, shift-converter, anode of cell stack and reformer burner. Other submodels included are air line model, cell stack model, cell stack cooling model, inverter model and controller model.

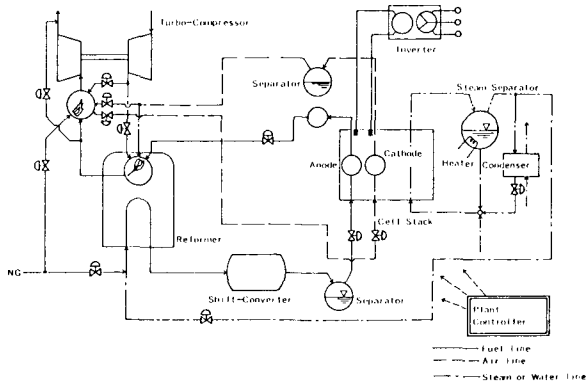


Fig.1 Basic Schematic of FCPP Dynamic Simulator

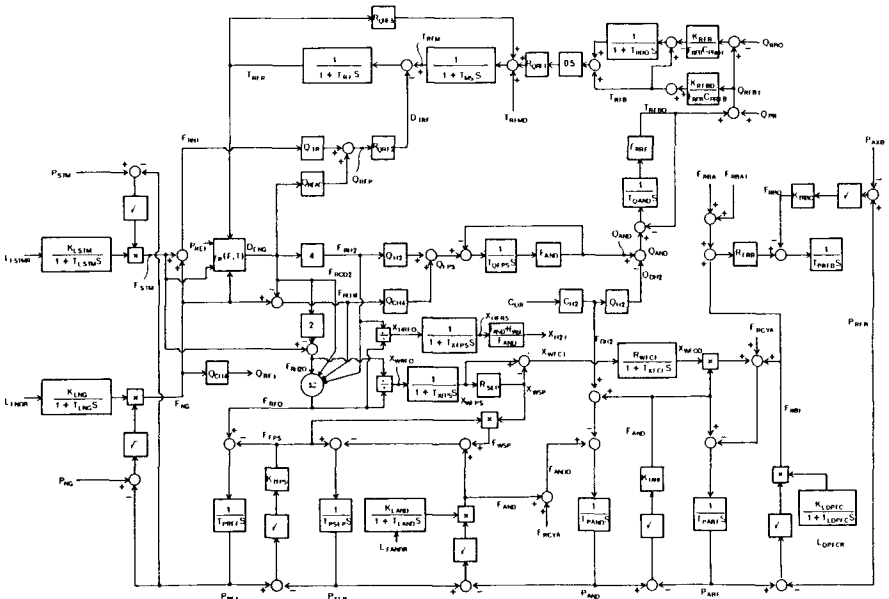


Fig.2 Block Diagram of Fuel Line Model

SIMULATION RESULTS

Simulation studies are applied to improve dynamic characteristics of FCPP. An example of simulation results is shown in Fig.3. This result shows the dynamic response of FCPP major variables when the load reference is decreased from rated power (11MW) to the minimum power at the rate of 1MW/sec, where the symbol denotations in Fig.3 are listed in Table 1.

In this result, FCPP finally settles down to the minimum power indicated. But problems are found in the transient state, which are listed in the following.

- (1) Immediately after the sudden decrease of the active power, the cell voltage (VCEL) goes up. Especially the overshoot of VCEL is recognised in the transient state, which is not desirable for the span of the cell life.
- (2) Maximum value of the fluctuation of the pressure difference between the anode and the cathode is about 750mmAq and this value is severe to the performance of electrolyte.
- (3) The response of the combustion at the reformer burner is not stable. The combustion temperature (TRFB) varies with wide range and the incomplete combustion occurs.

CONCLUDING REMARKS

The authors investigate the dynamic characteristics in detail based on the actual load pattern and aim to develop better design of FCPP and control system based on these studies.

REFERENCE

1. EPRI, "Description of a Generic 11-MW Fuel Cell Power Plant for Utility Applications", EPRI EM-3161 Interim Report, Sep 1983.

Table 1 Simulation Output Variables

PAC	Active Power	FAND	Anode Flow Rate
QAC	Reactive Power	FCAT	Cathode Flow Rate
IA	Current Density	FNG	Reformer NG Flow
VCEL	Cell Voltage	FACBF	AUX. BRN. NG Flow
PAND	Anode Pressure	TRFM	Reformer Metal Temp.
PCAT	Cathode Pressure	TRFR	Reformer Reac. Temp.
DPFC	Stack ΔP	DTRFM	Metal Temp ΔT
PSEP	FPS Sep. Pressure	TRFB	Reformer Comb. Temp.

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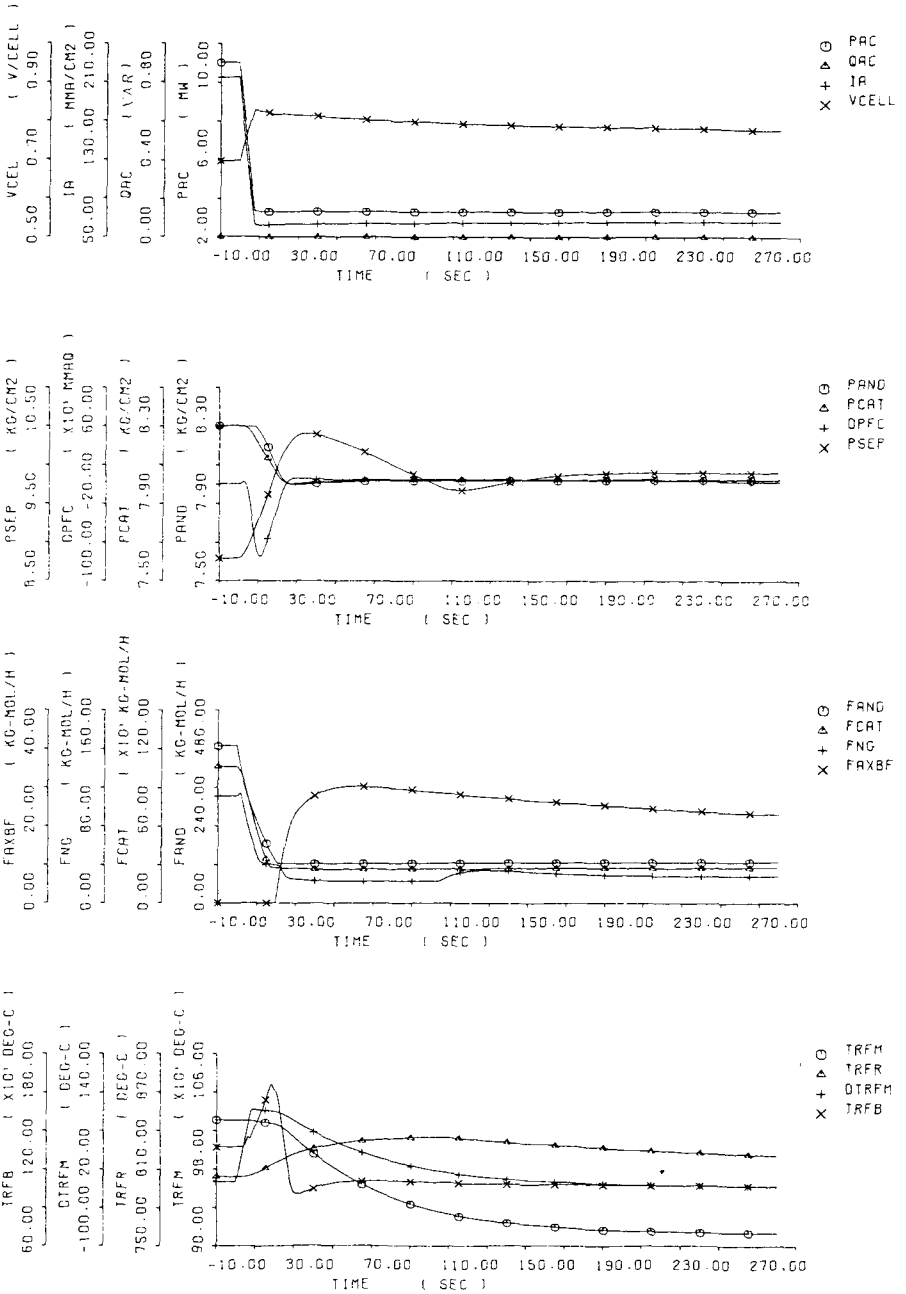


Fig.3 Simulation Result (Case of the Load Decrease)

POWER GENERATION TEST RESULTS OF 50kW PAFC
TEST PLANT PRESSURIZED BY 2-SHAFTS 2-STAGE TURBOCOMPRESSORS

TOKYO ELECTRIC POWER CO., INC.
AND
TOSHIBA CORPORATION

An abstract of this presentation was not available
at press time.

ELECTRIC UTILITY PHOSPHORIC ACID FUEL CELL TECHNOLOGY DEVELOPMENT

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International Fuel Cells Corporation (IFC) is conducting a number of component technology programs for electric utility phosphoric acid fuel cell power plant development under the sponsorship of the U.S. Department of Energy (DOE), with technical management provided by the National Aeronautics and Space Administration/Lewis Research Center (NASA-LeRC), the Electric Power Research Institute (EPRI), the Niagara Mohawk Power Corporation (NIMO), the Northeast Utilities Service Company (NUSCO) and IFC itself. Current programs are directed towards advancing the technology base established for IFC's multimegawatt power plant commercialization program. Specific areas to be addressed in this presentation include cell stack technology, reformer technology, inverter technology and power plant control system studies.

Large area cell stack development was continued under DOE and IFC programs. Materials and manufacturing processes have been verified in three (3) 10-ft², 28-cell stacks. Components for the 10-ft², 469-cell stack have been manufactured and assembly will be started shortly. A structural mock up of the full-height stack with manifolds attached is shown in Figure 1.



Figure 1. Full-Height 10-Ft² Mock Up with Manifolds Installed

The stack will be tested in a semi-automated test facility for up to 4500 hours. Testing will be initiated in the last quarter of 1986.

Under EPRI sponsorship, a full-scale single-tube reformer utilizing a low pressure drop catalyst was evaluated for a total of 396 hours of testing with both natural gas and naphtha, with the objective of significantly increasing fuel throughput. Increased fuel throughput per tube would allow fewer but longer tubes to make up an equivalent rated reformer. Under DOE/NASA sponsorship, the same low pressure drop catalyst, described above, was evaluated for tolerance to carbon formation. Over a range of specific fuel flows (W/A) of 1.0 to 3.5 lb fuel/hr-ft² at 125 psig, no carbon formation was observed.

The success of these tests has led to the design of the longer reformer tube started under EPRI and completed under DOE/NASA. A test facility, shown in Figure 2, was constructed by EPRI to verify performance of a longer single tube at power plant operating conditions later this year. A 18-foot reformer tube is being constructed by DOE/NASA for this test.



Figure 2. Tall Reformer Tube Test Facility

EPRI has also sponsored construction of the reformer burner test facility shown in Figure 3. This facility will test commercial burners sized up to the equivalent heat release of 2MW. Testing of the first commercial burner will be conducted in late 1986.



Figure 3. Reformer Burner Test Facility

A 2-MW power switching pole for a two-bridge inverter system constructed under an EPRI Program was tested under DOE/NASA sponsorship, to its full rated 3000 Vdc. Dynamic operating parameters were in agreement with analytical predictions. A full size set of advanced inverter controls for a two-bridge inverter was successfully tested at design and off-design conditions on IFC's two-bridge inverter model. One of these control units, shown in Figure 4, was procured by EPRI and used to control the power switching pole test. In preparation for the design and construction of an advanced multimegawatt inverter bridge, a semiconductor manufacturer's survey is currently being conducted.

Definition of applications software requirements for an 11-MW power plant were generated under a program jointly sponsored by Niagara Mohawk and Northeast Utilities.



Figure 4. Control Unit for Power Switching Pole Test

ACKNOWLEDGEMENTS

The work upon which this abstract is based was performed in part pursuant to NASA Contract DEN3-364 funded by DOE (Mr. P. Prokopius of NASA, Project Manager), DOE Contract DE-AC21-83FE60338, (Mr. P. Prokopius of NASA, Project Manager and Mr. E. Beyma of DOE, Program Manager), EPRI Agreement RP-1777-1 (Mr. D. Rastler, Project Manager and Mr. E. Gillis, Program Manager), Purchase Order No. 34094 with Niagara Mohawk Power Corporation (Mr. A. Stefanski, Technical Manager) and Purchase Order No. 647129 with Northeast Utilities Service Corporation (Mr. R. Bumstead, Technical Manager).

AIR COOLED STACK DEVELOPMENT STATUS
WESTINGHOUSE PHOSPHORIC ACID FUEL CELL PROGRAM

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INTRODUCTION: The Westinghouse Phosphoric Acid Fuel Cell Program key objective is to commercialize the technology in the 1990's as a world class product for Utility power plant applications. The Corporation has been developing the PAFC technology for over a decade. In 1980, the Advanced Energy Systems Division began an aggressive program for the application of this air cooled technology for power generation to utility (all electric) and industrial (cogeneration) needs. The technology development is sufficiently in hand such that large stack demonstrations are proceeding. The program performance goal of 690 mV per cell at beginning-of-life has been exceeded by 10 mV. The program goal for performance loss with time of 8 mV/1000 hours or less has yet to be fully demonstrated in long term testing. These goals are for rated conditions of 190°C, 70 psia, 267 mA/cm², with air to the cathode at 50% oxygen utilization and simulated reformat fuel (75% H₂, 24% CO₂, 1% CO) to the anode at 83% hydrogen utilization.

SMALL STACKS: To date 37 nine and ten cell small stacks have been built and tested for an accumulated test time of over 33,000 hours (by time of seminar over 42,000 expected) with one (two by seminar) stack having accumulated over 5000 hours. Currently, the small stack program is in the technology verification phase where three stacks are on test for 5000 hours each and one of which will continue for 10,000 hours. Figure 1 is a photograph of this demonstration stack. The beginning-of-life performance for these stacks is 700 mV/cell with a standard deviation of 7 mV. The performance decay is presented in Figure 2 for these stacks. As noted, this goal is achieved early in life (<1500 hours) but on the average is about -12 mV/1000 hours. The cause of this higher decay rate is being investigated.

Typical stack performance characteristics at the rated operating point as influenced by the operating parameters are as follows:

<u>Operating Parameter</u>	<u>Performance Characteristics</u>	<u>Range</u>
Polarization	-0.46 mV/mA cm ⁻²	215-315 mA cm ⁻²
Air Utilization	-0.47 mV/% Utilization	40-60%
Fuel Utilization	-0.16 mV/% Utilization	70-85%
Stack Temperature	+1 mV/°C	180-200°C
Stack Pressure	+1 mV/psi	65-75 psia
H ₂ to SRG Loss	-16 mV/cell	-

LARGE STACKS: Development effort has shifted to the non-repeating components associated with large stacks. Seven large stacks are planned for fabrication by May 1987. The first large stack is on test, the second is being readied for test and the third is in fabrication. This stack has 152 cells and is rated at 32 kW. Its photograph is provided in Figure 3. This stack is the basic building block for the larger stack containing three 32 kW stacks and rated at 96 kW. An artist rendition of this stack is shown in Figure 4. The 375 kW module will consist of four of these stacks assembled as a cruciform with a common air cooling exit plenum at the center.

The first large stack initial performance is 690 mV/cell average with a standard deviation for the 6 cell groups of 20 mV. This beginning-of-life performance compares very well with the small stacks.

CONCLUSIONS: The technology and design data bases are complete for small stacks with the large stack development effort well underway and being given the primary program emphasis. Small stack endurance testing of up to 10,000 hours is in process with indications that the degradation rate is 50% greater than the goal and this is being investigated. The beginning-of-life performance goal is demonstrated and exceeded.

The technology is sufficiently in hand to proceed with large stack and module development as required for the 1.5 MW Pilot Power Plant demonstration.

ACKNOWLEDGEMENT: Funding for the work was provided by the U. S. Department of Energy through the NASA Lewis Research Center, Contract Number DEN3-290, Mr. R. B. King, Project Manager.



FIGURE 1

RATED PERFORMANCE OF WESTINGHOUSE AIR COOLED SMALL STACKS

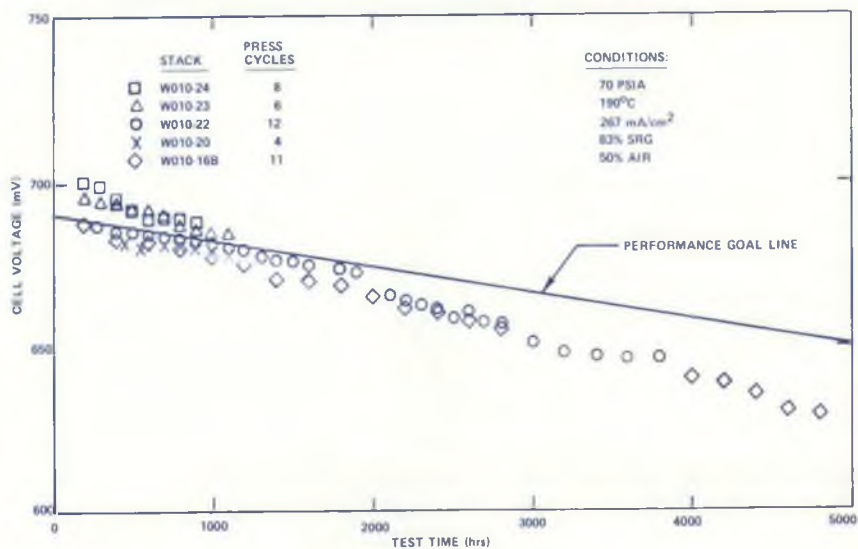


FIGURE 2



FIGURE 3

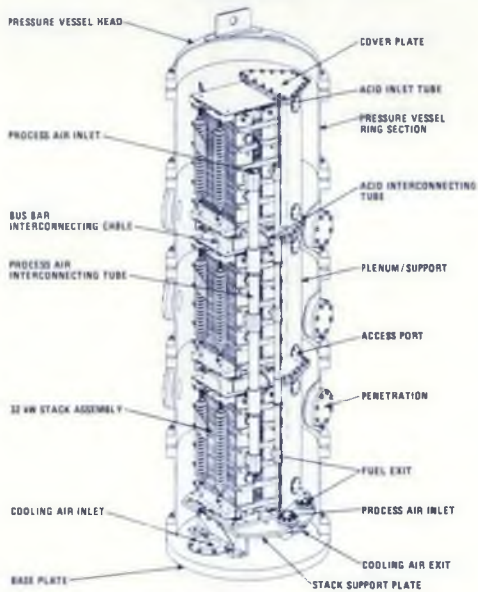


FIGURE 4 100 kW STACK ENGINEERING MODEL

CONSTRUCTION OF DISPERSED TYPE 1 MW PAFC PILOT PLANT

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INTRODUCTION

Mitsubishi Electric Corporation, Fuji Electric Co., Ltd. and Fuji Electric Corporate Research and Development, Ltd. constructed the 1 MW phosphoric acid fuel cell power plant under contract with the New Energy Development Organization (NEDO). The pilot plant is located in Sakaiko thermal power station, the Kansai Electric Power Company, Inc. (KEPCO). KEPCO provided buildings and supply of fuel and so on under contract with NEDO. Demonstration operation test is scheduled to start in December, 1986. The design target of the pilot plant is shown in Table 1. The construction schedule is shown in Fig.1.

Table 1 Design Target of the Pilot Plant

Item	Design Target
Output Power	1 MW AC
Efficiency	40% (HHV Base)
Operating Condition	4kg/cm ² G, 190°C
Fuel	Natural Gas
Cooling Method of Fuel Cell	Water Cooled

Fig.1 Construction Schedule

Item	FY	1984				1985				1986				1987			
		A	J	O	J	A	J	O	J	A	J	O	J	A	J	O	J
1. System Design		-----															
2. Components																	
(1) Cell Stacks		-----										=====					
(2) Other Components		-----							=====								
3. Civil Works						-----											
4. Piping and Wiring						-----											
5. PAC Test										-----							
6. Trial Operation												=====					
7. Operation														=====			

----- Design ----- Manufacture ===== Installation

OUTLINE OF PLANT LAYOUT

The main part of the pilot plant was housed in a building. This layout was chosen to check the environmental conditions of future dispersed type PAFC power generation plant in urban or suburban area and to make favourable conditions for construction, operation and maintenance of the pilot plant.

The outline of the pilot plant is shown in Fig.2.

DETAILS OF SUBSYSTEMS

Fuel cell stacks

Each of four 260 kW dc fuel cell stacks was divided to several blocks containing about 100 cells. After assembling cells to blocks, each block was tested in the factory. In this block test, the expected cell performance was confirmed. The 260 kW dc fuel cell stack contained in a pressure vessel is shown in Fig.3.

Reformer

The fuel processing subsystem including the reformer, shift converters, heat exchangers was inspected by MITI's conventional standard for thermal power generation.

By the end of last year, the reformer was installed at the site. Fig.4 shows the reformer assemblies under construction at the site.

Control system

Control system consists of the system controller, unit controllers, computers and operator console and so on. As for the system controller, the man-machine interface system and record/report format including CRT display were designed. Fig.5 shows the operator console. The testing of each control system component was completed and the PAC test began in the beginning of May, 1986.

B.O.P

As for the turbine-compressor unit, all components were assembled and tested in the factory before shipping.

Power conditioning system consists of two 500kW inverters connected in parallel at 6.6kV ac bus, converting the dc output power of two series-connected 260kW dc fuel cell stacks to ac power respectively.

Water treatment system, flare stack, cooling tower, air compressor system, hydrogen system, nitrogen system and other equipments were manufactured. By the end of March 1986, the installation of B.O.P subsystem has been completed at the site.

PAC TEST

The pilot plant except for fuel cell stacks had been constructed at the site by the end of April, 1986. Instead of the fuel cell stacks, the dummy stacks were also installed in the pilot plant.

In the middle of May, 1986, the natural gas was introduced to the system. After the testing of each components, system control and interlockings, the PAC test of the system is going now on.

Acknowledgement

The work of this pilot plant is performed in the Moonlight Project of MITI and authors express their gratitude to Messrs. K. Joko, K. Nozaki and K. Shimamura of AIST (Agency of Industrial Science and Technology), MITI.

Reference

N. Itoh et al. "Outline of Dispersed Type 1 MW PAFC Demonstrator", Fuel Cell Seminar Abstracts, 1985, pp67-70.



Fig.2 Outline of
the pilot
plant

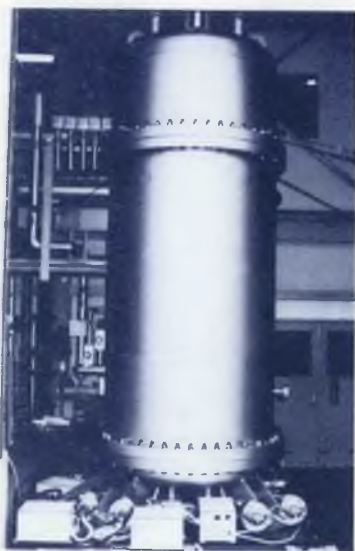


Fig.3 Fuel Cell Stack



Fig.4 Reformer

Fig.5
Operator
console



OUTLINE OF PAC TEST FOR 1MW PAFC
PILOT PLANT-HIGH TEMP., HIGH PRESSURE TYPE

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Introduction

The pilot plant was constructed by NEDO's fund at Chita Daini Thermal Power Station, Chubu Electric Power Co., Inc. (CEPCO)
The targets of the plant design are shown in table 1.

Table 1 Targets of 1MW Pilot Plant

Item	Target
Output Power	1MW ac
Efficiency	42% (HHV base)
Operating Condition	7 ata, 205°C (Fuel Cell)
Fuel	Natural Gas
Start up Time	4 hr
Load Following	25→100% 1 min.
Emission	NOx<20ppm, SOx<0.1ppm

Design, manufacture and installation of the plant were performed jointly by Hitachi and Toshiba and schedule management, civil work, building and supply of fuel and utilities were done by CEPCO.

Outline of the pilot plant

The pilot plant consists of generating unit building, main building including electric machine room, control room and meeting room, utilities as shown in figure 1.



Figure 1
Outline of
the pilot plant

The power section consists of four stacks of fuel cells which were made by Hitachi and Toshiba half and half. Natural Gas fuel consumed in the pilot plant is supplied from the main fuel pipeline of Thermal Power Station. The pilot plant output is connected to power supply system (6.6kV) of Thermal Power Station.

Progress of PAC Test

PAC Test was begun from February '86 and will be completed in September '86.

Main items of PAC test are plant pressurized test, air processing subsystem test, fuel cell cooling water subsystem test, fuel processing subsystem test and plant overall test using dummy cell stacks.

Schedule and progress of PAC Test is shown in figure 2.

Item	'86								
	1	2	3	4	5	6	7	8	9
Plant Pressurized									
Air Processing Subsystem									
Cell Cooling Water Subsystem									
Fuel Processing Subsystem									
Plant Overall									
Using Dummy Stacks									

Figure 2 Schedule and Progress of PAC Test

Results of Main Subsystems Testing

(1) Air Processing Subsystem

The test of Air Processing Subsystem (APS) consists of the following four major items.

1. Air Starting Test

Verification of turbine compressor start control.
Checking out air purge in auxiliary combustor.

2. Auxiliary Combustor Burner Ignition Test

Verification of Pilot and main burner ignition failure routine. Pilot and main burner ignition.

3. Acceleration Test

Verification of turbine compressor acceleration control.

4. APS Test

Verification of plant base pressure control.
Confirmation of turbine compressor characteristics.
Confirmation of APS general characteristics combined with the fuel processing subsystem. Auxiliary combustor burner fuel transition test from natural gas to process gas.

An example of the APS test result is shown in figure 3. The plant base pressure control was successfully performed and it was verified that APS had satisfactory performance.

(2) Fuel Processing Subsystem

The test of Fuel Processing Subsystem (FPS) consists of the following five major items.

1. Nitrogen Recirculation Test

Verification of start recycle blower control.
Checking out air purge in reformer combustion chamber.

2. Reformer Burner Ignition Test

Verification of Pilot burner ignition failure routine.
Pilot burner ignition. Verification of main burner ignition failure routine. Main burner ignition.

3. Heat-up Test

Heating up the fuel processing subsystem with start recycle blower. Steam-in test.

4. Low Temperature Shift Converter (LTSC) Catalyst

Activation
Removal of oxide film on catalysts with hydrogen.

5. Reforming Test

Confirmation of reformer characteristics. Activation of high temperature shift converter (HTSC) catalyst.
Confirmation of general characteristics combined with the reformer, HTSC and LTSC.
Reformer burner fuel transition test from natural gas to process gas.

An example of the reforming test result is shown in figure 4 and 5. Fuel transition was successfully performed and it was verified that the reformer, HTSC and LTSC had satisfactory performance.

Acknowledgement

The pilot plant is performed under Moonlight Project of Agency of Industrial Science and Technology, MITI and we express our gratitude to Messrs. K. Joko, K. Nozaki and K. Shimamura of MITI.

Journal Article

N.ITO ET AL, "Outline of 1 Megawatt PAFC Demonstrator
- High Temperature, High pressure type "National Fuel Cell Seminar Abstracts, May 19-22, 1985, pp.75-78.

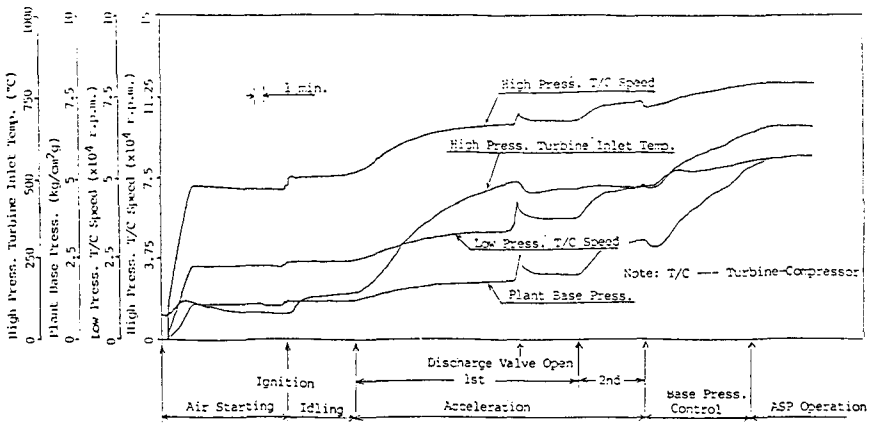


Figure 3 Characteristics of APS Starting

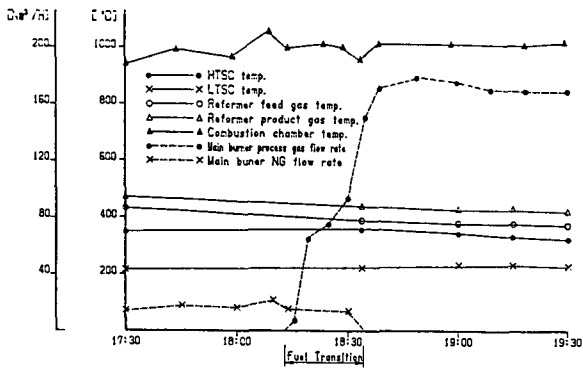


Figure 4. Characteristic of temp. & flow of FPS

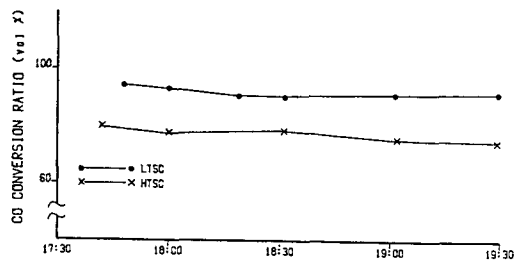


Figure 5. Characteristic of shift converter

FUEL PROCESSING SYSTEM DEVELOPMENT AND
REFORMER TEST RESULTS

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Fuel processing systems for phosphoric acid fuel cell power plant applications require design changes and process improvements relative to conventional hydrogen plants. Although the process chemistry is still based on hydrocarbon-steam reforming, the plant must be more efficient, modularized, faster responding, pressurized on the combustion side, cost-effective, and capable of withstanding frequent thermal cycling. Westinghouse Electric Corporation, under sponsorship of the Electric Power Research Institute (EPRI), has conducted a multi-year development program to define and assess fuel processing system requirements and to develop concepts satisfying them.

Early work on this program identified the shortcomings of conventional steam reforming hydrogen plants and established design requirements for both the overall fuel processing system and the steam reformer. In particular, it was determined that the conventional unpressurized radiant reformer furnace must be replaced by an advanced reformer. Haldor Topsoe A/S of Copenhagen, Denmark, and their U.S. subsidiary, Haldor Topsoe, Inc. of Houston, Texas, who are world leaders in the design and construction of steam reforming hydrogen plants, joined the program as the reformer developer.

Haldor Topsoe has developed a high-efficiency steam reformer for the fuel cell power plant application. The steam reformer is the key item in the fuel processing system and in order to improve the thermal efficiency of the plant, the heat content of the process gas and the flue gas must be utilized to a higher degree than in a conventional steam reformer. This is accomplished by use of a reactor, which uses a patented principle with combination of co-current and countercurrent heat exchange between the process gas and the flue gas in order to maximize the thermal efficiency and at the same time taking the limitations imposed by the construction materials into consideration. A description of the heat exchange reformer was given at the 1985 Fuel Cell Seminar (1).

On the basis of the above-mentioned principle, a development program, co-sponsored by EPRI and Haldor Topsoe, with program monitoring and direction by Westinghouse, was initiated in 1983. Under this program, one full scale module of the heat exchange reformer has been designed, constructed and erected at the pilot facilities of Haldor Topsoe, Inc. as shown in Figure 1. The unit produces hydrogen, which corresponds to an electricity production equal to 1.25 MW. The installation of the reactor is shown in Figure 2.



FIGURE 1

HEAT EXCHANGE REFORMER PILOT PLANT AT
HALDOR TOPSOE, INC., HOUSTON, TEXAS

The test program for 1986 includes commissioning and startup, runs at constant load, cycling tests, and mechanical inspections as shown in Table 1.

The pilot plant was started in March 1986, and has, until July, been in operation for approximately 800 hours. During the commissioning and startup, the pilot ran smoothly for more than 300 hours at capacities ranging from 25 percent through 80 percent load; in the proof-of-concept run, the pilot ran for more than 400 hours at 100 percent load, demonstrating desired conversion and capacity. Key figures around the reformer for the 100 percent load case are shown in Table 2.



FIGURE 2

INSTALLATION OF FULL SCALE HEAT EXCHANGE
REFORMER MODULE IN PILOT PLANT

TABLE 1

HEAT EXCHANGE REFORMER PILOT PLANT
1986 TEST PROGRAM

- A. Commissioning and Initial Startup
- B. Proof of Concept
- C. Detailed Mechanical Inspection
- D. Performance Optimization
- E. Cycling/Transient Test
- F. Mechanical Inspection

TABLE 2

KEY DATA AROUND THE HEAT EXCHANGE REFORMER

Inlet Pressure	91 psig
Inlet Temperature	804°F
Inlet Flow	9174 SCFH
Outlet Temperature	943°F
CH ₄ -Conversion	92%
H ₂ + CO Production	34181 SCFH

The experiments have verified that the two bed catalyst system with the combined co-current and countercurrent flue gas flow operates as predicted and gives the desired decrease in the metal wall temperatures.

During the experiments, many complete data sets were taken which consist of corresponding measurements of temperatures, pressures, flows, and gas compositions in and around the heat exchange reformer. These data were treated on an error smoothing program which calculates the basic heat and material balances taking the experimental uncertainties into consideration.

The experiments were also simulated on Topsoe's REFRAD program which calculates the conversion, pressure drops, and heat transfer given the reactor size and configuration and the inlet data. In Figure 3 are shown the calculated and measured axial temperature profiles inside the heat exchange reformer.

After the proof-of-concept run, the pilot unit was intentionally shutdown for a detailed mechanical inspection including pulling of the catalyst basket and removing of catalyst. The mechanical inspection revealed that the heat exchange reformer was in excellent condition.

The reformer was then reassembled, and the pilot unit was restarted in mid-August for continuation of the 1986 test program. This test program includes demonstration of non-stationary operating conditions, as well as a run simulating anticipated fuel cell conditions with daily cycles from hot standby to full load.

References

1. H. Stahl, J. Rostrup-Nielsen, and N. R. Udengaard, "High Efficiency Heat Exchange Reformer," Abstracts from the 1985 Fuel Cell Seminar, Tucson, Arizona.

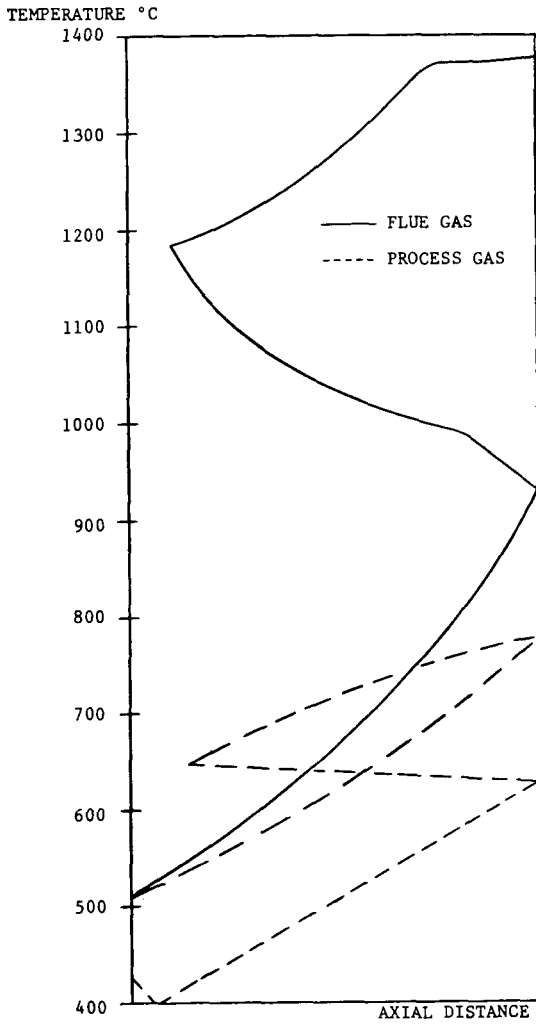


FIGURE 3
AXIAL TEMPERATURE PROFILE IN HEAT EXCHANGE REFORMER

MOLTEN CARBONATE FUEL CELL TECHNOLOGY DEVELOPMENT

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Recent activities in Molten Carbonate Fuel Cell (MCFC) technology development at IFC have centered on two related issues: (1) a system update for coal gasifier applications to account for the use of NiO cathodes, and (2) cell area scale-up to 8-ft² to be demonstrated in an upcoming short stack test.

System Update for Coal Gasification Applications

IFC updated its reference system design of a MCFC power plant integrated with an O₂-Blown Texaco Coal Gasifier. Earlier studies did not account for the CO₂ pressure of the oxidant gas affecting cell durability. Subsequently, IFC defined the CO₂ pressure of the oxidant to achieve a projected NiO cathode life of 40,000 hours or greater. The reference system was updated to incorporate this understanding.

The major change was to bypass a portion of the CO₂-rich anode exhaust stream and inject the balance into the oxidant supply. This change is shown as a dashed line on the powersection system schematic illustrated in Figure 1. The reference system was also updated to incorporate details of the fuel processing subsystem based upon recent EPRI data from their Cool Water studies (1).

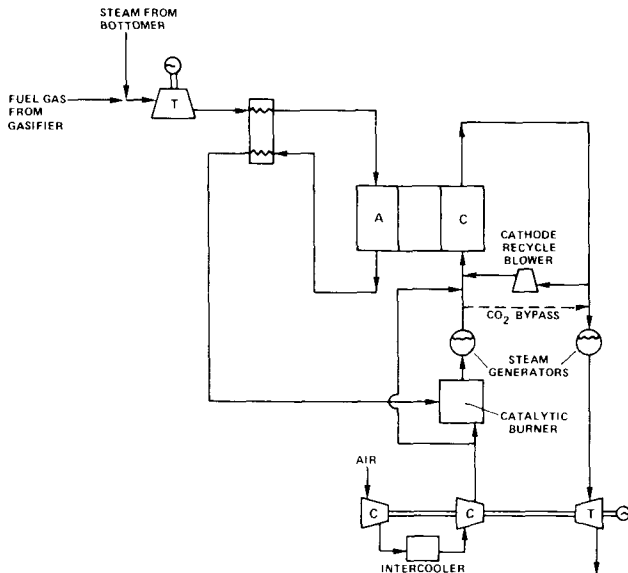


Figure 1. Updated System Schematic

The results of this system update provided the basis for revising the experimental test conditions used by IFC in its MCFC stack technology development program.

Stack Scale-Up

IFC's most recent activities in MCFC stack development have been aimed at evaluating the design issues of scale-up required for commercial size hardware. A subscale stack was first tested for this purpose and final preparations for the test of an 8-ft² short stack are in progress.

The major objective of the subscale stack test was to demonstrate that cell sheet metal components, scalable to larger sizes, could be used without penalty to cell performance. The objective was met in the 1500 hour test of this stack.

Figure 2 shows that the average cell performance of the stack met prediction and duplicated the bench-scale cell data. This demonstrated capability to achieve the performance characteristics assumed in the reference system update, presented above, and confirmed the design of cell sheet metal components for use in the 8-ft² short stack.

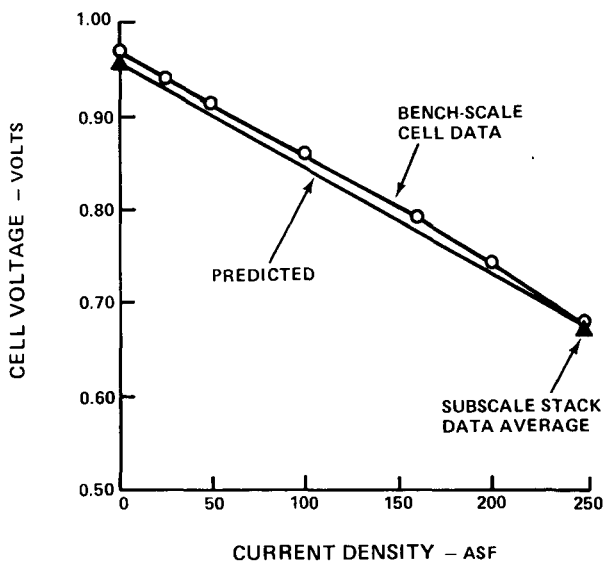


Figure 2. Subscale Stack Performance vs. Prediction

The 8-ft² short stack (20 cells) has been assembled and installed in the test stand (Figure 3). A test duration of up to 2000 hours is planned. The primary objective of this stack test is to demonstrate that cell performance and stability are maintained in scaleup required for commercial size hardware. The initial results of the 8-ft² stack test will be presented.

Acknowledgement

The activities presented herein were sponsored by the U. S. Department of Energy under Contract DE-AC21-79ET15440. The DOE Program Managers have been Mr. F. Gmeindl and Mr. J. Copley. We express our appreciation for their support, contributions and guidance to the success of the program.

Reference 1.

Cost and Performance for Commercial Application of Texaco-Based Gasification-Combined-Cycle-Plants, EPRI AP-3486 Final Report, prepared by Fluor Engineers, Inc., April 1984

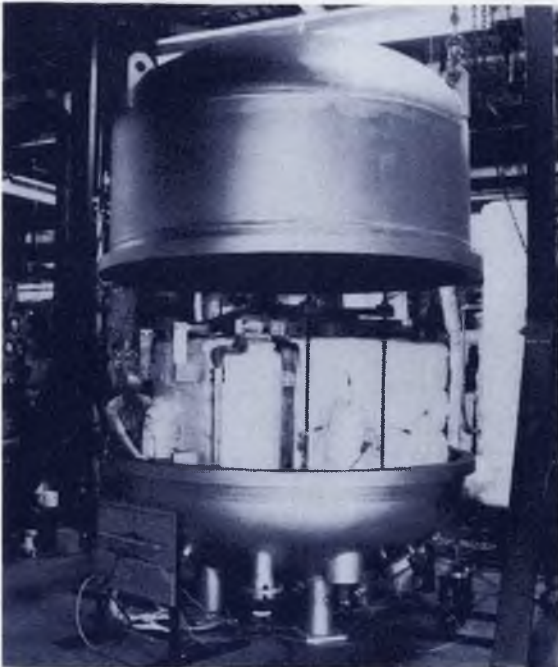


Figure 3. 8-Ft² Molten Carbonate Stack
Installed in Test Stand

DIRECT FUEL CELL DEVELOPMENT

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Development of the direct molten carbonate fuel cell (DFC) has recently emphasized both single cell component improvements and multi-cell testing of these improvements. Individual component specifications and goals are derived from considerations of system design and application requirements. The performance and endurance of stackable components have been characterized in bench-scale cells and 2 to 10-cell stacks. Operability of DFC was confirmed in a 10-cell stack with 1 ft² size components. Results of these studies are discussed below.

System Design

System designs for an atmospheric pressure, natural gas fueled DFC have been presented at the National Fuel Cell Seminar in the past (1). An advanced system has been designed recently to ensure high overall utilizations of available fuel value and to improve the reactant gas composition. This design incorporates an electrochemical hydrogen transfer device (HTD) resembling a phosphoric acid fuel cell stack (2). As shown in Figure 1, the anode exhaust from a fuel cell containing H₂, CO₂, CO and H₂O is cooled to recover water, passed through a shift reactor to convert CO to CO₂ and H₂, and then fed to the HTD to separate H₂ from the exhaust stream.

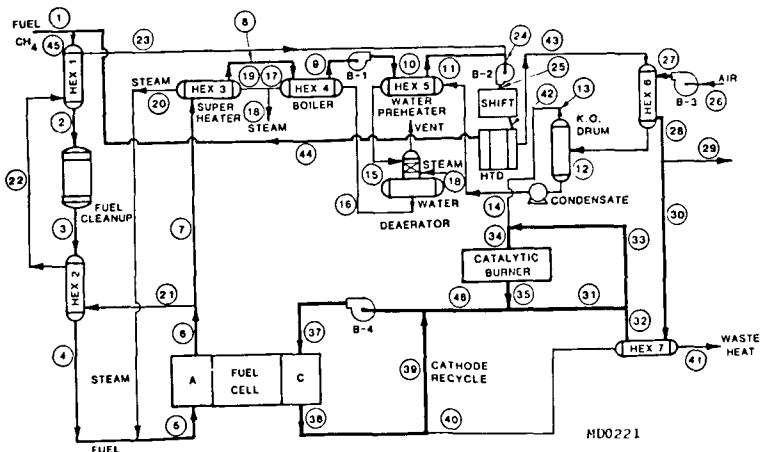


FIGURE 1. SCHEMATIC FOR DIRECT FUEL CELL SYSTEM WITH HYDROGEN TRANSFER DEVICE

The H_2 thus separated is recycled back to the anode, while CO_2 is mixed with oxidant stream and fed to the cathode. This modification in system design can result in very high, >95%, utilization of fuel value in the fuel cell, and at the same time provide higher partial pressures of H_2 in the anode and CO_2 in the cathode. Parametric analyses have shown that very high efficiencies can be achieved with this system, even after the small electric power required for the HTD is supplied. The concept of HTD has already been demonstrated at ERC in a multicell stack.

A system efficiency of 53% has been estimated, which assumes presently attained cell performance. An efficiency of 56% can be obtained if one assumes a reasonable 37 MV improvement in cell performance. Thus a very high power plant efficiency is obtained in a relatively simple power plant even at sizes as small as 2 MW. No bottoming cycle is required, except that mechanical auxiliary power (2.7%) is recovered from the cathode waste stream. The installed power plant cost for this system has been estimated to be \$1250/kW. The cost of electricity, with 4 $\$/10^6$ Btu natural gas has been estimated to be 58 to 60 mills/kWh.

Based on this system design, the stack and other subsystem specifications, and performance and endurance goals have been defined. Development and testing to meet these goals is in progress as described below.

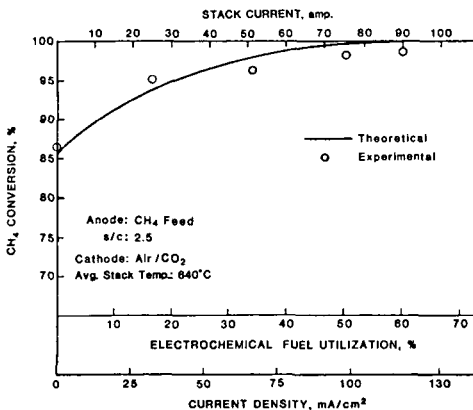
Endurance of Internal Reforming Catalyst

One important consideration of the cell design is endurance goals of the internal reforming catalyst in the anode compartment. The selected material for internal reforming in the DFC is a supported nickel catalyst. Bench-scale endurance testing of this catalyst in a single cell demonstrated 7,000 hours of acceptable methane reforming activity (3). Post-test analyses showed that the reformer life was limited by electrolyte contamination in the peripheral area of the catalyst bed near the cell edge seals. At the cell periphery, film creepage is the principal mode of electrolyte transport. Electrolyte creepage penetrated only 1/2 in. of the catalyst bed during the 7,000 hour test. The area of this 1/2 in. band of contaminated catalyst around the periphery of the reformer amounts to 30% of the total bed area in a bench-scale cell. Scaling up the fuel cell to larger dimensions reduces the importance of such edge effects. The size of the direct fuel cell is going to be scaled up to 4 ft². At this larger size a 1/2 in. band of contaminated catalyst amounts to only 8% of the total catalyst bed area. If the assumptions are made that contamination of 30% of the catalyst area is tolerable and that the rate

of electrolyte creepage is constant, then the reforming endurance of a 4 ft² DFC will increase to 26,000 hours. An additional factor on top of fuel cell scale-up is also expected to extend the reformer endurance: Since the time of the 7,000 hour endurance demonstration, an improved MgO/Ni catalyst formulation has shown a five-fold improvement in reforming stability in out-of-cell tests. Thus, fuel cell scale-up and recent improvement in catalyst stability are projected to extend the direct fuel cell reformer endurance well beyond the 25,000 to 40,000 hour economic life requirement.

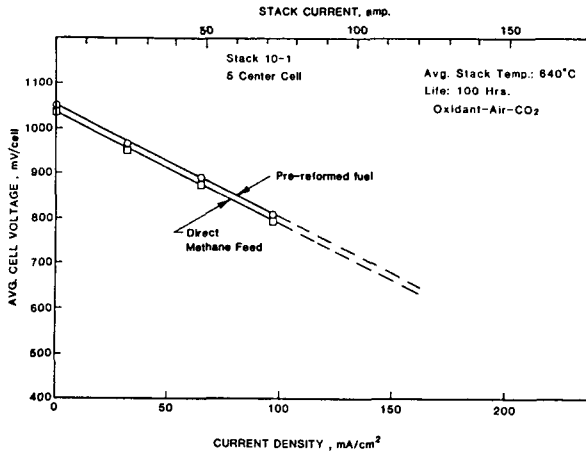
Reforming Stack Development

The feasibility of internal reforming of methane was demonstrated in a 10-cell stack. The performance of subscale (1 ft²) cells in the stack was comparable to that of bench-scale cells assembled with similar components. The benefits of internal reforming due to the internal product exchange were verified. At ~1200°F and OCV conditions, the stack exhibited close to theoretical (~85%) conversion of methane. The conversion, as expected, increased to 100% when the fuel utilization in the anode chamber was increased above 50% (Figure 2). No significant cooling in the fuel entry region due to the highly endothermic reforming reaction was observed. The stack operated in a thermally self-sustaining mode with pre-reformed fuel, as well as with a direct methane feed. The pressure drop through the reforming anode chamber under practical utilizations was measured to be less than 2 in. H₂O. The stack performance on a direct methane feed was comparable to that with pre-reformed fuel (Figure 3).



MDO098a

FIGURE 2. EXPECTED AND OBSERVED METHANE CONVERSION
 AS A FUNCTION OF FUEL UTILIZATION
 IN A 10-CELL STACK



MD0107a

FIGURE 3. COMPARISON OF STACK PERFORMANCE WITH METHANE AND PRE-REFORMED FUELS

More recently, the compatibility of direct fuel cell hardware with tape matrix and interactions between these components are being investigated. Initial results of a stack test indicated a need to modify the assembly and start-up procedures. These changes, along with bipolar plate design have been incorporated in a stackability test currently in progress. Initial results show excellent performance and low gas leakage, as expected.

Acknowledgment

The effort described here was in part supported by the Department of Energy and Electric Power Research Institute.

References

1. Snyder, W.G. et al, "High Efficiency Direct Fuel Cell Systems for Dispersed Generation," National Fuel Cell Seminar Abstracts, 1985, pp. 149-152.
2. Baker, B.S. and Ghezal Ayagh, H., "Fuel Cell Systems", U.S. Patent 4,532,192, July 30, 1985.
3. Tarjanyai, M., Paetsch, L., Bernard, R., and Ghezal Ayagh, H., "Development of Internal Reforming Catalysts for the Direct Fuel Cell", National Fuel Cell Seminar Abstracts, 1985, pp. 177-181.

STATUS OF MCFC DEVELOPMENT AT TOSHIBA

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Toshiba Corporation has been evolved in the development of MCFC since 1981, under the contract of MITI-NEDO's MOON-LIGHT project. The objectives of the project during the Phase-1 are to accomplish the basic cell and stack technology and to conduct the 10kW class stack demo-operation in 1986 Japanese fiscal year. Full stack development work is planned to follow the Phase-1.

The program of Toshiba is to develop paste type electrolyte MCFC, where the paste type is denoted as the electrolyte layer made of the pre-mixed powders of alkaline carbonate and electrolyte support. Toshiba has developed new paste-type electrolyte fabrication process(1), where the mixture of alkaline carbonate, LiAlO_2 support, crack arresting ceramic fibers and polyethylene binder are molded at low pressure(100kg/cm²) and low temperature(140°C). The binder is burned out on the way of the cell heating up procedure. Though the electrolyte layer is not so impervious to gaseous reactants as hot pressed ones even after the binder burn out, combination with the dual porosity anode, which works as bubble pressure barrier(BPB), provides a good performance cell.

For the 10kW stack assembling, 50cm square cell components are developed, considering the scale up step to the full stack and economical standpoints. Cell components, above mentioned process and scale, have been fabricated.

For the 10kW-stack configuration, external manifolds and reactant gas cross flow pattern are adopted by putting the priority on the simplicity of reactant gas supply. Besides the cathode gas cooling, independent air cooling was adopted, by providing the cooling plates at each few cells. Because, more effective heat dissipating method will be required as the cell scale becomes full stack one, where the process gas cooling would result in larger pressure drop.

SHORT STACK TESTS

Several short stacks utilizing 50cm square cells (1600cm² effective reaction area) were assembled, and the applicability of the cell components and the stack configuration were evaluated. In FY1985, 20cell stack, where three cooling plates were inserted each five cells to

uniform the vertical temperature distribution, was assembled and output power of 2.75kW was attained. Recently another 10cell stack, which took the flattening pre-treatments to reduce the cell-to-cell contact resistance, was assembled. Fig.1 shows the outer view of the stack. Fig.2 and 3 show the stack and each cell performances. Except the 10th cell, whose lower performance was attributed to the less reactant gas supply due to the carbon deposition which was found from the post test teardown examination, each cell had good and uniform performance.



Fig.1 Photograph of the ten 50cm-square-cell stack.

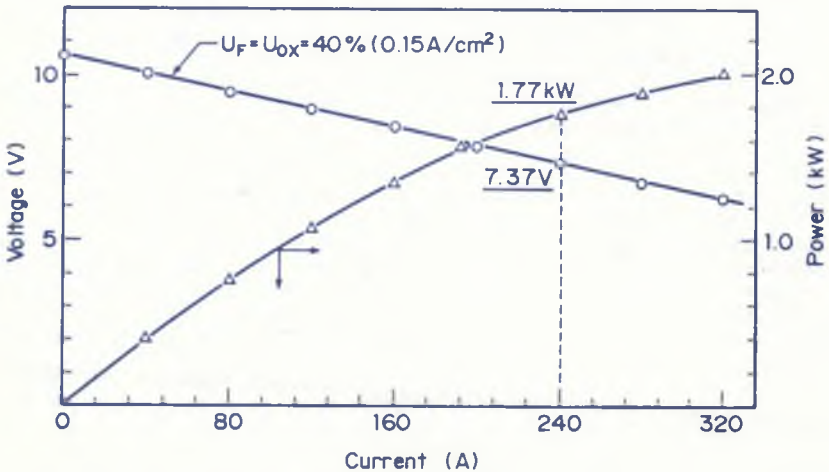


Fig.2 Performance of the ten 50cm-square-cell stack.
(Fuel; 80% H_2 /CO $_2$, humidified at 55°C, 40%utilization,
Ox; 70%Air/CO $_2$, 40%util. Compression load; 1kg/cm ^{2} , 650°C)

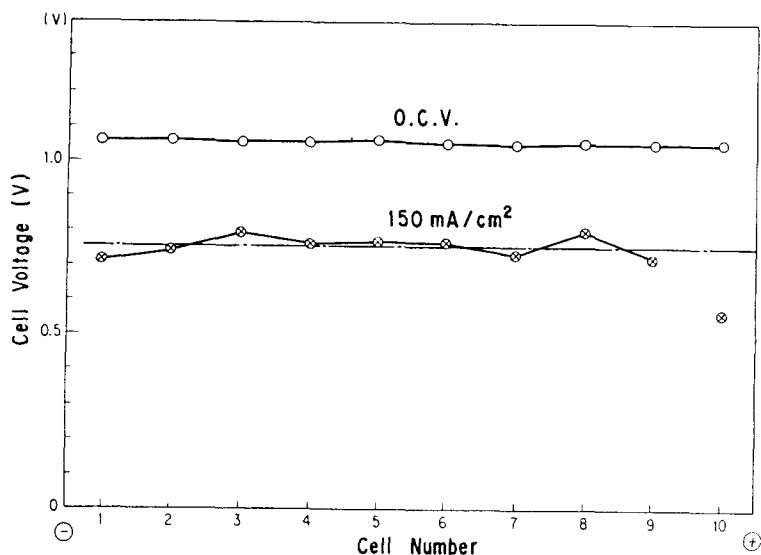


Fig. 3 Cell performance distribution of the ten 50cm-square-cell stack.

ENDURANCE IMPROVEMENTS

ANODE BPB: Anode BPB layer is formed on the porous Ni sintered substrate by coating the slurry of the finer Ni powder and binder by the blade gap of 0.7mm, and by sintering the layer in the H₂ furnace. The finer pore layer, 0.2mm thickness and average pore diameter of about 1.0 microns, is formed. Chromium oxide or alumina is added into the dual porosity anode body by dipping it in nitrate aqueous solutions, neutralizing and oxidizing at 430°C in air, to improve the stability of the BPB layer. The additives are effective for suppressing the BPB structure degradation during the binder burning out procedure.

THERMAL CYCLABILITY: Crack generation in the electrolyte layer during thermal cycle is evaluated by observing the crack pattern of the electrolyte plate in the removable simulated cell, and by measuring the bending strength of the plate. Crack initiation would be suppressed by the addition of a few% stable and wettable ceramic fibers, because the fibers disperse the vacant pores. For the fibers, LiAlO₂ and Li₂ZrO₃ are favored.

MANIFOLD SEALING: For the sealant applied at the external manifold flange, plasticity, low ionic conductivity and low mutual solubility with molten carbonate at the operating temperature are desired, to form the mutual sliding allowed and the pumping action suppressed interface. Family of the borate glass, which is thought to be less soluble into the carbonate melt and has low ionic conductivity compared to

carbonate melt as shown in (Fig.4), would be applicable as sealant, when mixed with LiAlO_2 fine power as support and combined with the zirconia fiber felt. The cell-to-cell electrolyte redistribution due to the ion migration through the manifold sealing layer was investigated through the post-test teardown analysis of the ten 30cm-square-cell stack, which operated for about 1500 hours under the continuous electric load. The results show the glass melt seal thought to be effective to suppress the carbonate transportation.

ACKNOWLEDGEMENT

This work was sponsored by New Energy Development Organization(NEDO) and Agency of Industrial Science and Technology(AIST) of Ministry of International Trade and Industry(MITI), Japan.

REFERENCES

1. T.Shirogami, K.Murata, Y.Sakamoto, DEVELOPMENT STATUS OF TOSHIBA ADVANCED PASTE ELECTROLYTE MOLTEN CARBONATE FUEL CELLS", Fuel Cell Seminar Abstracts, pp162-165, May, 1985.

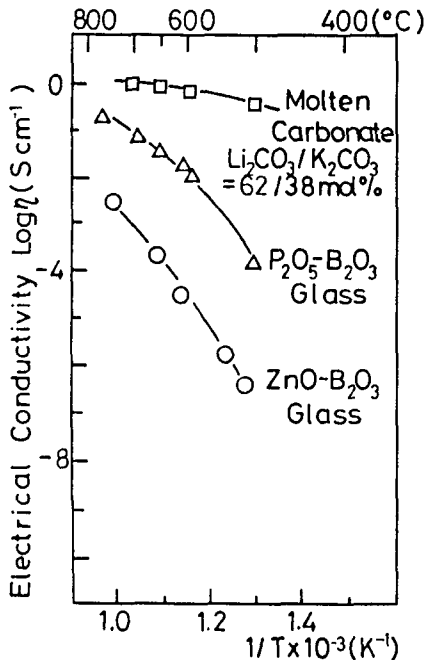


Fig.4 Electric conductivity of molten carbonate and borate glass families, candidates for the manifold sealants.

AN OVERVIEW OF THE DUTCH MCFC PROGRAM

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PEO - Utrecht
The Netherlands

Introduction

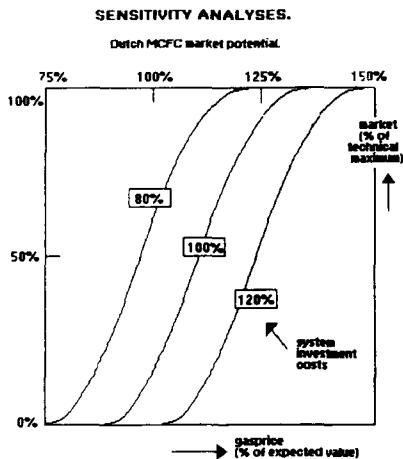
In december 1985 the Dutch government approved a PEO-proposal for a three year MCFC development program and made available to PEO 10 million dutch guilders (appr. US \$ 4 million) for the execution of the program. The objectives of the program are:

- to build up the level of knowledge on MCFC technology in order to be able to contribute to international developments;
- to create possibilities for a Dutch industrial product-development of MCFC technology.

The main reasons for the Dutch government to invest in a MCFC development program were the following:

- a potential interesting market in the Netherlands and Europe;
- high efficiency and low pollution of MCFC-systems;
- suitability of natural gas as fuel;
- available R&D capabilities;
- spin-off for other new technology areas (e.g. new materials).

The results from a Dutch marketstudy show that the estimated market potential depends very much on system investment costs (see figure below). Since these costs are still a matter of speculations, it is unwise to state firm future marketpotential figures.



The Dutch program has been set up with the help of IGT (Chicago), IIT (Chicago) and EPRI. The main contractor for the program is the Netherlands' Energy Research Foundation (ECN) in Petten (Holland), with some universities as subcontractors. The program will be executed with support of and in close cooperation with IGT and IIT in Chicago. The total budget for the three year program (including own contributions of ECN and support from the European Commission) will be appr. 20 mln. Dutch guilders (appr. US \$ 8 million).

In the following paragraphs a brief description will be given of the main activities under this program. For a more extensive description, motivation and first results the reader is referred to mr. K. Joon's presentation.

Development of components

Objective: To establish the design of components that can be used for the construction of a cell/stack with specific Dutch know-how.

Main items to be studied under this subprogram are the following.

Fundamental research will be conducted to determine the reaction mechanisms and kinetics at the NiO cathode, with emphasis on the Ni dissolution in the carbonate melt. This work will be performed at a technical university, with main sponsor the European Commission.

As a contribution to a worldwide search for alternative anode materials, fundamental research will be conducted at a technical university to elucidate the reaction mechanisms and kinetics at such alternative anodes. Also, the influence of internal reforming on the anode reactions will be investigated.

On the basis of experimental data valid models for reaction kinetics and local mass and heat transport phenomena at the electrodes will be developed. This development will be experimentally supported by measurements on present day Ni anodes and by the results of the cathode and alternative anode reaction measurements.

Materials research will be performed at ECN to develop new materials for use in anodic environments. The efforts will focus on production and processing methods for obtaining highly characterized (monodisperse if necessary) powders of LiFe₅O₈ as a base material for conducting ceramics.

Processing and manufacturing techniques will be developed by ECN for well-characterized powders as starting materials for the fabrication of electrolyte tiles and electrodes. The processes will be suited for upscaling and will cover both standard and new materials.

To support materials and component development and fabrication, a series of lab-scale cells (3 cm^2) will be operated to determine component and cell performance, electrical characteristics and to identify mechanisms leading to eventual degradation.

Design, construction and testing of a pilot-cell

Objective: Optimisation of cell-design through endurance and performance testing of lab-cells

Following activities take place under this subprogram.

The most promising and versatile fabrication technique for cell components seems to be tape casting, whether or not followed by sintering. The tape casting and sintering process will be further developed at ECN in order to improve product specifications, optimize the process (parameters) and enable upscaling to mass production.

Starting with an evaluation of current and old designs, a new separator plate for stackable MCFC's will be developed at ECN. The final design will be optimized in various respects, such as material performance and cell performance. Furthermore, fabrication processes and construction techniques to be applied will be investigated.

As a follow-up of lab-scale cell testing, promising new developments will be subjected to long term tests at ECN with larger electrode surface area ($10 \times 10 \text{ cm}^2$) in bench-scale cells. Important parameters to be investigated are endurance, electrolyte inventory and migration, macro-cracking, tile compaction, gas flow configurations, mechanical load, etc.

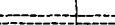
Cell models will be further developed, based on available models in the USA. They will be used for evaluation of the cell-testing results and will support the design of a small stack.

Design, construction and testing of a pilotstack

Objective: Optimisation of the stack-design by means of investigation of crucial stack properties (such as electrolyte stability, flowpatterns and efficiency)

Based on existing technology, adapted by successful developments from the projects mentioned above and supported by model calculations, a stackable $30 \times 30 \text{ cm}^2$ cell will be designed, constructed and tested. This will be the basis for further development of a stack consisting of some 10 cells with an output of about 1 kW.

TIME SCHEDULE MCFC PROGRAM

	1986	1987	1988	1989	1990
feasability studies					
component testing					
cell performance testing					
cell modelling					
stack modelling					
construction 1 kW stack					
testing 1 kW stack					
construction 10 kW stack					
testing 10 kW stack					
design 100 kW stack					
construction 100 kW stack					

Organizational aspects

In cooperation with leading experts from the USA a program has been defined in a way that a meaningful contribution to the international MCFC developments is aimed at. This first phase of the national fuel cell R and D program will be executed as a cooperative effort between Dutch and US-organizations. Participation of other interested parties will be encouraged and is expected.

The projects as formulated form a coherent program. Thus, the interrelations between the different projects and jobs are numerous. This requires close cooperation, a high degree of information exchange and strict management. Also, the relations with the fuel cell program of the European Commission are assured. Further possibilities for national and international cooperation on a bi- or multilateral basis will be explored.

DEVELOPMENT OF MOLTEN CARBONATE FUEL CELL TECHNOLOGY

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INTRODUCTION

Mitsubishi electric corporation has been performing R&D of molten carbonate fuel cell technology as the highest priority program. Emphasis during past year was focused on the estimation of electrolyte loss during long period operation and the development of stack leading to scale up of components. This paper reports on the electrolyte analysis of single cell and stack.

CELL TECHNOLOGY

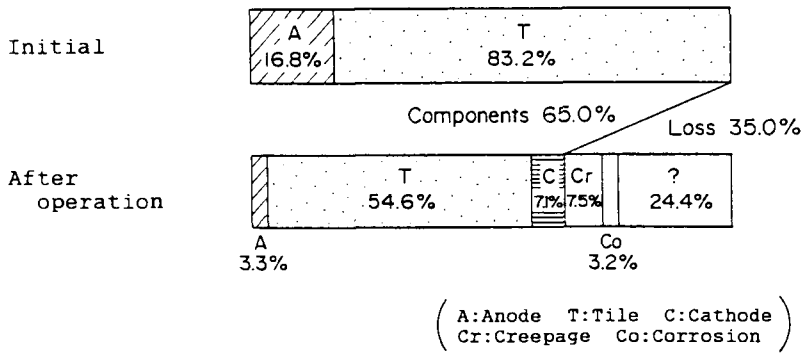
One of the major technical issue of cell and stack technologies is electrolyte loss during operation by corrosion, creepage and evaporation et al.. Many small cell testing and post testing have been conducting to make clear this electrolyte loss mechanism.

Figure 1 shows the result of electrolyte loss analyses of the cell operated for 9811 hours. The 65% of initial amount of electrolyte stayed in the active components (anode, cathode and tile) and the remain 35% was consumed in the support component (current collectors, separator and cell housing). The released electrolyte loss separated into three groups which consist of 3.2% loss by corrosion, 7.5% loss by creepage (migration loss through component) and 24.4% loss by unknown mechanism including vaporization.

At the same time, the Li/K ratio in electrolyte was analysed and it was found that potassium contents was found rich in the electrolyte and lithium contents was found rich in the corrosion products. Since the initial Li/K ratio is 1.0, the change of Li/K ratio indicates that potassium ion migration takes place and lithium tends to react with the support components.

ML-17

9811hr



Loss (Creepage + Corrosion) = 100%

□ Li ▨ K (Mole ratio)

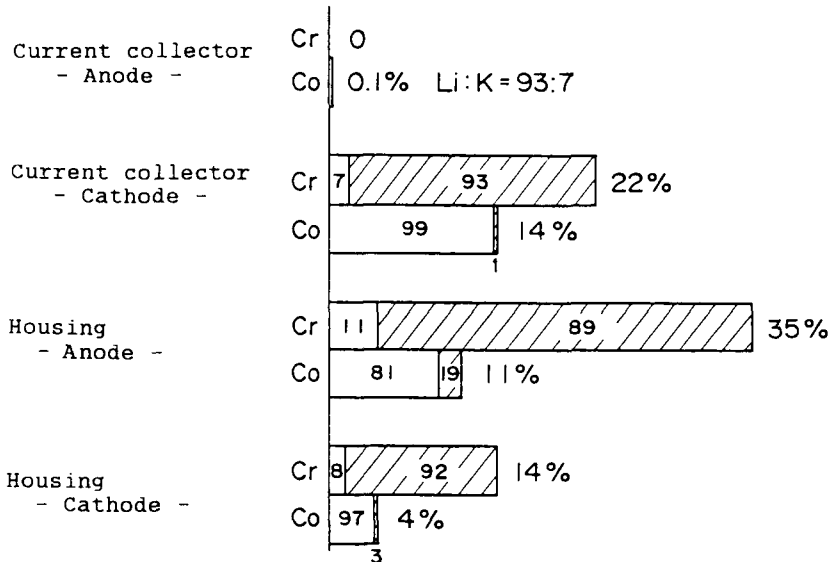


FIGURE 1. ELECTROLYTE DISTRIBUTION ANALYSIS OF SINGLE CELL

STACK TECHNOLOGY

Two short stacks had been constructed and tested. One was 1kW stack consisting of 10 cells with effective area of 1024 cm^2 and hot pressed matrix. A continuous load test at the current density of $100\text{--}150\text{ mA/cm}^2$ had been conducted for 1500 hours. The average cell voltage was 0.7 V at 150 mA/cm^2 with 40% utilization of both anode gas ($80\text{H}_2\text{--}20\text{CO}_2$) and cathode gas ($70\text{Air--}30\text{CO}_2$).

The other 700W stack consisting of 3 cells with effective area of 2000 cm^2 and tape matrix has been operating over 800 hours since this August. The average cell voltage is 0.8 V at 150 mA/cm^2 with same condition of 1 kW stack. Figure 3 shows the operating history.

100 mV improvement of cell performance has been achieved in which half of the improvement is ascribed to reduction of iR obtained by changing the electrolyte matrix from a hot pressed tile to a tape matrix.

1 kW stack was disassembled and a post test examination was thoroughly conducted. One of the findings was the redistribution of electrolyte in the stack. As shown in Figure 3, somewhat higher electrolyte content was found in the upper region of the stack (minus pole) where potassium was richer.

TALL STACK FABRICATION

10 kW tall stack has been designed and is under construction. The specification are shown in Table 1.

TABLE 1. SPECIFICATION OF 10 kW STACK

Effective area	2000 cm^2
Cell number	50 cells
Cooling	Process gas
Manifold	External
Operating pressure	Atmosfer
Output	11 kW

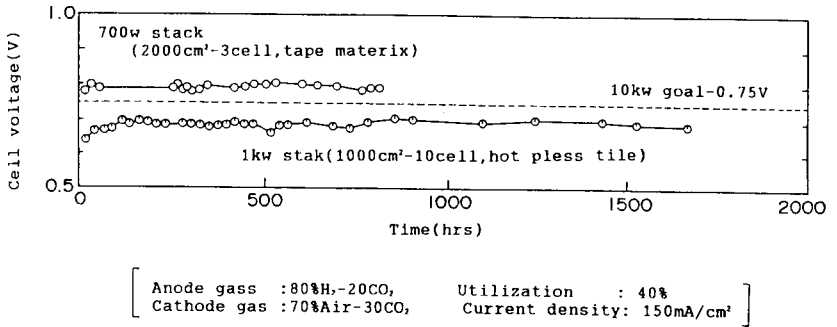


FIGURE 2. STACK PERFORMANCE

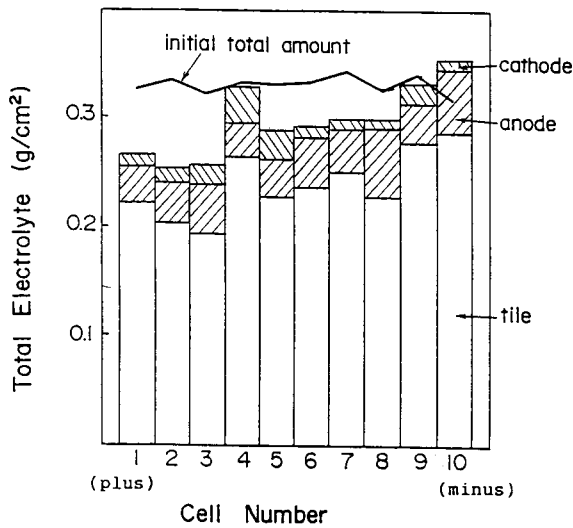


FIGURE 3. ELECTROLYTE DISTRIBUTION ANALYSIS OF STACK

MOLTEN CARBONATE FUEL CELL TECHNOLOGY DEVELOPMENT AT FUJI

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Introduction

Fuji Electric started the research and development of molten carbonate fuel cells in 1961. The studies were, however, stopped several years later. In 1980, we restarted, and our studies have been concentrated on the development of components such as electrolyte plates, electrodes, and cell stack configurations. In 1985, a 30-cell stack with 200 cm² electrodes was built and tested at CRIEPI.

In parallel, we have been developing new electrolyte matrix fabrication methods under the contract with NEDO since 1984. In 1986, a 2900 cm² size single cell using the new matrix was built. We are now promoting to build a 2500 cm² size 24-cell stack using the new matrixes, which will be tested by the end of this fiscal year.

Stack configuration

Fuji's stack is a hybrid manifold type, i.e., consisting of an inner manifold for fuel gas and a external manifold for oxydant gas. Figure 1 shows a 200 cm² size 30-cell stack of this type. In this stack, the electrolyte plates made by means of the hot-pressing method are used, and the cooling plates are inserted every ten cells. The average cell voltage of the stack was 0.756 V/cell at 150 mA/cm². Figure 2 shows the performance of the each cell. The voltage scattering was relatively small at 0-200 mA/cm² except for five cells. The post analysis made it clear that the low performances of the five cells were caused by the insufficient contacts of the electrodes with the electrolyte plates. During the operation, the cracking of the electrolyte plates occurred around the holes of the inner manifolds in some cells, and the fuel gas leaked out. In spite of the gas leakage, the stack was successfully operated for about 500 hours, and it was proved that the hybrid manifold configuration is fundamentally acceptable. The problem of cracking was solved by using the new matrix which will be mentioned later.

Electrode

Anode: The anodes made of Ni, Ni-8Co, and Ni-10Cr alloy were subjected to a 2000 hours compression creeping test, and the relations between the creep deformation and the electrode polarization were determined. The creep deformation increased in the order, Ni » Ni-8Co > Ni-10Cr, and the polarization increased in the order, Ni » Ni-8Co ≈ Ni-10Cr. The

effects of the porosity, mean pore size, and specific surface area on the anode polarization were also determined. The mean pore size and the specific surface area increased sharply with increase of the porosity when it exceeded 60 %, and the polarization also became sufficiently low at the porosity above 60 %.

Cathode: The effects of the porosity, mean pore size, and specific surface area on the electrode polarization were determined. The polarization was low enough at the porosity above 70 % and the mean pore size above 10 μm . However, the mutual relation between the polarization and the specific surface area was not found in the range of 0.1-0.2 m^2/g .

Electrolyte matrix

Two matrix fabrication methods have been developed: a paper making method and a callender rolling method.

Paper making method: A green sheet matrix is fabricated in a similar way as making a paper. On being mixed with pulp in water, LiAlO_2 powder adheres to the pulp, forming flocks, and the matrix sheet is prepared by filtering the flocks. The fabrication process is shown in Fig.3.

We tried the scale-up of the matrix up to 650x600 mm size. Since the large sized matrix is susceptible to crack, two improvements were adopted to prevent it from cracking: the addition of alumina fiber in the matrix, and mixing of different sizes of LiAlO_2 powders. There was another problem that the matrix² contains relatively large pores which are left after the pulp is burnt out. So the relation between the amount of pulp and the pore size distribution was determined. The pore size distribution curve became sharp and shifted to the smaller pore side as the amount of pulp decreased. Therefore, we got a closed packed fine pore matrix by using the minimum amount of pulp as possible.

On the bases of the results described above, a large size 650x600 mm matrix was fabricated by an automatic paper making machine, and a 184x184 mm matrix was cut out from it. A 200 cm^2 size cell with this matrix showed the performance of 820 mV at 150 mA/cm^2 . A 2900 cm^2 size single cell with a 650x600 mm matrix was also built and tested. The performance was, however, lower than that of the 200 cm^2 size cell. At present, an improved 2500 cm^2 size stack is being built.

Callender rolling method: We found that the callender rolling method can produce a closely packed matrix. The fabrication process is shown in Fig.4. Alumina fiber was added to strengthen the matrix. A 200 cm^2 size cell using this matrix showed the performance of 730 mV at 150 mA/cm^2 . A 650x600 mm matrix was also fabricated by this method.

Conclusion

We have been developing the molten carbonate fuel cells since 1980, and have reached the technical level capable of making a 3000 cm^2 size cell. We have also developed the new

matrix fabrication methods, i.e., the paper making method and the callender rolling method; both are suitable for fabricating large sized matrixes. At present, we are making efforts to develop the cells which endure long-term operation, and to complete the stack technologies.

Acknowledgement

This work was supported in part by NEDO. We also express our thanks to Toppan Printing Co., Ltd. for providing us with the matrixes fabricated by the paper making method.

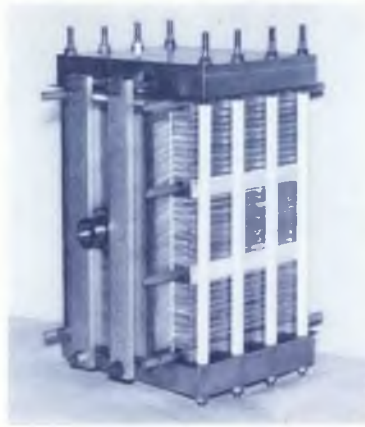


Fig.1 30-cell stack with 200 cm² electrodes

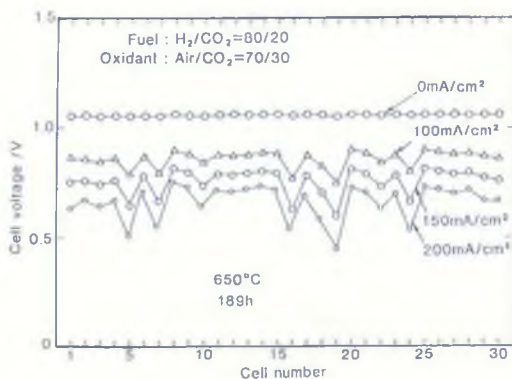


Fig.2 Performance of each cell in 30-cell stack

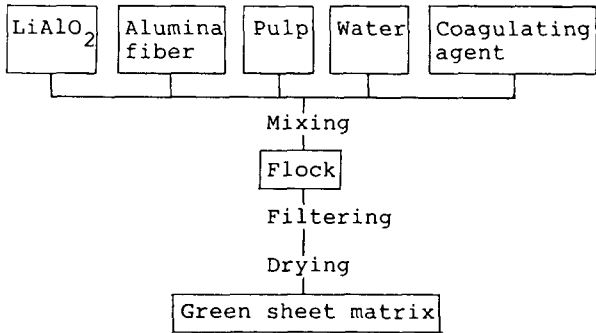


Fig.3 Flow sheet of paper making method

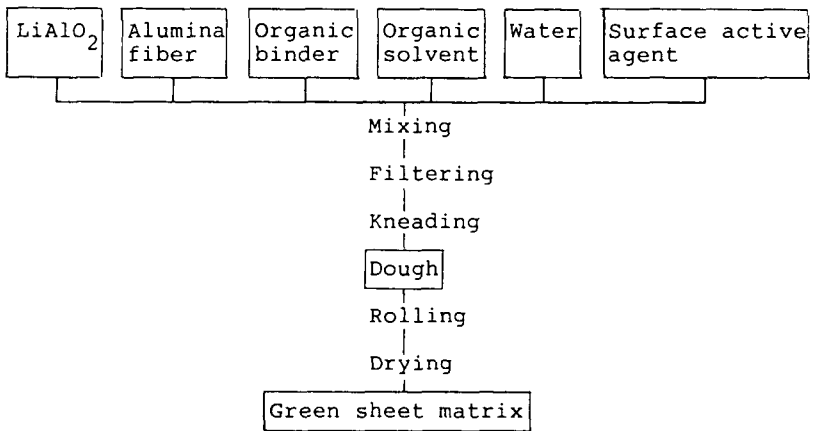


Fig.4 Flow sheet of callender rolling method

PROGRESS ON MOLTEN CARBONATE FUEL CELL ALTERNATIVE CATHODES

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INTRODUCTION

LiFeO_2 and Li_2MnO_3 in doped forms appear to meet the requirements for cathode materials. These were chosen from a larger number of compounds which were identified as being thermodynamically stable in the cathode environment. The undoped forms were extensively tested and meet the requirements of low solubility, nonmigration, and stability (1,2). Doping can be used to enhance the conductivity of these two materials.

Their conductivities are very dependent on stoichiometry, and therefore on environment. In typical cell environments, the undoped materials have resistivities of from a few hundred to about one thousand ohm-centimeters resistivity. The precise requirement for cathode use has been ill defined due to the complex nature and incomplete understanding of the cathode's operation.

A cathode model developed by Physical Sciences Incorporated was used to examine predicted performance of various cathodes, with microstructure and electronic conductivity of the material as parameters (3). The conclusion is that material resistivity of as high as $\sim 20 \text{ } \Omega\text{-cm}$ under operating conditions may be acceptable with proper microstructure.

Resistivities of $\sim 10 \text{ } \Omega\text{-cm}$ can be achieved with doped materials under realistic cell conditions. The emphasis has therefore shifted toward fabricating appropriate microstructures with doped materials, then testing them in cells. The fabrication of the cathode structures will be discussed.

DOPED MATERIALS

LiFeO_2 in the undoped state is a good conductor ($\sim 3 \text{ } \Omega\text{-cm}$ resistivity at 650°C) when synthesized in air, but is about two orders of magnitude more resistive when synthesized in higher levels of CO_2 (4). The objective of doping is to reduce the resistivity to the levels of air-prepared material and to eliminate the CO_2 sensitivity.

LiFeO_2 has successfully been doped with manganese, copper, and cobalt. These dopants can produce LiFeO_2 with potentially useful resistivity. The manganese-doped material has been most extensively studied. Under realistic 10 atm conditions the optimum dopant concentration results in a resistivity of $\sim 25 \text{ } \Omega\text{-cm}$ at 650°C . There is excellent correlation between dopant level, resistivity and lattice parameter (Figs. 1 and 2). The material is a p-type conductor in cathode conditions as indicated by its conductivity behavior and by Seebeck measurements. Any simple substitution of an Mn^{3+} or Mn^{4+} would result in a n-type, so it is probable that a more complex defect structure is occurring with, for example, oxygen interstitials.

LiFeO_2 doped with copper produces a resistivity of $\sim 10 \Omega\text{-cm}$ under high p_{CO_2} conditions. This conductivity should be adequate for cell testing. Of concern is the migration and subsequent precipitation of copper; this is an issue that must be answered through cell testing. The material is a p-type conductor, and therefore improves in conductivity with increasing p_{O_2} .

Cobalt-doped LiFeO_2 has resistivity in the $< 10 \Omega\text{-cm}$ range at 650°C (Fig. 3). While the optimum dopant concentration has not been determined for this system, at the maximum dopant level in Fig. 3 the conductivity is still improving, so it is probable that further improvements will be seen.

Li_2MnO_3 in the undoped state is a poorer conductor in realistic environments than LiFeO_2 . It is an n-type conductor, rather than a p-type. It has very low solubility, and from cell tests, appears to have no migration tendencies in a cell environment. The doping of this material has received less attention than that of LiFeO_2 , but has resulted in resistivities of $\sim 20 \Omega\text{-cm}$ in realistic environments.

CELL TESTING

The cell testing will begin with 25 cm^2 boiler-plate cells, and nickel anodes. The major problem in preparation for cell testing is the cathode microstructure. Analyses indicate (3) that resistivities of cathode materials of up to about $20 \Omega\text{-cm}$ could give comparable performance to nickel-oxide cathodes, if care is taken to achieve the correct microstructure.

The particles from which the cathode is to be fabricated must be of submicron size to get adequate catalytic surface area and to form flooded agglomerates. The agglomerate size is of importance because the reactants must diffuse to the reaction site through liquid-phase in the agglomerate. The path length is minimized by keeping the agglomerate size small. The objective is set at $3\text{--}8 \mu\text{m}$ typical diameter. There must be the usual large gas passages, of $\sim 10 \mu\text{m}$ diameter. This diameter is, of course, determined by the pore characteristics of other components. Finally, a porosity of $\sim 45\text{--}55\%$ is being sought.

Spherical agglomerates alone cannot be used to achieve the desired structure, as it would be impossible to obtain the combination of small agglomerates and large pores. Consequently, pores are being made using a variety of pore formers and agglomerates are being made in nonspherical geometries.

Pore formers, such as starches, cellulose, flours, etc., generally do not produce the desired interconnected pores without a very high porosity. With fibrous pore formers, it is difficult to get the desired orientation normal to the surface of a thin planar body with conventional fabrication techniques. The fibers tend to lie along the fluid's streamlines in a tape casting or similar process, and therefore will not penetrate the faces in sufficient numbers.

A process to provide 10-15 μm dia holes through the plane of such a cathode has been developed, but the number density is such that lateral channels will be required for sufficient gas access. These may best be formed by fabricating the structure using preformed agglomerates. The agglomerates are formed by several methods. One is to fill a foam or other porous organic body with a ceramic slip, burn off the organics, and sinter. Depending on the degree of fill, this procedure can result in a replica of the foam (Fig. 4), or of the voids in the foam. This then can be crushed to provide nonspherical agglomerates. In a similar process, organic fibers can be mixed with a ceramic slurry and sintered. This process can yield small ceramic tubes (Fig. 5), which can be crushed to provide the agglomerates. Many other organics could be used to produce such agglomerates.

SUMMARY

Li_2MnO_3 and LiFeO_2 have been developed to the point that they should perform well in a cell. The cathode microstructure is of critical importance in obtaining good performance with these materials whose resistances are higher than NiO . Several methods have been developed to provide the dual porosity materials for fabrication of the required cathode structure for cell testing.

ACKNOWLEDGMENT

Work supported by the U.S. Department of Energy, Morgantown Energy Technology Center, Fuel Cell Projects Section under Contract No. W-31-109-ENG-38, and performed under the direction of W. J. Huber.

The submitted manuscript has been authored by a contractor of the U.S. Government under contract No. W-31-109-ENG-38. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

REFERENCES

1. J. L. Smith, T. D. Kaun, N. Q. Minh, and R. D. Pierce, "Stable Materials for Molten Carbonate Fuel Cell Cathodes," 1983 National Fuel Cell Seminar Abstracts, p. 65, Orlando, Florida, November 13-16 (1983).
2. G. H. Kucera, N. Q. Minh, J. L. Smith, and F. C. Mrazek, "Molten Carbonate Fuel Cell Cathode Development," 1985 National Fuel Cell Seminar Abstracts, p. 158, Tucson, Arizona, May 19-22 (1985).
3. G. Wilemski and J. L. Smith, in preparation.
4. N. Q. Minh, G. H. Kucera, and J. L. Smith, Proc. of the Fifth Int. Symp. on Molten Salts, M. L. Saboungi-Blander, et al., Eds., The Electrochemical Society, Pennington, NJ (1986) p. 597.

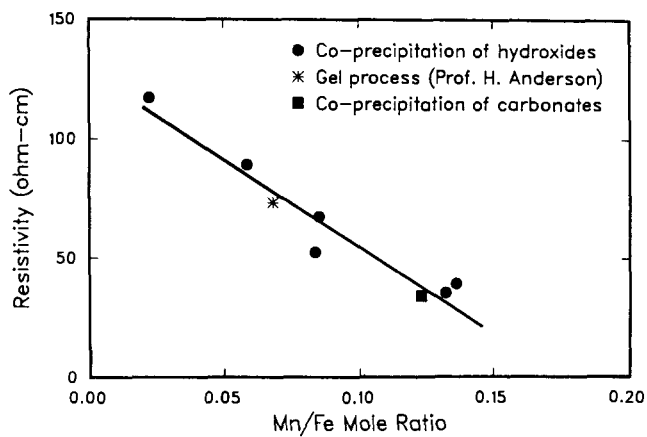


FIGURE 1

RESISTIVITY OF MN-DOPED LiFeO_2 AS A FUNCTION OF DOPANT LEVEL.

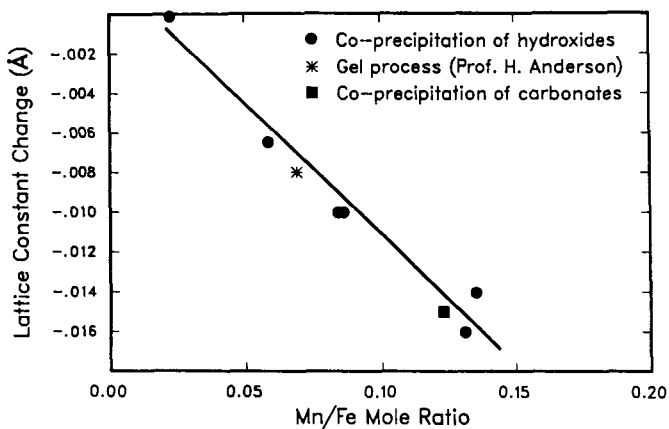


FIGURE 2

LATTICE CONSTANT OF MN-DOPED LiFeO_2 AS A FUNCTION OF DOPANT LEVEL.

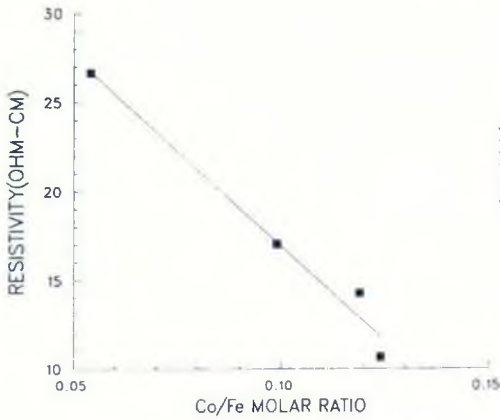
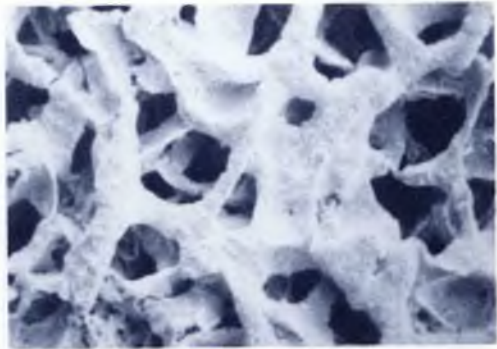


FIGURE 3

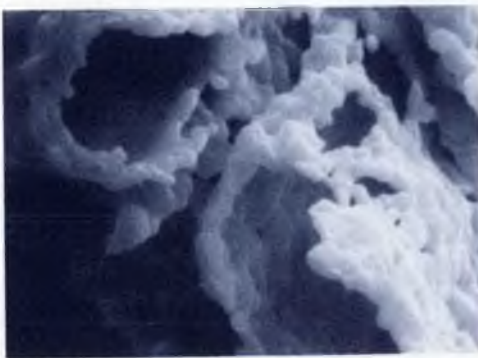
RESISTIVITY OF CO-DOPED LiFeO_2
PREPARED IN HIGH CO_2 AND TESTED
IN AIR AT 650°C VS. COMPOSI-
TION 0.

FIGURE 4

LiFeO_2 STRUCTURE PREPARED BY
IMPREGNATING FOAM WITH SLIP
AND SINTERING.



100 μm



3 μm

FIGURE 5

LiFeO_2 "TUBES" PREPARED BY
SINTERING WITH PORE FORMERS.

OXIDE DISPERSION STRENGTHENED (ODS) ANODE

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State-of-the-art (SOA) molten carbonate fuel cell (MCFC) anodes are porous plaques prepared by sintering a physical mixture of metallic nickel and a variety of stabilizing additives in a reducing atmosphere at about 1000°C. The anode provides reaction sites for the electrochemical oxidation of hydrogen in the fuel, which is enhanced by increased surface area, good electronic conductivity, and sufficient wetting by the carbonate electrolyte. To maintain these characteristics, the pore structure and the wetting characteristics of the anode are important and, since the fuel cell will be required to endure 40,000 hours of operation, the stability of these properties must be assured. In consideration of stack designs, several shortcomings of the anode began to surface, among the most important were cost, creep, and morphological stability. As a result, each developer and technology supporting group included experimental efforts in their programs to improve and/or eliminate these shortcomings.

Changes in porosity of a Ni + 10% Cr anode up to 10,000 hours of cell test are presented in Figure 1. A significant amount of submicron pores formed as a result of LiCrO_2 formation. However, very little change in porosity occurred after 600 hours, indicating that LiCrO_2 formation was practically completed by that time. Micrographs of a Ni + 10% Cr anode before and after 10,000 hours of test in a fuel cell are shown in Figure 2. Apparently, each nickel particle precursor became somewhat porous as a result of LiCrO_2

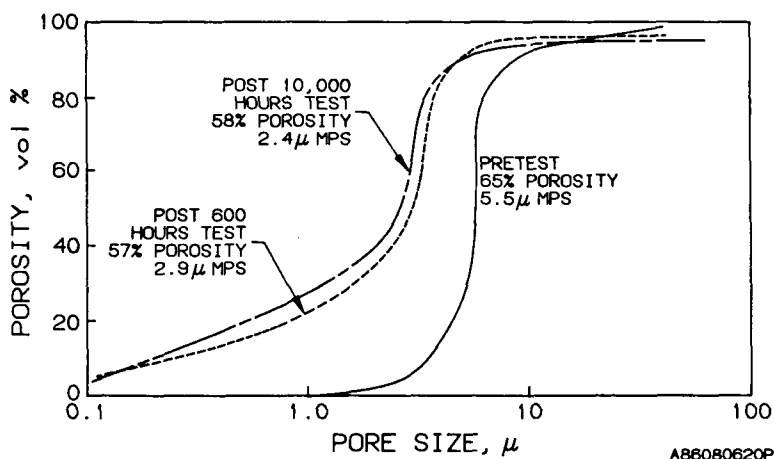


Figure 1. CHANGES IN PORE SIZE DISTRIBUTION OF
Ni + 10% Cr ANODES IN CELL

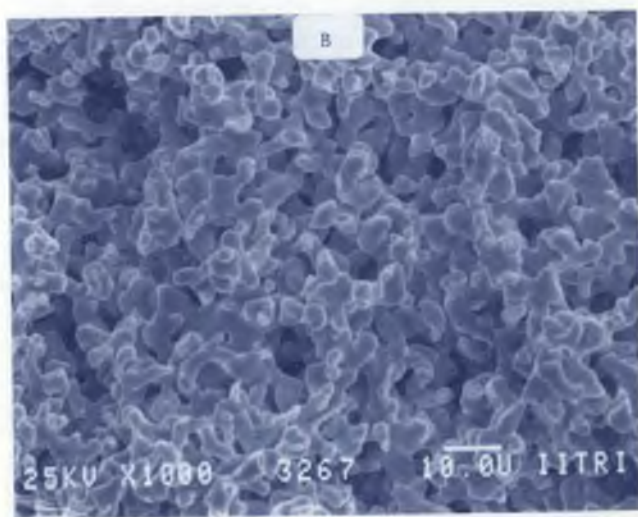
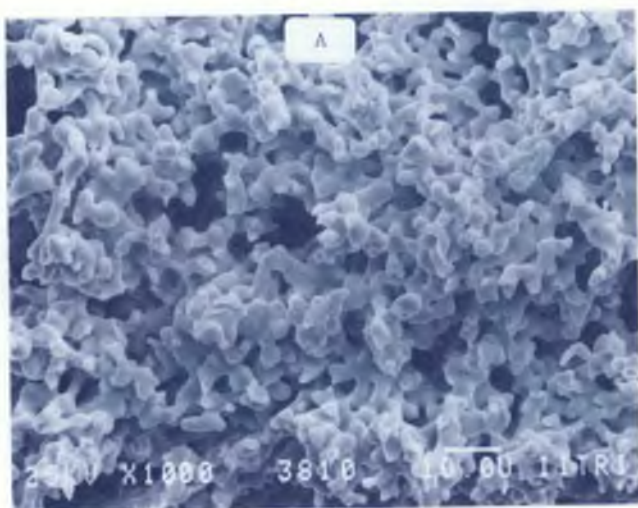


Figure 2. Ni-10% Cr ANODE (a) AS RECEIVED AND
(b) AFTER CELL TESTING

formation. The rather rapid change, during the first ~600 hours of operation, from the initial anode morphological condition to one that does not appear to change significantly thereafter would place the burden of long-term performance decay mostly on changes in the electrolyte, matrix, and cathode. However, long-term changes in the anode due to creep, although very slow and not as influential as the changes taking place in the other components, do contribute to performance decay and to the changes in stack height. Consequently, a stabilized porous anode structure whose morphology and thickness do not change substantially during the life of the stack needs to be developed. We believe that this can be achieved in a cost-effective manner by a proper approach to dispersion hardening where small (<2%) amounts of oxide particles (Cr_2O_3 , Al_2O_3 , etc.) in the nickel may provide enough resistance to creep, and control long-term changes in the anode.

Under an Electric Power Research Institute (EPRI) sponsored project, work has been conducted at IGT toward the development of oxide dispersion strengthened (ODS) MCFC anodes. Included in this effort are the following: characterization of the sintering and creep properties of the SOA and ODS anodes through out-of-cell creep testing, correlation between ODS microstructural characteristics and creep properties; and the development of cost-effective ODS anode fabrication techniques. Shown in Figure 3 are the $650^\circ\text{C}/100$ psi creep curves for two promising ODS anode microstructures as compared to that obtained for the SOA Ni-10% Cr anodes tested under the same conditions. The ODS anodes exhibited less overall shrinkages with stabilization of the creep rate occurring at shorter times. The microstructural changes expected for the ODS anodes are much less than for the Ni-Cr SOA anodes due to the lower amount of second phase material to react with the molten carbonate. For example, in Figure 3, the initial Ni-10Cr porosity was 62%. After LiCrO_2 formation, the porosity drops to ~50%. The final porosity, from mercury porosimetry measurements, is 47%, representing a total porosity decrease of 15%. On the other hand, the total porosity change for the ODS anodes was only 0.5-1.3%.

IGT experience has shown that ODS anodes present a very promising alternative to the SOA anodes in terms of improved creep resistance. Future work will be directed toward optimization of the microstructural design and fabrication parameters with respect to cell test and creep test performance. Optimal ODS microstructures will be compared to SOA microstructures in terms of long-term creep behavior, microstructural stability, and cell performance.

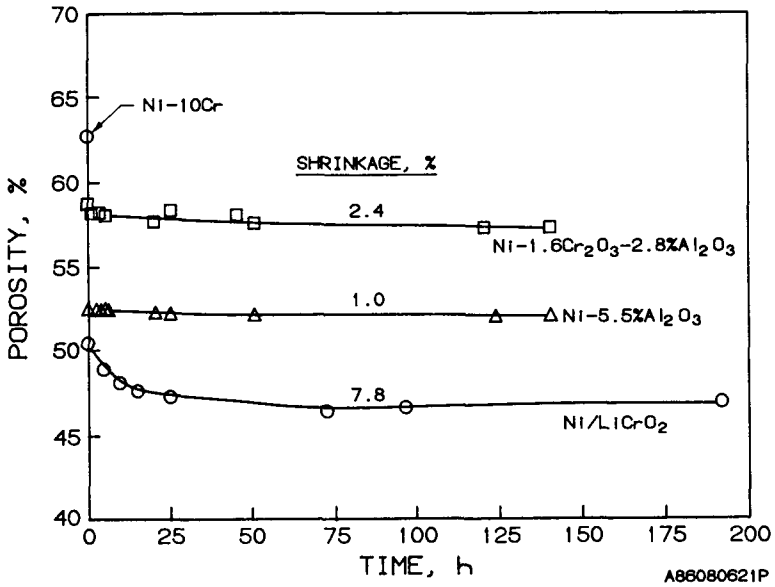


Figure 3. CREEP OF ODS AND SOA ANODES AT 650°C
AND AN APPLIED PRESSURE OF 100 PSI

(NFCS85-DSE/RPE)

ANALYSIS OF THE DECAY OF AN ISOTHERMAL MCFC AT 893 K

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Preliminary results obtained at 893 K on a single MCFC recently installed in this Institute are reported. The fully automated test facility (1), which uses "state of the art" components supplied by the Institute of Gas Technology (IGT, Chicago), has been operated for more than two years under various conditions. The objective of these tests was to establish the performance and the endurance at lower than baseline T (923 K). It was reasoned that, since the most important rate processes affecting component's durability and cell's performance are marked by high activation energies (2), a better understanding of phenomena so occurring would constitute a reference for a preliminary evaluation of the attractiveness and limits of lower operating temperatures. Results obtained from a series of runs at 893 K are reported including "post-mortem" analyses of components after these tests, the longest of which (run 4) lasted ca. 4450 h.

Cell Performance

Runs were carried out with no replenishment of the electrolyte (Table 1); the cell was 81 cm². Performance was evaluated by periodic (12 h) recording of the cell impedance (Z, m Ω) and of the overall potentials (η , V). Two of the planned runs (runs 2 and 3) were discontinued due to accidental failure of CO₂ and thus were useless for the sake of component evaluation. Run 4 was discontinued at 4450 h (while still holding 90% of its initial rated power) and the components analyzed (see below). Plots of the output voltages at different loads (I = 0 (OCV), 13.2A and 15A), IR and the power output (as % of the initial rated power) are shown in Fig.1 (run 4). A slow decay in the initial rated power is observed from 1200 h up; the cell still retained 90% of its initial activity even after 4400 h of continuous operation. The results denote improvement in the life-time by operation at lower T, as manifested by an average performance decay of 4,5 mV/1000 h and a steady increase of the IR (4% per 1000 h) before catastrophic decay had occurred.

"Post-mortem" analysis

To identify structural and morphological changes, extensive analyses were carried out on individual samples of anode, cathode, matrix and hardware (Run 4). Porosimetric distribution was made, using a Microstructure Porosimeter C.E. Mod. 2000. SEM analysis was performed by using an Autoscan "E TEC" (4SA) Scanning Electron Microscope coupled with a Microprobe EDAX (PV-9100). Chemical analysis was performed by a Siemens D-500 diffractometer with monochromatic Cu/K α (Ni-filtered) as radiation source.

TABLE 1

SYNOPSIS OF LIFE ENDURANCE - TESTS ON TAE-MCFC

VARIABLES	UNITS	RUN 2	RUN 3	RUN 4
Temperatures	K	893	893	893
Pressure	Bar	1	1	1
Fuel Flow	cc/min	255	255	255
Fuel Composition	%	66 H ₂ 34 CO ₂	60 H ₂ 40 CO ₂	60 H ₂ 40 CO ₂
Fuel degree of utilization η_F	%	68	75	75
Oxid. Flow	cc/min	915	915	915
Oxid. Composition	%	75 Air 25 CO ₂	75 Air 25 CO ₂	75 Air 25 CO ₂
Oxidant Degree of utilization η_{ox}	%	50	50	50
Life-time	h	1144*	500*	4450
Initial power output (at 13,2 A)	m Watt/cm ²	107.4	108.0	108.0
OCV	m Volt	1010	1020	1020
Initial Internal cell resistance	m Ω	9.0	8.0	8.0
Holding pressure	atm	1.0	1.0	1.3

*Run discontinued because of failure in the CO₂ line.

Results of different analyses can be summarized as following. The spent anode is characterized by an increase (+ 15%)

in the total pore volume with some shift toward the lowest pore sizes. SEM analysis revealed traces of K and Al. XRD of the naked surface of the anode showed presence of Li_2CO_3 , LiOH and $\text{Li}_2\text{Al}_2\text{O}_2 \cdot \text{XH}_2\text{O}$ (from hydrolysis of $\gamma\text{-LiAlO}_2$). Porosimetric analysis of the spent tile revealed some shift to lower radii but the shape of the pore volume distribution was the same as for the fresh. The tile appears vitreous, poorly regular, with some white spots attributable, by back-scattering analysis, to Ni and Cr. A feature of the Ni is its even presence with thickening in the proximity of the cathode. Cr also appears dispersed but at a much lower intensity. Comparison between the fresh and used cathode showed a slight decrease (-10%) of total pore volume with concomitant appearance of some micropores. Visual inspection revealed change from a laminar (fresh) to an incoherent black powder (used). Absence of K was confirmed by SEM and XRD. Strong lines attributable to $\text{Li}_2\text{Ni}_8\text{O}_{10}$ and $\text{Ni}_7\text{S}_6\text{O}$ were also detected. Housing surfaces were found covered by a white powder (Li salts) especially concentrated on the anodic side. This can be taken as evidence of creep on the housing materials. This observation, together with overall electrolyte losses amounting to 25% of the original, seems to indicate that drainage of the electrolyte should followed by preferential attack of the housings by the Li_2CO_3 while vapor losses could have been predominantly in the form of KOH as expected (5). Moreover, lack of K (XRD and SEM) at the anode- and at the cathode-electrolyte interfaces suggests that insufficient electrolyte inventory in each electrode was the cause of the observed performance decay. This statement well complies with common belief that cathodes show optimum performance when the electrolyte fills small pores such that 20-25% of the cathode pore volume is occupied (4). With our spent cathode still holding 34% of the total volume as micropores, lack of the electrolyte contact at the cathode is posed as crucial for the life of the cell. In this view the end of the cell is marked by a still filled tile but the electrodes are "dry", the electrical interruption being localized at the tile-electrode interfaces. As to the fate of the electrolyte, even if a quantitative analysis was not carried out nor the fractional K/Li composition in the spent tile analyzed, we assume that the observed overall losses of the electrolyte (25%) could be accounted mostly by corrosion reactions. Such assumption is based upon the model earlier proposed by Marianowski (6) according to which overall losses in a MCFC operated at 923 K follow

an empirical rate law of the type:

$$\text{Losses} = 3.78 \times 10^{-4} t + 0.09 t^{0.365} + 3.4 \text{ g} \quad (2)$$

(vaporization) (corrosion) (creepage+lithiation, etc.)

The model, as such, gives in our case (4400 h) an estimated loss of 5.4 g, equal to 16% of the original mass of the electrolyte. As, however, this mass is roughly two-thirds of that observed, the question is open as to a readaptation of the model to any different prevailing conditions. Evidently, with the first term in Eq.2 expected to be lower at any lower T (function of the activation energies for vaporization, usually in the order of 35-59 Kcal/mole), it is inferred that the second and third terms in Eq.2 should have more than compensated, in our case, for the higher observed losses. Accordingly, simple considerations call for either an increase in the exponent of the corrosion term and/or an increase of the third term in eq.(2). However, as the observed very low increase of the IR (Fig.1) tends to exclude creepage and the lithiation of the anode was found not to be dramatic we conclude that, under circumstances, main concern should be posed upon the corrosion term, most likely as the wet-seal corrosion.

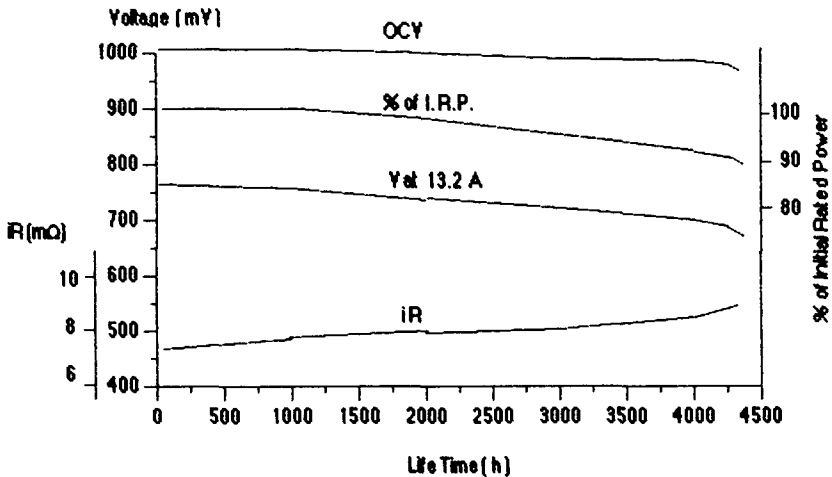


FIGURE 1
Endurance behaviour of a MCFC at 893 K

Conclusions

Operation of a MCFC at 893 K, without electrolyte replenishment, has led to 4400 h with performance equal to or higher than 90% of its initial rated power; the average decay rate was in the order of 4.5 mV/1000 h and the increase in IR of about 4% every 1000 h. Post-mortem analysis of the components indicated that the principal mechanism of performance decay could be associated with insufficient carbonate inventory in each electrode. As used components looked acceptable by SEM and porosimetric analysis, it is concluded that further work at lower than baseline T should be continued with emphasis on the corrosion behaviour.

Acknowledgment

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References

1. S. Freni, R. Quagliata, F. Romeo, P. Carbonaro and R. Di Leonardo, "Research Activity at CNR-TAE during 1984 on the IGT Molten Carbonate Fuel Cell Test Facility". Int. Rept. N.06/85 - April 1985.
2. B. Baker, S. Gionfriddo, A. Leonida, M. Maru and P. Patel, "Internal Reforming Natural Gas Fueled Carbonate Fuel Cell Stack". Final Rept. for GRI Contract N. 5081-244-0545, Energy Research Corp., Daubury, CT, 1983.
3. N. Giordano, S. Freni, R. Quagliata, G. Moleti, P. Carbonaro and E.H. Camara. Ext. Abstract N.412. The 179th Electrochemical Soc. Spring Meeting, Boston May 4-9th, 1986.
4. H.C. Maru, D. Patel and L. Paetsch, Ext. Abstract 81-1, Electrochemical Soc. Pennington N.J. (1981).
5. E.T. Ong and T.D. Clear in "Molten Carbonate Fuel Cell Technology" pag.54 (J.R. Selman and T.D. Clear, eds) pV 84-13, Electrochemical Soc. Pennington N.J. (1984).
6. L.G. Marianowski and J.B. O'Sullivan "Status of Molten Carbonate Fuel Cell Technology" Eight Annual Energy Technology Conf. and Exp. Washington, D.C. March 9-11, 1981.

MODELING OF H₂S EFFECTS ON THE PERFORMANCE OF MOLTEN CARBONATE FUEL CELLS

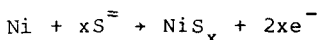
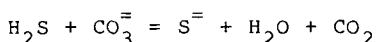
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Introduction

A model has been developed to predict the performance of a molten carbonate fuel cell (MCFC) operating on fuel contaminated by low levels (1-10 ppm) of H₂S. The calculation of voltage losses is based on a poisoning mechanism drawn from experimental studies at the Institute of Gas Technology (1,2). An existing MCFC performance model (3) was modified to include the effects of this mechanism on cell polarization. The performance model was also modified to account for the effects of SO₂ crossover from the cathode to the anode occurring when spent, H₂S-containing fuel is burned and added to the cathode stream for CO₂ makeup. For this application of the fuel cell performance model (3), a flooded agglomerate model (4) and a heterogeneous film model (5) were used, respectively, for the cathode and anode. These two models represent reasonably well the NiO cathodes and 90/10 Ni/Cr anodes used in IGT cells. Only counterflow geometry was considered in order to simplify the interpretation of results as well as the model development and validation.

Poisoning Mechanism

The mechanism developed at IGT (1,2) postulates the reaction of dissolved H₂S with carbonate ions to form sulfide ions which then react with the nickel anode to form a film of a nickel sulfide species of unknown composition:



Based on these reactions, a Nernst equation for the potential E_s at which this sulfide forms can be written,

$$E_s = E_s^0 + (RT/2F) \ln(P_{\text{H}_2\text{O}} P_{\text{CO}_2} / P_{\text{H}_2}) \quad (1)$$

where P is a partial pressure and E⁰_s (=-1.393V) was obtained from half-cell experiments^s(1).

Poisoning occurs only at anode potentials positive to E_s, where NiS_x forms. Thus, a poisoning threshold exists that depends on the electrode polarization and fuel composition. However, it was concluded from cell tests (1) that even a

fully poisoned anode continues to oxidize hydrogen, although with substantially reduced electrocatalytic efficiency.

Modeling of H₂S Poisoning

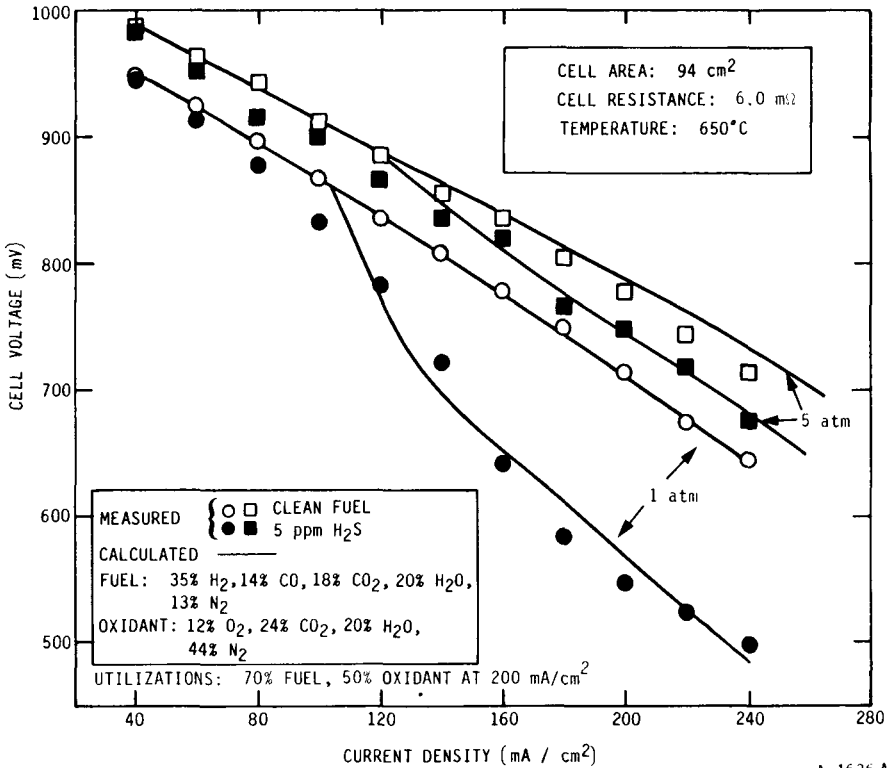
Poisoning of the anode is assumed to occur when the anode potential V_a is more positive than E_s . Due to fuel utilization, both E_s and V_a become more positive with increasing distance in the fuel flow direction. Since V_a also depends on the local anode overpotential, the anode's polarization characteristics also help to determine when the poisoning condition $V_a > E_s$ is first achieved. Typically, at constant flow rate, the condition $V_a < E_s$ will hold throughout the cell at low current densities, and no poisoning will occur. At high current densities, the condition $V_a > E_s$ will prevail everywhere, and the entire anode will be poisoned. At intermediate current densities, each inequality will hold over part of the anode, and partial poisoning will occur. In a counterflow cell, poisoning is predicted to occur first at the anode outlet.

Average cell current density is calculated in the usual way (3) except that at any point in the cell for which $V_a > E_s$, the assumed presence of NiS_x on the electrode surface must be accounted for. In computing the local current density at these points, the exchange current density for the anode model is decreased by a factor accounting for the reduced effectiveness of the electrode due to H₂S poisoning. Because there is no measured value of the exchange current density on NiS_x , the reduction factor was determined empirically from cell data with 5 ppm H₂S in the fuel. Best agreement with measured current densities in the range 160 to 240 mA/cm² (where complete poisoning is assured) was found for the value 1.4×10^{-3} .

Comparison of calculated and measured performance on clean and contaminated fuel is shown in Figure 1. Calculated results at 5 atm were actually obtained prior to the cell tests using the model parameter values determined from the 1 atm data. The good agreement represents a successful predictive test of the model. The most striking feature is the clear prediction of substantially reduced voltage losses at 5 atm in the full-poisoning regime compared to those at 1 atm.

Modeling of Sulfide Accumulation Due to Crossover

This model accounts for performance degradation due to sulfide buildup via crossover from the cathode. Crossover can occur when anode exhaust gas is oxidized and fed into the cathode as a CO₂ source. Any H₂S present will be converted into SO₂ which may react to form sulfate ions that migrate to the anode. There they will be reduced, adding to the sulfide already present. The accumulation model is based on two principal assumptions. First, the absorption of



A-1626 A

FIGURE 1

COMPARISON OF MEASURED AND CALCULATED EFFECTS OF 5 ppm H₂S ON IGT (1) CELL PERFORMANCE AT CONSTANT FLOW RATE

SO₂ by electrolyte in the cathode is assumed to be first order in the partial pressure of SO₂ in the gas stream. Second, all of the SO₂ that dissolves is assumed to be transferred to the anode.

Mathematical development of this model (details in Appendix of Ref. (1)) for counterflow geometry leads to a simple expression for the local molar flow rate of H₂S in the anode, $\dot{n}(\text{H}_2\text{S})$, that depends on the inlet H₂S and cathode ($\dot{n}_c^0$) molar flow rates, cell length L , cell pressure p , SO₂ absorption coefficient α , and crossover fraction ϵ which is the fraction of H₂S in the anode effluent that returns to the anode via recycle through the cathode.

The expressions for $\dot{n}(\text{H}_2\text{S})$, E_s and V_a can be used to obtain an equation for the H₂S inlet concentration $X^0(\text{H}_2\text{S})$ below which no anode poisoning will occur (the poisoning threshold value) (details in Appendix of Ref. (1)):

$$X^O(H_2S) = (2\sqrt{3}/9) (1 + X_F^O U_F + 2 X^O(CH_4) \gamma) (1 - \epsilon f) X^e(H_2) \exp [E_s^O + E^O - \eta_a^e] 2F/RT \quad (2)$$

Here, E^O is the fuel cell standard state potential, η_a^e is anode overpotential at the anode exit, U_F and γ are the total fuel (F) and methane utilizations, X^O is an inlet mole fraction, X^e is an exit mole fraction and f is the fraction of SO_2 absorbed in the cathode. Variation of the poisoning threshold with changes in crossover parameters (ϵ , α) or operating conditions (e.g., fuel composition, flow rates, cell voltage, etc.) can be studied with Eq. (2) by using the performance code to determine η_a^e and other exit quantities.

Calculated poisoning threshold values are shown in Table 1 for a fuel cell operating at 200 mA/cm² and 0.725V with 75 percent fuel and 50 percent cathode CO_2 utilizations. A cell resistance of 5 m Ω was assumed; other operating conditions are specified in Figure 1. The value 1.1×10^{-3} mol/(cm $\cdot$ s $\cdot$ atm) was used for the SO_2 absorption coefficient α . This value adequately reproduces the experimental observations made at IGT (1) that all of the SO_2 is absorbed ($f=1$) within the first third of the cell.

TABLE 1

CALCULATED THRESHOLD POISONING VALUES, $X^O(H_2S)$ VERSUS CROSSOVER FRACTION ϵ for MEDIUM-Btu FUEL AT 200 mA/cm² AND 75 PERCENT FUEL UTILIZATION

ϵ	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
$X_{H_2S}^O$	1.35	1.22	1.08	0.95	0.81	0.68	0.54	0.41	0.27	0.14

Besides simply displaying the linear dependence of $X^O(H_2S)$ on ϵ seen in Eq. (2), the results illustrate how important it is to reduce the inlet H_2S concentration in order to avoid performance losses as the fraction of H_2S recycling through the cell via crossover is increased. The reason for this is obvious. Crossover increases the exit concentration of H_2S . To avoid poisoning, this exit concentration must be held below a critical value determined by the condition $E_s(\text{exit}) = V_a(\text{exit})$. Hence the inlet concentration must decrease as ϵ increases.

Calculated or measured threshold values for one type of electrode in a given state of performance cannot automatically be assumed to apply to other types of electrodes or to other performance states. Due to the exponential dependence on η_a^e of Eq. (2) calculated values of the poisoning threshold will depend on how well the anode is performing.

A good anode will have a higher poisoning threshold than a poor one. Besides fuel composition, the pore structure, electrolyte content and material composition of the electrode will affect its polarization characteristics. Even for a given type of anode, Eq. (2) makes it clear that fuel composition and utilization will also influence the threshold poisoning value. Cells operating with fuels rich in H_2 and/or at lower fuel utilization will tolerate higher H_2S concentrations before suffering performance losses than cells operating on fuels lean in H_2 and/or at higher fuel utilization.

Acknowledgment

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References

1. R.J. Remick, "Effects of H_2S on Molten Carbonate Fuel Cells," Final Report, DOE/MC/20212-2039, NTIS/DE86010431, Institute of Gas Technology, May 1986.
2. R.J. Remick and D.R. Vasil, "Fate of Sulfur Contaminants at the PPM Level in Molten Carbonate Fuel Cells," Fuel Cell Seminar Abstracts, 1985, p 173.
3. T.L. Wolf and G. Wilemski, "Molten Carbonate Fuel Cell Performance Model," J. Electrochem. Soc. 130, 48 (1983).
4. G. Wilemski, "Mathematical Modeling of Fuel Cell Electrodes," Final Report, PSI TR-350, Physical Sciences Inc., October 1982.
5. G. Wilemski, N.H. Kemp, and A. Gelb, "Molten Carbonate Fuel Cell Performance Model Update," Final Report, PSI TR-449, DOE/FE/15078-1742, NTIS/DE85003356, Physical Sciences Inc., January 1985.

STATUS OF MOLTEN CARBONATE FUEL CELL DEVELOPMENT AT HITACHI

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INTRODUCTION

Hitachi, Ltd., has been evolving development of molten carbonate fuel cells (MCFC) since 1960, and the matrix type electrolyte MCFC has been studied since 1981 under contract of the MITI/AIST and NEDO's MOON-LIGHT project. (Ministry of International Trade and Industry/Agency of Industrial Science and Technology, and New Energy Development Organization). (1) (2)(3)(4)

Large sized ($3,000\text{cm}^2$ class) electrolyte plates made by doctor brade (tape casting) method have been produced successfully, and single cell and 3-cell stack tests with $3,600\text{cm}^2$ components, and 15-cell stack and 30-cell stack tests with 900cm^2 components were achieved using the 10kW class test facility.

COMPONENT DEVELOPMENT

1 ELECTRODE: Nickel anode containing cobalt and nickel oxide cathode containing silver are produced continuously by the sticking method on the wire mesh. The $3,000\text{cm}^2$ class manufacturing apparatus shown in Fig.1 has been operated satisfactorily.

2 ELECTROLYTE PLATE: The doctor brade (tape casting) method is adopted for making the thin, easy handling matrix and for mass production. By use of high specific surface area LiAlO_2 powder and alumina long fibers, the micropore distribution and the strength of the matrix sheets were improved, and the retaining ability of electrolyte was also improved. The $3,000\text{cm}^2$ class electrolyte plates have been produced with the manufacturing apparatus shown in Fig.2.

3 SEPARATOR: By corrosion test on 28 kinds of steels against molten carbonate, it was found that the corrosion resistance improves with increase in chromium content and 25 Cr steel (TYPE 310) is superior to any other stainless steels.

CELL AND STACK PERFORMANCE

Single cells and cell stacks with 64,100,200,900 and 3,600cm² electrode areas have been assembled and tested. Fig.3 shows the 10kW class test facility and Fig.4 shows the 3,600cm² 3-cell stack. The performance of the stack is shown in Fig.5. The average cell voltage was 0.75V at a current density of 150mA/cm². The operating conditions are shown in Table.1.

ACKNOWLEDGEMENT

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REFERENCES

1. M. Tonami, M. Takeuchi, and F. Nakajima; "Development and Testing of Molten Carbonate Fuel Cell Materials", 1982 National Fuel Cell Seminar Abstracts, pp.99-107, Nov., 1982.
2. T. Kodama, K. Tamura, K. Murata and N. Horiuchi; "Status of Japanese Molten Carbonate Fuel Cell Program", 1983 National Fuel Cell Seminar Abstracts, pp.161-164, Nov., 1983.
3. M. Takeuchi, K. Tamura, Y. Hishinuma and A. Sohma; "The Status of Molten Carbonate Fuel Cell Development at Hitachi, Ltd.", 1985 Fuel Cell Seminar Abstracts, pp.153-156, May., 1985.
4. Y. Hishinuma; "The Status of Molten Carbonate Fuel Cell Development at Hitachi, Ltd.", IAE International Symposium on Fuel Cell and Advanced Battery Abstracts, pp.104-108, Jan., 1986.



Figure 1. 3,000cm² class electrode manufacturing apparatus



Figure 3. 10kW class test facility



Figure 2. 3,000cm² class electrolyte plate manufacturing apparatus

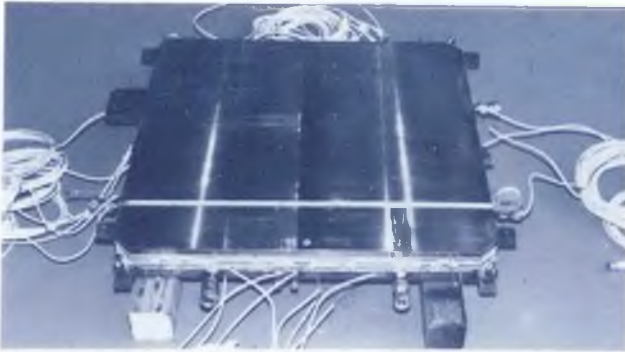


Figure 4. 3,600cm² 3-cell stack

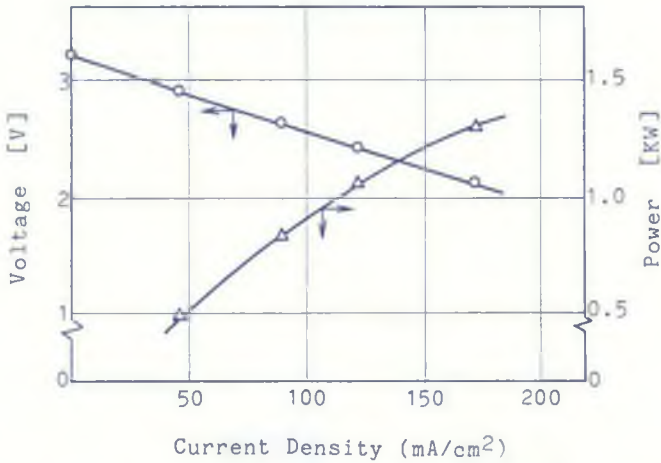


Figure 5. Performance of 3,600cm² 3-cell stack

Table 1. Operating conditions of 3,600cm² 3-cell stack

Temperature		650°C
Pressure		Atmosphere
Gas Composition	Anode	80% H ₂ - 20% CO ₂
	Cathode	30% CO ₂ - 70% Air
Gas Utilization	Anode	20%
	Cathode	50%

LOW COST METHANOL-PHOSPHORIC ACID FUEL CELL POWER PLANTS

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ERC is developing low-cost methanol fuel cell power plants for commercial applications in the 2-10 kW range. Our main objectives are: (1) Compact size, (2) Cost reduction, (3) Improved reliability, (4) Fully automatic operation and control.

Fig. 1 shows a fully automatic 7 kW DC prototype power plant with an on-board microprocessor. The unit is self-contained, portable and adaptable to field service and/or base power installation. The plant was built using commercial components for low cost and ready availability. Additional features which further decrease the cost are: (1) DC parasitic power required to operate the unit supplied directly from the stack center tap without auxiliary power converters; (2) Reliable low-cost passive controls replaced electrically driven units; (3) Subsystem design improvements provide compact, simple and functional operation that will yield low production costs.

FIGURE 1

PROTOTYPE POWER PLANT NO. 1



Fig. 2 depicts component arrangement for the power plant.

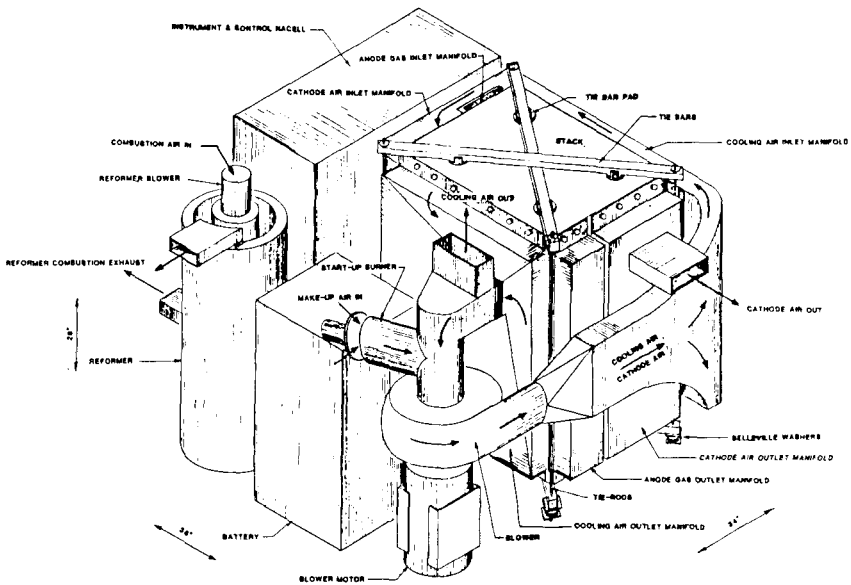
1. Fuel cell stack with 75, 12 in. x 17 in. cells.

Asymmetric Z gas channel pattern is used in the cells to reduce air side pressure drop and thus parasitic power loss. Also, Z pattern results in an increased oxygen concentration which leads to cell performance gain.

Separate air cooling system and a new type of compact burner provide fast stack start-up and simplify power plant operation. The unit can be heated from cold start to full load operation within 15 minutes.

Variable heat transfer area cooling plate channel design allows effective removal of heat generated in the stack to provide uniform fuel cell temperature for the optimum cell/stack performance and long life.

2. Reformer - A partially heated annular design resulted in compact size and improved performance. The temperature profile in the catalyst bed, as well as the conversion and the reformer product concentration, is presented in Fig. 3.



7 KW METHANOL FUEL CELL POWERPLANT

3. Instrument and Control Nacelle - This subsystem consists of microprocessor, power supply, power driver, control panel, relay box and battery charger.

4. Battery - Two 12V batteries internally recharged during operation are used for the start-up electrical power supply.

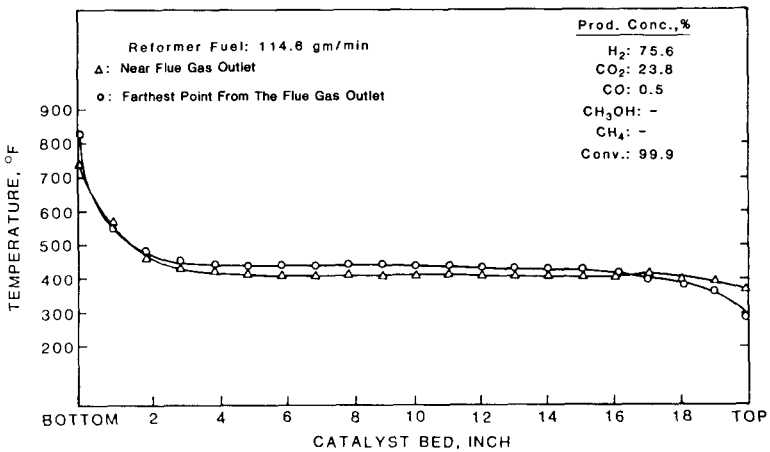


Fig. 4 describes how the stack power is distributed for the customer and parasitic loads. Typical operating data is summarized in Table 1. The key features are given in Table 2 and the most significant results are indicated below:

- Compact power plant, 20 cu.ft. for 7.6 kW (7 kW net).
- Low parasitic power, 0.6 kW which is about 8%.
- Cost reduction through use of off-the-shelf commercial components and passive control.
- Fully automatic operation and control.
- Stand-alone and portable unit.
- Overall power plant efficiency of 36% for full load.
- Stack hydrogen utilization of 69%.

Testing of this prototype power plant has been completed and has provided a basis for the pre-production prototype power plant.

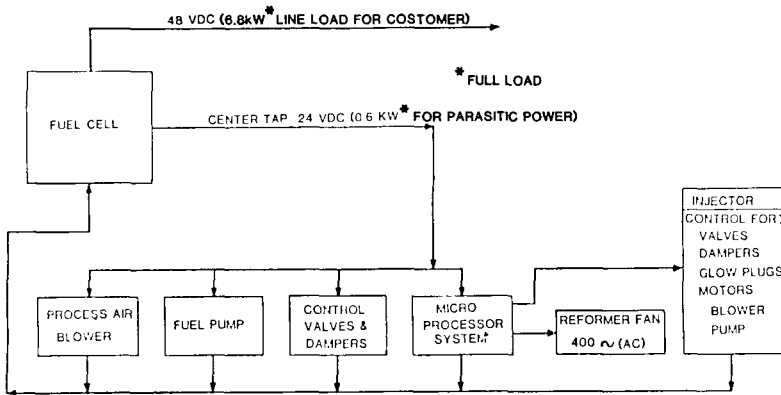


FIG. 4
7 kW METHANOL FUEL CELL POWER PLANT
POWER DISTRIBUTION

TABLE 1
7 kW Prototype Power Plant

OPERATING CONDITIONS:	Inter-				Inter-		
	Full	mediate	Idle		Full	mediate	Idle
Stack avg. temp., °F	365	346	338	Fuel Consumption, kg/h	6.42	4.73	3.63
Bottom 40 cells load, A	174.4	126.7	94.9	Stack H ₂ utilization, %	69	66	62
Top 35 cells load, A	150.0	101.0	68.6	Plant Efficiency, %			
Average load, A	163.0	114.7	82.6	Gross/Net	36/33	36/32	35/30
Stack voltage, V	45.6	47.7	49.6	Reformer Product			
Stack power, kW	7.43	5.5	4.1	Concentration, %			
Parasitic current, A	24.4	25.7	26.3	H ₂	74.5	74.1	73.6
Parasitic voltage, V	24.1	25.2	26.3	CO ₂	4.0	24.0	24.1
Parasitic power, kW	0.59	0.6	0.70	CO	1.5	1.9	2.3
Customer power, kW	6.84	4.85	3.40	CH ₃ OH	--	--	--

TABLE 2
7 kW PROTOTYPE POWER PLANT

Power Plant I.D.	Prototype G-2
kW, Gross/Net	7.6/7.0
Size, ft ³	20
kW/ft ³ , Gross/Net	0.38/0.35
Operation/Control	Full Auto.
Housekeeping Pwr.	From Stack
Housekeeping Comp.	24V DC
Start-up Burner	4"D x 3"L
Reformer	10"D x 24"L
Start-up Heat Ex.	None
Idle Heaters	Incorp.

DEVELOPMENT OF SMALL CAPACITY PHOSPHORIC ACID
FUEL CELL POWER SYSTEM AT FUJI ELECTRIC

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Introduction

Fuji Electric started the research and development of PAFC in 1973. From 1982 to 1983, we performed 30 kW PAFC power plant testing under cooperation with Kansai Electric Power Company Inc.. The plant was installed in premises of Sakai-ko Thermal Power Station of Kansai Electric Power Company Inc. in April, 1982 and was operated by steam reformed LNG. The 30 kW stack was a ribbed separator type which has an active area of about 1000 cm² and was cooled by air. The plant recorded about 3500 hours of accumulated operation including un-manned 500 hours, continuous (non-interrupted) operation by remote control.⁽¹⁾

We also emphatically started the research and development of methanol reformer in 1984. We constructed 3-7 kW methanol reformers and evaluated their performances within one year. Being based on these actual results, we were developing 3-7 kW methanol reformed PAFC power systems. The purpose of this development is mainly to increase the usefulness of FC power systems in Japan, i.e., to replace diesel generators and batteries by FC power system.

For the present, we are promoting to investigate the problems which will occur on the practical use, such as operability, maintainability and performance under the actual conditions.

Also we are intending to enter into the field testing with our potential customers and to accumulate the real operation experience under various conditions.

In future, we will supply it to the more general application fields.

Development of 3kW power systems

We constructed 3kW DC methanol reformed PAFC power system model in 1984. Figure 1 shows the appearance of the 3kW power system model. The stack is a ribbed separator type and has an active area of 1000 cm². Cooling is achieved by air. The stack is operated at atmospheric pressure and 180 °C. Fuel processor operates on a 1:1.3 molar mixture of methanol and water. Methanol is converted to hydrogen rich gas by Cu-Zn catalyst in a steam reformer. Off gas from the stack is burned to provide heat to the reformer.

Figure 2 shows the schematic diagram of 3kW power system model. Figure 3 shows the profile of start up of 3kW power system model. Start up was performed in ten steps up to 100% load on account of the time delay of reformer response. We have completed about 100 times of start up and shut down testing in our laboratory.

Subsequently, we constructed 3kW DC power system in 1985. The stack power was a DC 29V 4kW and the system operation mode was full automatic. The start up time was approx 30 min from R.T. The power conditioner was the DC/DC converter which outputs a DC 110V 3kW. It was designed and manufactured based on the NEDO project as a power supply system which incorporated with solar-battery system for use in the recreation house of Hokuriku Electric Power Company Inc.. (2) This 3kW DC power system was installed in the end of 1985.

Development of 5kVA/4kW power systems

Currently, we are developing a 5kVA/4kW methanol reformed PAFC power system. The stack and the reformer configurations are almost same as the 3kW power system. Table 1 shows the specification of 5kVA/4kW power system. Rated output voltage and frequency of inverter are ordinary 1-phase 100 V AC and 50 or 60 Hz respectively.

Methanol/water mixing subsystem -the water is recovered from exhaust gas- and waste heat recovery subsystem are optional.

We are making efforts to simplify the operability and the maintainability of the system by the following improvements:

Reducing the start up time of the system by reducing the start up time of the reformer.

Eliminating of the stack storage heater by improvement of the tolerance of the electrolyte freezing.

We will be able to deliver the first 5kVA/4kW power system for the field testing by the end of fiscal 1986.

References

1. M. Yonehara, R. Anahara and K. Suzuki, "OPERATIONAL EXPERIENCES OF 30 KW PHOSPHORIC ACID FUEL CELL POWER PLANT" National Fuel Cell Seminar Abstracts, Nov 13-16, 1983, pp. 169-172
2. K. Shinobe, "DEVELOPMENT OF PHOSPHORIC ACID FUEL CELL TECHNOLOGY" Extended Abstracts IAE International Symposium on Fuel Cell and Advanced Battery, Jan 21-22, 1986, p. 84



Figure 1 The appearance of 3kW DC power system model

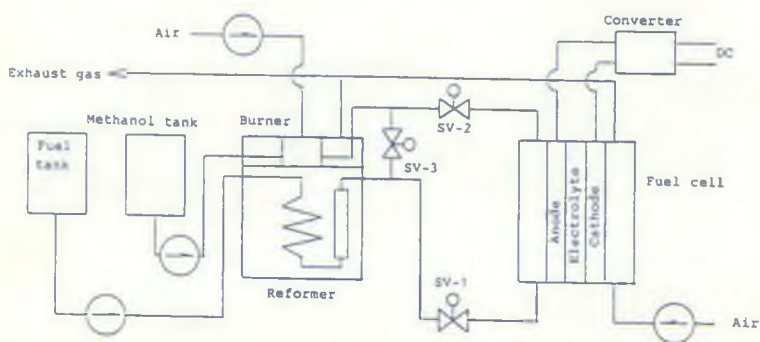


Figure 2 Schematic diagram of 3kW DC power system model

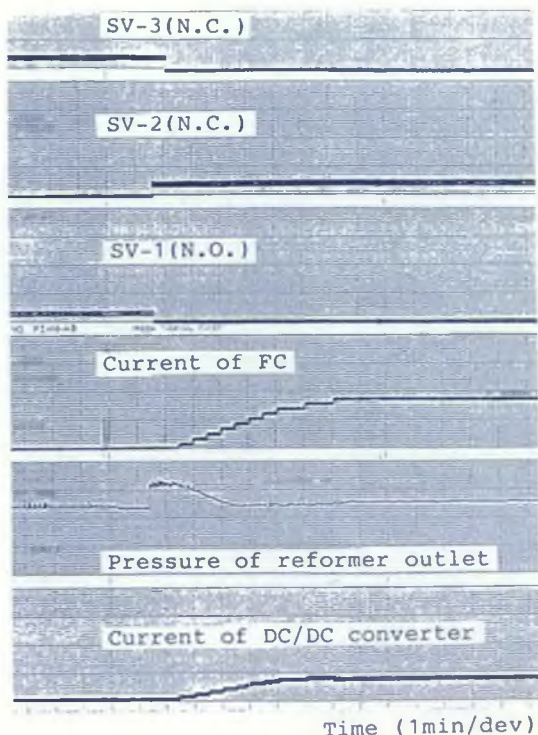


Figure 3 The profile of start up of
3kW DC power system model

Table 1 5kVA/4kW specification

Rated output	5kVA/4kW
Output voltage	1-phase 100 V AC
Frequency	50/60 Hz
Fuel cell power	5.9 kW
Methanol consumption	3.5 l/H
Operation mode	Full automatic
Start up time	approx 30 min from R.T.
Noise	55 dB(A) 7m
Installation location	Indoor (Outdoor...option)
Ambient temperature	5-40 °C
Dimension	650Wx1600Lx1200H
Weight	700 kG(except fuel)

ENGELHARD TECHNOLOGY UPDATE

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The Engelhard phosphoric acid fuel cell stack technology - directed toward multi-kilowatt, atmospheric-pressure applications - continues to be based on the following key features: single-phase liquid cooling, cooling plates and bipolar plates comprising commercial graphite, electrolyte-matrix configuration that incorporates an acid-transport layer, continuous acid-replenishment system, and in-house developed catalysts. Recent emphasis in the technology development program has involved implementation of thinner graphite elements, selection of the most attractive graphite plate bonding resin, simplification of the acid-replenishment system configuration, and qualification of an improved acid-transport layer structure.

The improved acid-transport layer configuration serves to improve performance, primarily through a reduction of cell IR-loss. This component is now electronically non-conducting; therefore, while it is thinner than the previous version, it also allows the adjacent matrix layer to be thinner. The resulting reduction in IR-loss is substantial, but an unanticipated benefit has been a higher IR-free performance as well.

The key test vehicles for confirmation of technology improvements have been stacks of the 4kW size. These stacks typically consist of 24 cells of the 13 inch x 23 inch size; the active area is 1.75 square feet. One such stack was built in late 1985 to examine the improved acid-transport layer as well as other new-technology features. This stack incorporated a six-cell sub-stack (group of cells between cooling plates) that utilized the improved acid-transport layer, while the remaining three sub-stacks utilized the previous configuration.

The above 4kW stack was tested for 3200 hours and then torn down for examination of several novel features. Overall stack performance had been steady throughout the test; also, it is notable that the six-cell sub-stack with the improved acid-transport layer sustained a sizable performance advantage over those with the prior design during this period.

Improvements such as that cited above are currently being implemented in a 25kW stack. This stack will reflect technology features qualified through the early part of 1986. Stack testing will be carried out in conjunction with a methanol processing sub-system during the last quarter of 1986. A natural gas processing sub-system, currently under development, will then be integrated with the 25kW stack early in 1987.

CONSTRUCTION AND TESTING
OF PAFC DEMONSTRATION POWER PLANT

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1. Introduction

The Tokyo Electric Power Co., Inc. (TEPCO) is now carrying out a small 200kW class air-cooled type PAFC plant under the joint work with Sanyo Electric Co., Ltd. The plant is scheduled to be installed at the site of the Shin-Tokyo Thermal Power Station located at Toyosu, Tokyo and be tested from next April for about 1.5 years. Sanyo is one of the most active enterprizes in PAFC field and has successfully completed two 50kW PAFC demonstration programs.

2. Outline of the Demonstration

To predict the future of the cogenerator based on small size PAFC system, following points are studied during the demonstration.

- (1) Cogeneration characteristics of the 200kW class PAFC plant
- (2) Reliability and safety
- (3) Maintenance
- (4) Compactness
- (5) Economics

3. Outline of the System

Figure 1 shows the flow diagram of the 200kW class PAFC demonstration power plant.

The characteristics of the plant are as follows:

- (1) Fuel is natural gas (town gas)
- (2) The fuel cell is air cooled type and consisted of 4 stacks of 60kW rated dc power. The operating pressure and temperature are atmospheric and 180°C respectively. The structure of the fuel cell stack is shown in Figure 2.
- (3) Aiming for practical use in the future, 2500 cm² cell size is used for the first step. The area of 2500 cm² was designed based on actual results of the former 1000 cm² cell.
- (4) To make the system more compact, the rectangular reformer is used. This rectangular shape is one of the first steps to practice the small PAFC plant in the future.

Figure 3 shows the structure of the reformer.

(5) The inverter, in which GTO elements are used, can be self commutated and operatable under var operation.

(6) The controller uses DDC to keep high reliability in accordance with many kinds of experiments during the whole testing period. The control system can be automatically operated and makes the whole system transit automatically into safe status in emergency.

(7) To enhance safety and reliability, heat exchangers of shell-and-tube type are adapted as well as taking consideration that combustible gas and air do not flow through same heat exchangers.

(8) This plant has a heat exchanger to make various kinds of thermal load. Figure 4 shows the schematic diagram of the thermal-load simulation test system to survey cogeneration characteristics.

(9) Various equipments are so arranged that testing, operation, maintenance etc., can be easily done.

(10) The data aquisition system is fully equipped to measure various characteristics of the plant.

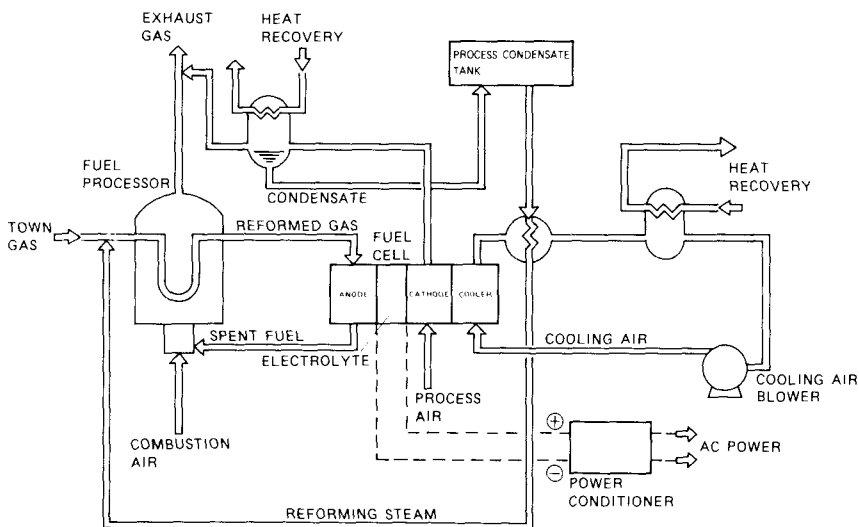
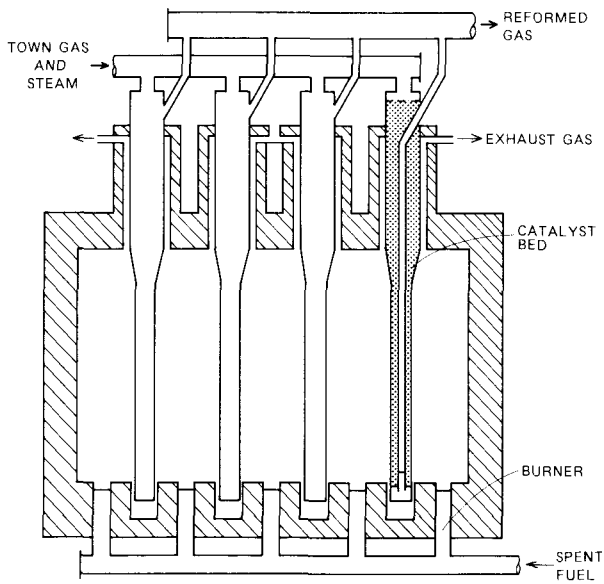
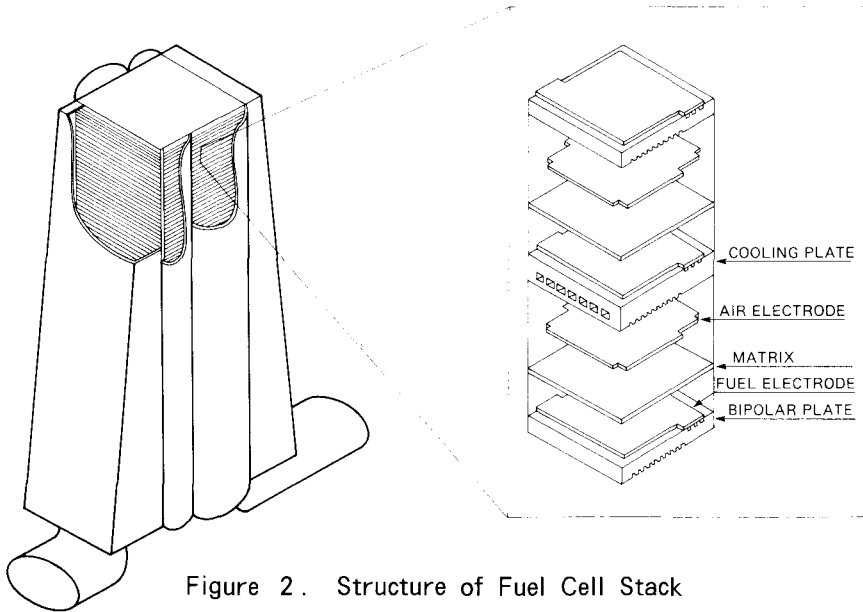


Figure 1. Flow Diagram of 200KW Class PAFC Demonstration Power Plant



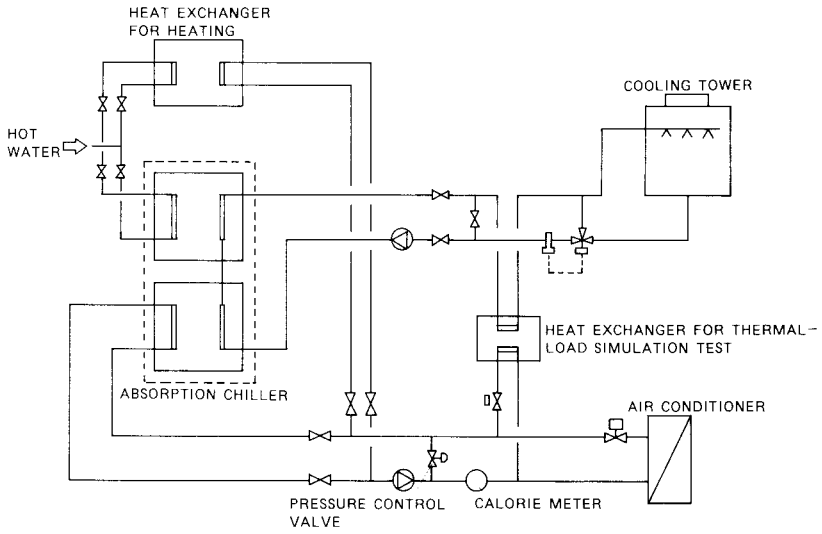


Figure 4. Schematic Diagram of Thermal - Load Simulation Test System

ON-SITE FUEL CELL TECHNOLOGY AND SYSTEM PROGRESS

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The purpose of this On-Site Fuel Cell Technology Development Program is to develop the technology base for a 200-kW power plant that will meet requirements for on-site electric power generation. Present activities are focused on building and testing a 200-kW Verification Test Article (VTA) and transistor inverter.

The VTA is a dc system test rig which includes:

- 1) A Fuel Processing System to convert natural gas fuel into a hydrogen-rich fuel gas mixture,
- 2) A cell stack to produce dc power from hydrogen and oxygen (in air),
- 3) A Thermal Management System to reject waste heat and recover water for the fuel processor, and
- 4) A Water Treatment System to clean the recovered water.

The Verification Test Article is scheduled to begin testing in early 1987. Prior to operation of the VTA, key subsystems and controls will be evaluated separately.

The Water Treatment and Thermal Management Systems, shown in Figure 1, were fabricated and tested in the first half of 1986. The systems include equipment to clean the recovered water from the condenser, pump the water to the cell stack



Figure 1. WTS/TMS

cooling water loop, and reject cell stack waste heat to the facility coolant system. Successful operation over the full power range was demonstrated by simulating stack waste heat with electric heaters. Control stability and response evaluations were made to ensure that the systems were ready for operation with the cell stack in the VTA.

The Fuel Processor System, shown in Figure 2, was also fabricated in 1986. In addition to the full-size reformer, built and tested last year, the system includes the first full-scale application of the hydrodesulfurizer catalyst evaluated as part of this on-site technology program. A new process control approach featuring process feedback and electric actuation to lower cost and increase reliability is also included. The fuel processor evaluation started in June. Operation at rated power flows has been achieved, and testing is expected to be completed this fall.



Figure 2. FUEL PROCESSOR - INSTALLATION IN TEST STAND

The cell stack for the VTA is being fabricated. This stack will include improvements demonstrated in previous short stacks of full area cells. A mock-up of the 200-kW stack is shown in Figure 3 along with a 40-kW stack from the On-Site Field Test Program.



Figure 3. COMPARISON OF 40-kW AND 200-kW

In addition to fabrication and development of the VTA, testing of an advanced single-bridge transistor inverter was also conducted. The transistor inverter shown in Figure 4 is smaller, simpler and less expensive than the two bridge thyristor inverter it replaced. The transistor inverter bridge has completed verification testing over the full power and voltage range, operation with a resistive load bank. Later this year, this inverter bridge will be tested with output magnetics.



Figure 4. BREADBOARD TRANSISTOR INVERTER

Acknowledgements

This effort conducted by a team of International Fuel Cells personnel was sponsored by the Gas Research Institute and the U.S. Department of Energy, Morgantown Energy Technology Center (DOE-METC). NASA-Lewis Research Center manages the DOE contract.

MCFC R&D IN THE NETHERLANDS

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1. INTRODUCTION

In another paper at this conference, Pietersz gives an "Overview of the Dutch MCFC Programme". Reference is made to this paper for general information and head lines of the specific activities. The present paper details the latter.

The programme is a nationally coordinated effort, which for about 60% is financially supported by the government. However, it is limited both in budget and time and thus in scope. Therefore, compromises had to be reached both with respect to goals and to specification of actual activities.

Based on state-of-the-art know-how to be bought, available relevant capabilities, international cooperation and avoiding redundancy as far as possible, 13 projects have been defined. These cover and strike a balance between fundamental and applied research, development of materials and components as well as manufacturing techniques, and construction and engineering. The results will be instrumental in establishing a basis for fundamental understanding and in providing industrial partners with commercially interesting technology.

2. TECHNOLOGY TRANSFER

In order to give impetus to the programme and to maximize its results, it was decided to buy existing knowledge abroad. For this purpose an agreement has been concluded with GDC/IGT, Chicago, for support and education as well as mutual cooperation in MCFC R&D. The agreement covers a large number of subjects on which both fundamental knowledge and practical information are transferred. An expansion

to include also technological issues is envisaged. So far, both the concept and the way in which it is effectuated have proven to be highly effective.

3. RESEARCH

Fundamental and applied research will be conducted in two areas: electrochemistry and materials science. In the first area three projects were defined aiming at improved performance and durability by optimization of operating conditions and materials properties. For this purpose advanced theoretical and experimental techniques will be applied for investigating fundamental processes at each of the electrodes.

Parameters are composition and physico-chemical properties of each electrode, composition of electrolyte and feed gasses, feed gas pressure, and operating temperature. Recently the Eindhoven University of Technology THE announced that it will not participate in the programme, in spite of the fact that it was designated as the contractor and its experts were involved in defining the programme of work. Presently, therefore, the work is being redefined but at a substantially lower level of effort.

Materials research is performed along two lines. The first involves determination of a relatively large number of physico-chemical properties and characteristics of materials used in cell components, and their influence on processability, component fabrication techniques, properties and characteristics of the final product, and cell performance. Such work is of course a necessary part of materials, component and fabrication technique development, and is therefore actually incorporated in those projects. All necessary measuring techniques are available already, and presently modelling support is being acquired and (further) developed.

The second line focusses on preparation of starting powders with optimal characteristics for component fabrication and performance. Both state-of-the-art and new materials are addressed. As an example of the first group, an investigation has been started on the influen-

ce of the morphological properties of LiAlO_2 powder on matrix performance, which might lead to an adaption of the powder preparation process.

As for new materials, the preparation of lithium ferrites is studied. From these, conducting ceramics may be produced for manufacturing improved anodes and cathodes. This research has yielded spherical lithium-containing iron (hydro)oxyde particles with reasonable sintering properties. However, the starting iron sol does not seem suited for large scale production. Presently, an alternative way for preparing this sol is studied and thermodynamic calculations for supporting the project have been initiated.

4. DEVELOPMENTS

Some of the development projects include a research stage. Because of the recent start of the programme (May 1st, 1986) these have not yet reached the actual development stage. This is true for the development of new materials, i.e. conducting ceramics for improved long-term behaviour of both electrodes. And also for the powder technology development, where research will indicate which adaptations in the chemical preparation or physical conditioning of what powders will be successful. The development will then also include process upscaling to at least pilot production levels.

Mastering component fabrication techniques is a pre-requisite for both R&D and commercial activities. Such techniques will be (further) developed and optimized as well as adapted in response to new developments and product specifications. The development includes upscaling to commercial application. Presently, state-of-the-art techniques have been acquired, a comparative study of different techniques is underway, pressing techniques are being explored and an adaptable-size tape casting machine has been constructed and put into operation. New developments may include issues such as a multi-layer tape casting process that could produce e.g. cathodes with a pore size gradient to prevent cathode flooding and improve the resistance of the interface with the matrix.

The programme will also engage in the developments concerning the separator plate, as this is one of the weakest points in stack construction and operation. This project will include design studies, materials and corrosion R&D, evaluation and development of construction techniques, etc. The aim is an optimized plate design with respect to configuration, functions to be fulfilled, construction, (long term) performance and cost. The work has only very recently started with technology transfer and evaluation of existing designs.

Though many of the R&D subjects need support by model calculations, no large efforts in model development are envisaged. Existing models from IGT have been acquired, implemented and made operational. They will be used as such and updated when appropriate, while further development will depend on experimental requirements and results.

5. CONSTRUCTION AND ENGINEERING

Practical experience in this field will be gained with the different types of test cells that will support much of the R&D work described earlier. Apart from some single cells, a 6-cell semi automatic test train for 3 cm² laboratory cells has been designed and construction is nearing completion. A similar 5-cell train for 10 x 10 cm bench-scale cells has been designed and construction has started. Shortly, a design of a 30 x 30 cm cell for testing upscaled manufacturing techniques and separator plate developments will be started.

Finally, the engineering, design, construction and operation of a sub-scale MCFC stack is planned. This will be based mainly on IGT technology, but where possible and feasible developments mentioned above will be incorporated. This will be the prototype for larger test and demonstration plants to be constructed immediately and shortly after the termination of the present programme period. Engineering and design studies for these will be initiated much earlier, as they will also give guidance to the R&D work.

COOLING CHARACTERISTICS OF MOLTEN CARBONATE FUEL CELL

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1. Introduction

Of the three basic methods of flowing fuels and oxidizers in a molten carbonate fuel cell (MCFC), the cross flow, the co flow, and the counterflow, the first is being used today to amazement of any heat engineers. This may simply be a custom from an early day of phosphate FC development, which needed no more than steam to control temperature. But, whatever the reason, situation is not that simple for MCFC.

As little is known of cooling characteristics of MCFCs (1), we report the results of simulator tests and calculations we conducted to analyze the FC performances under those three different flow conditions.

2. Heat Transmission within an MCFC

The heat generated in an MCFC consists of the chemical reaction heat due to electrochemical reactions, that due to fuel reformation reactions, and the ohmic heating of electrolyte, the first two occurring in the anode, and the last in the electrolyte. As shown in Fig. 1, those heats transmit themselves through convective heat transfer from electrodes to fuel and oxidizer, movement of gases, radiation and contact heat transfer from electrodes to separator plates, and heat exchange between fuel and oxidizer through separator plates.

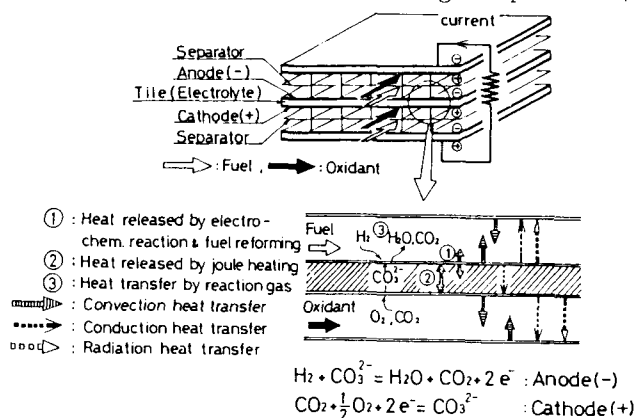


Fig. 1 Heat Transmission within a Fuel Cell

Here, the following are noted as characteristic of MCFC;
(1) the flow rate and the gas composition of the process gas change due to diffusion of reaction product gases;
(2) the heat transfer coefficient at anode decreases due to

welling effect of the reaction product gases; and
 (3) as the resistance to heat transfer of electrode is only $R \sim 0.0015 \text{ m}^2\text{h/kcal}$, the heat generated at the anode is transferred through electrolyte as well as through anode itself to cathode, there to be removed by the oxidizer.

3. Experiments and Results

The Simulator, which models an internal manifold type 4-cell MCFC of an electrode area of $50 \times 37 \text{ cm}$, complete with mock electrolyte plates and separator plates, is shown in Fig. 2, while Fig. 3 depicts an example of temperature distribution within a cell, both as measured and as calculated, for cases of co-flow and counterflow. The mock electrolyte plate consists of three sintered stainless steel plates of such porosity that allows simulated passage of reaction product gases, while the heat a real electrolyte will generate is supplied by electrically, heating the central plate. The channel depth is 2 mm for oxidizer and 1 mm for fuel, and air is used for either.

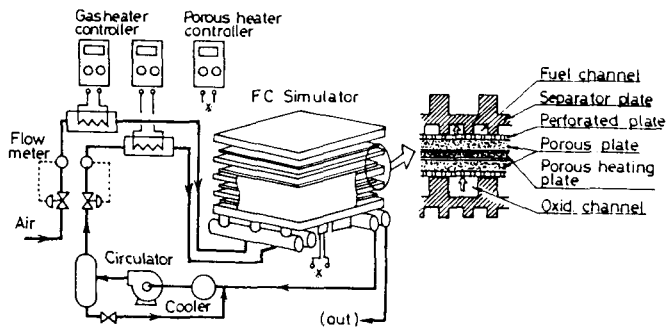


Fig. 2 The Experimental Apparatus - An FC Simulator

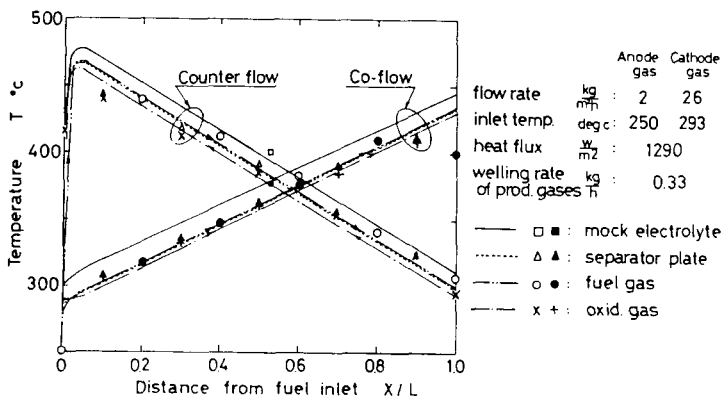


Fig. 3 Temperature Distribution within a Cell for Fuel-Oxidizer Co-Flow and Counterflow

It will be noted in Fig. 3 that in the case of co-flow, the temperature becomes monotonically higher in the direction of flow, whereas in the case of counterflow, a maximum appears near the fuel inlet end, because the fuel flow rate is only a fraction of that of the oxidizer.

Further, the result of calculation, presented by lines, gave a good agreement with the actual measurement. This is taken as proving the reliability of the present computational scheme for immediate application to the cases of cross flow also.

4. The Cooling Effects

The power generation performance of MCFC was analyzed on the basis of mass balance between fuel and oxidizer and Nernst's formula, with heat transmissions taking place within the MCFC to be as discussed in the previous section. Here, the over-voltage was calculated by the effective resistance Z due to Sampath et al. (2), i.e., $Z = R_{ohm} + (\eta_{an} - \eta_{ca})/I$, where a formula due to Ogawa et al. (3), i.e., $Z = 10.44 - 0.0129 \cdot t$ (t , the tile temperature in $^{\circ}\text{C}$) was used for Z .

Calculation was conducted both for co-flow and for cross flow in terms of temperature distribution, current density distribution, and utilization rates of fuel and oxidizer, of which the case of co-flow is given in Fig. 4.

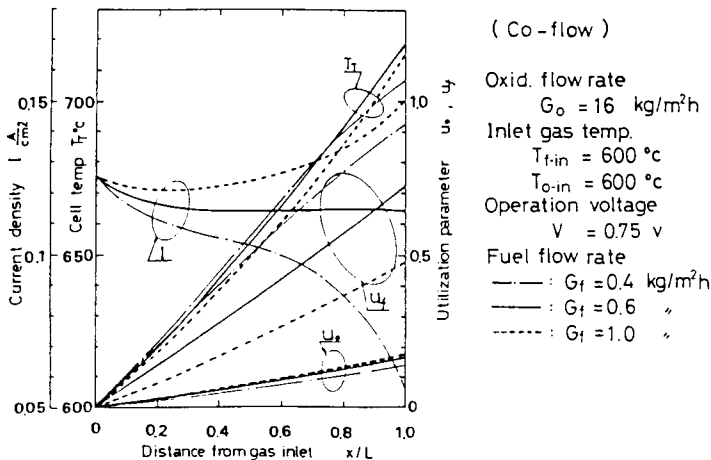


Fig. 4 Temperature Distribution, Current Distribution, and Utilization of Fuel and Oxidizer in Co-Flow

It can be shown, though not illustrated here, that cross flow will give rise to a more complicated distribution of both current and temperature, and that the maximum temperature is some 50°C higher than the case of co-flow shown in Fig. 4.

The changes in the cell temperature (maximum, mean, and minimum) and the power generation due to changes in the oxidizer flow rate is shown in Fig. 5. As the cooling performance of an MCFC should be considered better, the lower the cell maximum temperature and the more uniform the temperature distribution, the co-flow method should be the one that is to be adopted for the supply of process gas.

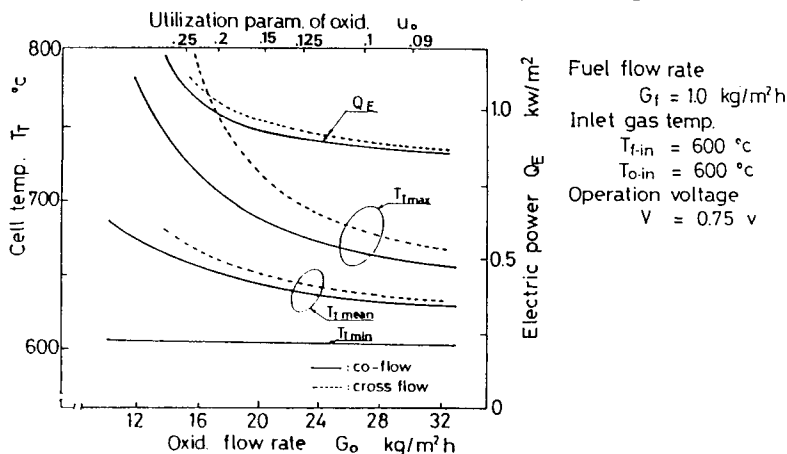


Fig. 5 Changes in Power Output due to Changes in Flow Mode and Flow Rate of Process Gas

References

- (1) T. L. Wolf and G. Wilemski, "Molten Carbonate Fuel cell Performance Model" J. Electrochem. Soc.; Electrochemical Science and Technology, Vol.130, No.1, pp.48-55, Jan. 1983.
- (2) V. Sampth et al., "A Performance and Current Distribution Model for Scaled-Up Molten Carbonate Fuel Cells" J. Electrochem. Soc., Electrochemical Science and Technology, Vol. 127, No.1, PP.79-85, Jan. 1980.
- (3) T. Ogawa et al., "Performance Model of Molter carbonate Full Cell" Denki Kagaku, Vol.53, No.8, pp.626-627, 1985.

MODELING OF ELECTROLYTE MIGRATION IN THE MOLTEN CARBONATE FUEL CELL STACK

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INTRODUCTION

Electrolyte Management in the MCFC to prevent loss of electrolyte from active cell components has been a concern. Contributing causes are:

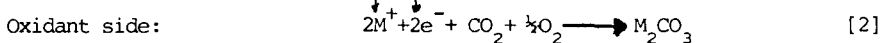
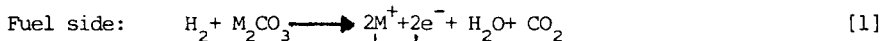
- Vapor Loss; minor and mostly in the anode exit gas as KOH vapor,
- Loss due to Corrosion Reactions; mostly Li-rich scale formation,
- Loss due to Carbonate Creepage and absorption in oxide scales,
- Electrolyte Migration losses; main concern in a stack situation.

Although as stated in a recent paper (1), it is difficult to eliminate vapor loss from gas fed molten carbonate fuel cells, corrosion and electrolyte creepage can be, and have been, substantially reduced by suitable choices of stainless steel hardware and surface coatings. The mechanisms of Electrolyte Migration are modeled in this paper to understand how best to eliminate their causes by either changing stack geometry, gasket porosity, and/or coatings to modify the electrochemical activity of the hardware surfaces.

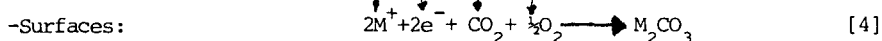
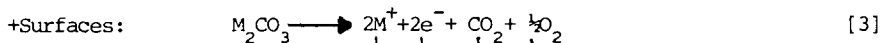
THEORETICAL BASIS

Electrolyte migration due to so-called electrochemical "pumping" of carbonate melt occurs as a result of two different carbonate electrolysis reactions, the 1/2-cell equations of which are the following:

Chemical-Potential driven Carbonate Transfer



Electric-Potential driven Carbonate Transfer



A simple 2-cell stack is illustrated in Figure 1 showing where cations and electrons are transferred from the inside to the outside of individual cells (Equations 1 and 2) and from one site on the outside of a stack to another (Equations 3 and 4). Summation of both sets of equations shows that the driving forces produce parasitic (lateral and vertical, respectively) electrolysis currents which consume electrolyte, fuel, and fuel cell generated current. Thus electrolyte migration from one location to another can be expressed in terms of short-circuit electrolysis currents.

APPROACH TO MODELING

Multistep electrolyte transfer occurs mainly on the oxidant entry and exit faces of the stack because abundant oxygen and CO_2 are available there. The sequence of transfer steps is illustrated in Figure 2, showing that a

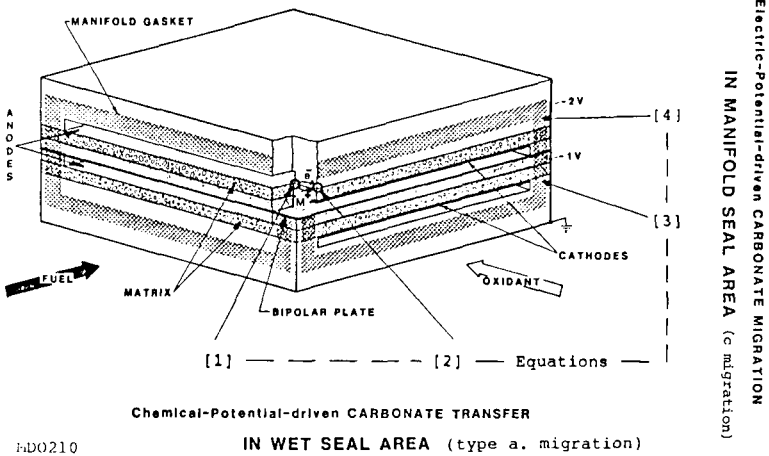
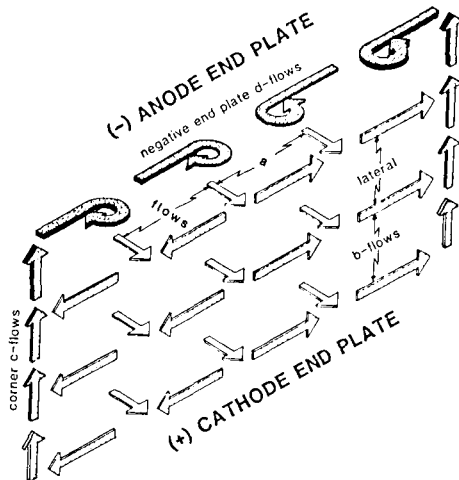


FIGURE 1. LOCATION OF CARBONATE MIGRATION AND TRANSFER IN THE MCFC STACK

continuous flow of alkali cations occurs from inside the cells to external stack surfaces (e.g. type a migration; cation flow due to reactions 1 and 2). This is followed by migration to the corners of the stack by capillary forces (i.e. type b migration) and then by decomposition/formation electrolysis to the more negative cells and end-plate of the stack (e.g. type c migration or transfer due to reactions 3 and 4). Finally the matrix of the most negative cell, by capillary pressure, will absorb much of the excess electrolyte and in that process the cell will become heavily flooded (i.e. type d migration) while the most positive cells dry out.



MT0248R

FIGURE 2. ELECTROLYTE TRANSFER SEQUENCE ON OXIDANT FACE OF MCFC STACK

STACK CONFIGURATION

To convert the conceptual model to a scheme for computational purposes, the folded-open drawing of Figure 3 was constructed. This third version of our Stack Electrolysis Model (SEM III) illustrates a corner between two faces of a cross-flow stack. This figure, in contrast to the previous sketches shows the assembly with the negative end-cell at the bottom of the stack. It should also be noted that the gasket footprints are off-set with respect to each other to minimize the dimension $W_{\text{bottom}}(-)$. These changes were suggested by preliminary work which showed that type c electrolysis can be substantially reduced by minimizing the exposed area on the outside of the most negative cells. In this connection, it is helpful when the negative end-plate is at the bottom of the stack -- where very little settling of the cells can occur in a multicell situation -- so that the above mentioned dimension cannot increase with time the way it will at the top of the stack, i.e. $W_{\text{top}}(+)$.

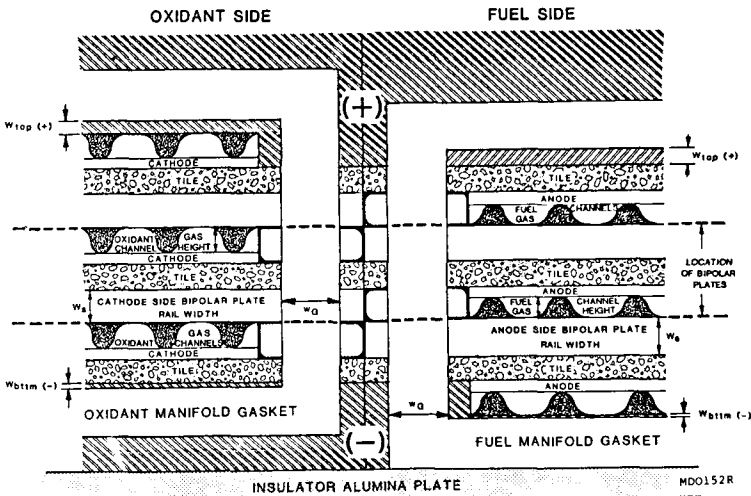


FIGURE 3. SCHEMATIC OF FOLDED-OPEN CORNER OF CROSS-FLOW, EXTERNALLY MANIFOLDED, MCFC STACK (3-CELLS)

BASIC EQUATIONS

Initial modeling focussed on estimating type c migration or vertical transfer of carbonate at the corners of the stack, assuming that all metal surfaces are always wetted with an electrolyte film estimated from 10^{-3} to 10^{-5} cm in film thickness. In an early version of our stack electrolysis model, we determined the equation below for the current density, j_G which equals the parasitic c-migration in a manifold gasket of an N-cell stack. It showed that j_G increases with N until it reaches a critical value above which it is constant and therefore independent of the number of cells in the stack:

$$j_G = \frac{NV}{2Z + Nd/\kappa_G} \quad [5]$$

where V = potential of a single cell,
Z = polarization resistance
at electrolysis boundary

d = spacing per cell
 κ_G = effective gasket
ionic conductivity

The above expression for the vertical (c flow) current density between end plates is approximate because a linear Butler-Volmer equation is assumed for the overpotential range of interest and in this simple form the equation also neglects the small current densities (estimated at a few percent) that are consumed or generated by the intervening bipolar plate strips. However, the approximations were assumed to be valid for stacks of moderate size (e.g. $N \leq 50$) whose effective ionic gasket conductivity is low enough to use up most of the driving potential (ΔV) as IR-loss thereby keeping the end plate polarizations relatively small (Z is a small fraction of the overall resistance). We have recently ascertained, however, that the linear polarization assumption used is inadequate, by calculating the mass flux of melt transported through the gasket and comparing it with the maximum possible mass flux supportable by O_2 -reduction kinetics to form CO_3^{2-} on the negative end-plate when this is a limiting current controlled process.

Accordingly, the main goal of our latest Stack Electrolysis Model (SEMIII) has been to use a non-linear B-V equation for calculating the current and hence mass flux through the gasket; solutions now have to be obtained numerically, iterating until convergence is achieved. But with this model, it is now also possible to directly include contributions of the individual bipolar plate strips and electrolyte matrices as well as to increase the number of cells in the stack without significant computational penalty.

RESULTS

In accordance with the upper bound of current transportable to the negative end-plate (i.e. limiting current density for O_2 -reduction), we have calculated by SEM III the total mass flux of M_2CO_3 in g/kh migrating via c-flow. Different values of carbonate film thickness and effective gasket conductivity were the parameters employed in the following tabulation using a standard configuration, 3-cell, cross flow stack:

Effective Gasket Conductivity, $1/\Omega\cdot\text{cm}$ \backslash Melt Film Thickness, μm	0.1	1.0	10.0
0.06	8.03	5.13	0.513
0.006	1.87	1.93	0.513
0.0006	0.29	0.31	0.291
Limiting Mass Flux (O_2 -reduction)	51.3	5.13	0.513

For the very largest gasket conductivity, we observe O_2 -kinetics limiting behavior for both 1 μm and 10 μm melt film thickness. ² For medium gasket conductivity only a 10 μm carbonate film is limiting.

REFERENCE

1. H.C. Maru et.al., "Electrolyte Management in MCFCs", Proc'ds. of Symposium on Electrochem. and Thermal Modeling of Battery, Fuel Cell and Photoenergy Systems; Electrochemical Society, Pennington, N.J. (Oct. '86).

ACKNOWLEDGEMENT

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DEVELOPMENT OF ELECTRODE AND ELECTROLYTE PLATE FOR MOLTEN CARBONATE FUEL CELL

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INTRODUCTION

Research and Development of molten carbonate fuel cell (MCFC) in Japan was started in 1981, as one themes of Moonlight project by the Agency of Industrial Science and Technology, Ministry of International Trade and Industry (MITI). This program is now being promoted by MITI and New Energy Development Organization (NEDO). Hitachi has been participated in the program from the first. Research and development of MCFC in Hitachi has recently focused on the improvement of cell component properties and cell performance and the establishment of cell stacking technologies.

COMPONENT DEVELOPMENT

CATHODE : The porous nickel oxide plate containing silver (NiO-Ag, Ag : 2~5 atom%) is used as cathode. This cathode is made by impregnation of silver nitrate solution to the sintered porous nickel plate and calcination of it in air atmosphere.

The polarization of cathode is affected by the temperature to sinter the porous nickel plate in hydrogen atmosphere.

The cell using the NiO-Ag cathode (sintering temperature : 700°C, calcination temperature : 700~850°C) shows high performance.

ANODE : The porous nickel plate containing cobalt (Ni-Co, Co : 5 atom%) is now used as anode. This anode is made by impregnation of cobaltous nitrate solution to the sintered porous nickel plate and calcination of the plate in inert gas atmosphere.

The cell using the Ni-Co anode shows high performance.

ELECTROLYTE PLATE : The characteristics of the electrolyte plate made by impregnation of molten carbonate electrolyte, $\text{Li}_2\text{CO}_3/\text{K}_2\text{CO}_3$, to lithiated alumina fiber matrix was investigated.

The matrix made of alumina fiber did not so strongly keep the electrolyte. Therefore, the composite type matrix made of the alumina fiber and lithium aluminate powder was studied. The method of making the electrolyte plate is very important

for keeping the long life of MCFC at high performance. Two kinds of method have been adopted for making the electrolyte matrix. One is the filter-accumulation method similar to a paper making method and the other is the tape casting method using a doctor blade. The pore distribution of these electrolyte matrices made by each method are shown in Figure 1.

The matrix made by the tape casting method possesses the pore of smaller diameter compared with the other matrix. The mean pore diameter of the matrix was changed into about $1.5 \times 10^{-3} \mu$ across by the improvement of the condition to make the matrix using the alumina fiber and fine lithium aluminate powder (surface area : $23 \text{ m}^2/\text{g}$).

As shown in Figure 2, the bubble pressure of the electrolyte plate was about 0.4 kg/cm^2 when the matrix was made by the tape casting method.

The gas cross-over phenomenon was prevented because the property of the electrolyte plate was improved.

The tape casting method is suitable for making the thin matrix and the mass production of it.

CELL PERFORMANCE

The labo-scale single cell (effective electrode area : 64 cm^2) was assembled with the NiO-Ag cathode, the Ni-Co anode, the electrolyte plate and a stainless steel separator. Electrolyte was put between matrices and impregnated to the pore of the matrices in the cell at the stage of heating the cell. Figure 3 shows the effect of the electrolyte added to matrices on the resistance of the electrolyte plate at 650°C . The resistance of the electrolyte plate became constant when the volume ratio of the added electrolyte to the matrix pore was over 1.1. The pore of the matrices was successfully filled with the electrolyte.

Figure 4 shows the effect of the electrolyte added to electrodes on the cell performance.

The single cells showed high performance in a wide range of the volume ratio of the added electrolyte to the electrode pore, $0.0 \sim 0.9$.

The cell voltage at 150 mA/cm^2 was $0.78\text{V} \pm 0.04\text{V}$.

ACKNOWLEDGEMENT

Most of the work described in this paper was performed under the support of the Agency of Industrial Science and Technology, Ministry of International Trade and Industry (MITI) and New Energy Development Organization (NEDO).

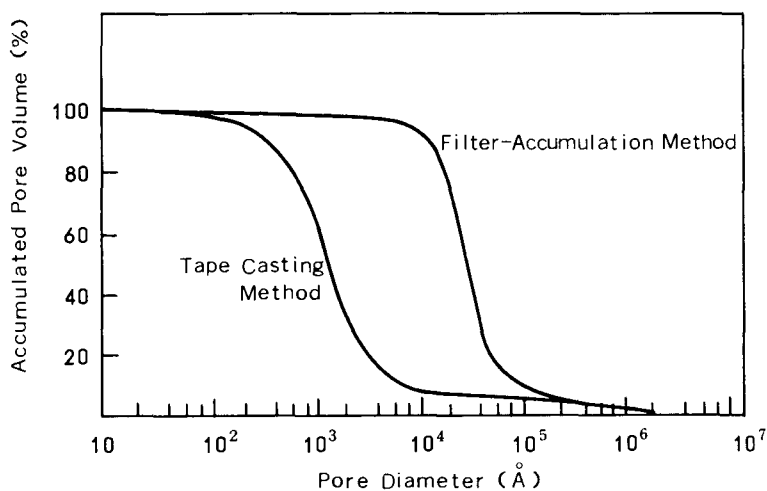


Fig.1 Pore Distribution of Electrolyte Matrices

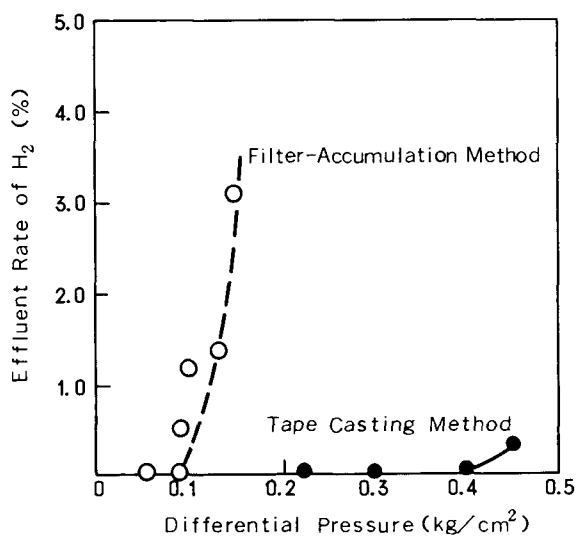


Fig.2 Strength of Electrolyte Plates

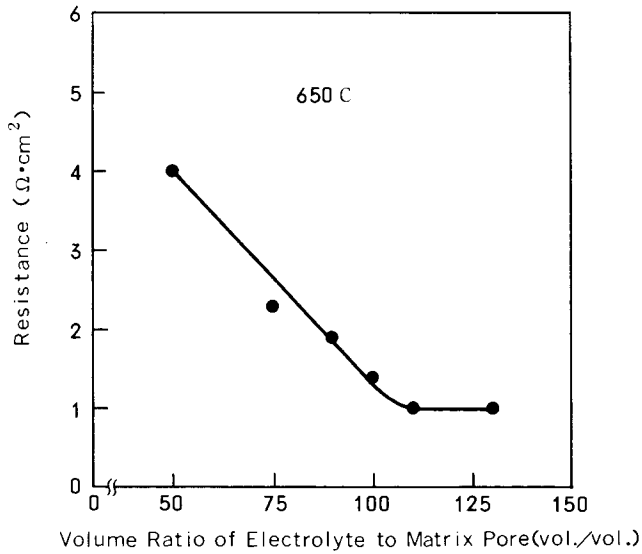


Fig.3 Effect of Electrolyte Added to Matrix on Resistance of Electrolyte Plate

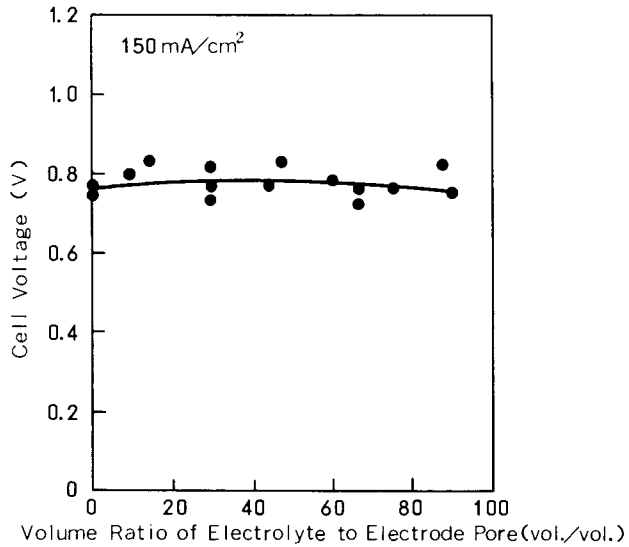


Fig.4 Effect of Electrolyte Added to Electrodes on Cell Performance

THE CONTROL OF NiO CATHODE DISSOLUTION

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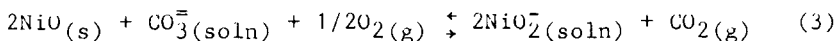
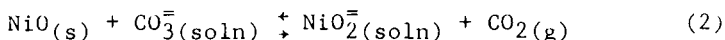
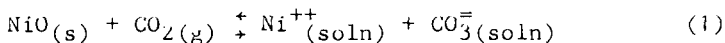
Although nickel oxide cathodes have been used in single cells for periods in excess of 40,000 hours at atmospheric pressure, cathode dissolution is believed to be a potential problem at elevated pressure operation due to increased CO_2 partial pressure of the oxidant. Cathode dissolution involves transport of the dissolved species into the electrolyte structure where they are reduced and deposited as nickel. This process leads to eventual thinning of the cathode and a possible short-circuiting of the cell by the deposited nickel. Cathode dissolution studies at IGT are being carried out in two separate but parallel programs. The EPRI-sponsored program (EPRI Contract No. RP-1085-10), involves in-cell testing of alternative cathode materials and also the implementation of measures to control the dissolution. The measures under investigation are based upon an understanding of dissolution and transport mechanisms and upon observation of the microstructural changes that take place within the cathode and the precipitation behavior of the nickel within the electrolyte structure itself. On the other hand, the objective of the program sponsored by DOE (under DOE Contract DE-AC21-85MC 22224) was to investigate the rate of dissolution and the mechanism of transport of dissolved nickel species from the cathode into the molten electrolyte.

Alternative Cathodes

A number of porous materials were tested as cathodes in 3-cm² cells. They included LaNiO_3 , Ni + 3% Ag, Ni + 10% Cr, Cu + Spinel, and Ni + 25% Co. Among them, the nickel-cobalt appears to be promising, exhibiting a nickel dissolution rate of 64% of that observed for the pure NiO cathode.

Acid/Base Chemistry

NiO may dissolve in molten carbonates in three different ways according to the reactions



each having a different p_{CO_2} (and hence acid/base) dependency. Our dissolution data from cells operated with 60% H_2 /40% CO_2 fuel and oxidants with different p_{CO_2} , presented in Figure 1, show a linear dependency on p_{CO_2} consistent with Reaction 1.

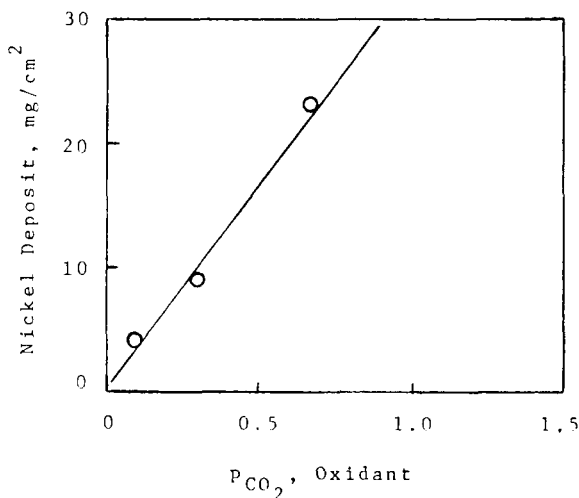


Figure 1. NICKEL DEPOSITED IN 70 MILS ELECTROLYTE STRUCTURES TESTED IN 3-CM² CELLS FOR 2000 HOURS WITH OXIDANTS OF DIFFERENT COMPOSITION (Electrolyte Molar Composition was 62 Li₂CO₃/38 K₂CO₃)

However, the acid/base chemistry can also be affected by the carbonate composition with lithium being the most basic component. Therefore, to examine the effect of electrolyte composition, three different hot-pressed electrolyte matrices containing electrolytes with lithium carbonate to potassium carbonate molar ratios of 50 Li/50 K, 62 Li/38 K, and 75 Li/25 K respectively, were tested in bench-scale (94-cm²) fuel cells. The cells were assembled with cobalt anodes to quantitatively account for the amount of dissolved cathode that was transported to the electrolyte structure and the anode. The cells were operated for 1800 hours on medium-Btu fuel and on an oxidant containing 24% CO_2 , 20% H_2O , and 56% air. Post-test analysis was performed on the electrolyte tiles and on the cobalt anodes to determine the nickel content. Table 1 lists the results.

Table 1. RESULTS FROM NICKEL TRANSPORT STUDIES

<u>Electrolyte Composition</u>	<u>Nickel Found in Tile, mg/cm²</u>	<u>Nickel Transported to anode, mg/cm²</u>
50 Li/50 K	14.9	0.6
62 Li/38 K	8.6	--
75 Li/25 K	6.9	1.0

Analysis of the cobalt anode indicated that small amounts of nickel did succeed in crossing the electrolyte tile to deposit in the anode. In the 75 Li/25 K experiment, the top layer of the cobalt anode next to the electrolyte was found to contain 2 mg/cm² nickel after 1800 hours of operation. The original cobalt anode contained only 1 mg/cm² nickel as an impurity. Therefore, approximately 1 mg/cm² of the nickel cathode transported across the electrolyte to deposit in the anode. Less nickel was transported to the anode of the cell using the 50 Li/50 K tile, the average being about 0.6 mg/cm². The conclusions drawn from this work is that the nickel cathode dissolves via both Reactions 1 and 2 and that the nickel which transported across the electrolyte to deposit in the anode was transported rapidly as negative nickelate (NiO_2^-) ions produced according to Reaction 2. The larger concentration of nickel deposited in the tile results from slow chemical diffusion of positive nickel (Ni^{++}) ions produced via Reaction 1. Higher lithium carbonate content both favors the formation of nickelate (NiO_2^-) ions and decreases the amount of nickel deposited in the tile.

Nickel Deposition Behavior

The log of the amount of Ni found₂ in hot-pressed electrolyte tiles that were operated in 94-cm² cells at 650°C and 1 atm pressure plotted as a function of log time is shown in Figure 2. These cells were operated with 75 H₂/25 CO₂ fuel at 75% utilization and 30 CO₂/70 air at 50% utilization. The linear relationship indicates that the rate of deposition decreases with time. The data further show that nickel deposition rate is independent of the tile thickness. Since both tile and cathode undergo microstructural changes simultaneously during cell operation, the observed rate of Ni deposition could be associated with changes in either component, or both. Therefore, there is much to be gained in studying the microstructural development of the cathode and the nickel deposition behavior in the electrolyte structure. Results of these studies and their implications on the control of NiO cathode dissolution will be discussed in this presentation.

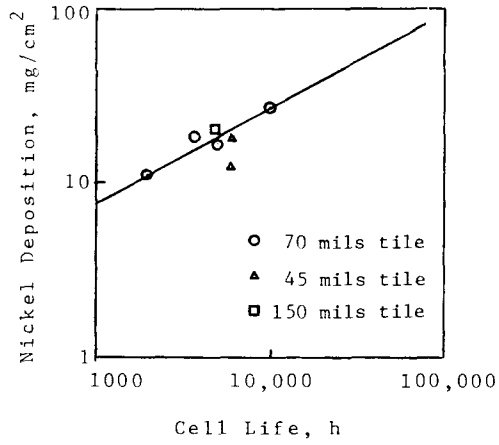


Figure 2. NICKEL DEPOSITED IN FUEL CELL
ELECTROLYTE STRUCTURES

(NFCS86-ETO/RPE)

IGT'S MCFC STACK TESTING PROGRAM

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The Institute of Gas Technology (IGT) has been involved in molten carbonate fuel cell (MCFC) stack testing for nearly 25 years. Figure 1 shows an early (1962) IGT stack operating on reformed natural gas and delivering 25 watts of dc power. The hardware used in this 1962 stack are shown to be heavy machined boilerplate in Figure 2. IGT's advanced light-weight sheet metal hardware is shown in Figure 3 and one stack design using this hardware is shown in Figure 4.

The major feature of IGT's sheet metal design is the use of a single corrugated separator plate in place of a flat separator plate with ribbed electrodes or separate current collectors. The advantages of the one-piece assembly are lower contact resistances, easier assembly, lower materials costs, and less weight. The design also presents some challenges associated with the inherent formability of the separator plate material. IGT's present design meets these challenges by providing adequate anode support and uniform flow distribution in 94-cm² cells and low pressure drop in flow simulation tests of 930 cm² hardware. However, the sheet metal is close to its formability limit, cathode strength must be improved, and manifolding presents additional challenges which can be solved by advanced techniques such as laser welding. Stack testing of the one-piece separator stack is planned for early 1987.

The latest phase of IGT's MCFC stack testing program began in late 1985 through two contracts with GDC, Inc. of Chicago.

The first GDC contract involves conceptual design and design analysis, identification and resolution of specific stack related issues such as carbonate management and dimensional stability, scale-up of components and fabrication processes including metal forming and joining, assembly and verification testing of stacks, and internal reforming.

The second GDC contract is for design, construction, and shakedown of a molten carbonate fuel cell stack testing facility for verification of designs and advanced components. The facility, now under construction and scheduled for completion early next year, has been designed to accept stacks of up to 3 kW operating at pressures up to 10 atmospheres. The facility has the flexibility required for either internal or external reforming stacks and either internal or external manifolding.

IGT's stack testing program will verify solutions to current life-limiting phenomena such as anode creep and cathode

dissolution and the other issues listed in Table 1.¹ Work to resolve these issues at the individual cell level is currently being funded by the Electric Power Research Institute (EPRI) and the U.S. Department of Energy (DOE).

Dimensional stability is one of the major challenges facing MCFC developers as R&D becomes more heavily stack-oriented. Two key aspects of component geometrical stability are being addressed at IGT: anode creep and cathode dissolution. IGT's approach to controlling anode creep is oxide dispersion strengthening (ODS) whereby a second metal is introduced into the nickel lattice and oxidized under very low oxygen partial pressures.² The effectiveness of the ODS anodes is being evaluated through out-of-cell comparisons of SOA and ODS anode sintering and creep behavior, correlation of ODS anode microstructure with creep properties, and development of cost-effective ODS anode fabrication techniques. Preliminary data indicate that ODS presents a promising approach to creep inhibition.

The cathode dissolution problem is being addressed on several fronts at IGT.³ Primary efforts are aimed at elucidation of dissolution and transport mechanisms, cathode microstructural changes, and nickel precipitation behavior in the electrolyte and at the anode. Acid/base chemistry is playing a major role in IGT's work. Sacrificial cathodes, nickel barriers, and alternative materials are being considered. The effect of electrolyte matrix thickness, electrolyte composition, and carbon dioxide partial pressure are also being evaluated.

The electrolyte support structure (LiAlO_2) long-term suitability is being improved by evaluation of particle size, shape, and uniformity.

References

1. "Molten Carbonate Fuel Cell Component Design Requirements," Petri, R. J. and Benjamin, T. G. Paper presented at the 21st Intersociety Energy Conversion Engineering Conference, San Diego, California, August 25-29, 1986.
2. "Oxide Dispersion Strengthened Anode," Erickson, D. S., Ong, E. T., and Donado, R. A. Paper presented at the Tenth National Fuel Cell Seminar, Tucson, Arizona, October 26-29, 1986.
3. "The Control of NiO Cathode Dissolution," Ong, E. T., Remick, R. J., and Donado, R. A. Paper presented at the Tenth National Fuel Cell Seminar, Tucson, Arizona, October 26-29, 1986.

Table 1. COMPONENT DEVELOPMENT REQUIREMENTS

ELECTROLYTE COMPOSITION	• Optimize Li_2CO_3 content between 62 and 75 mol%
ELECTROLYTE	• Develop continuous processing techniques
SUPPORT STRUCTURE	• Optimize particle size, shape, packing arrangements, geometry for carbonate management, cost ionic resistivity • Crack resistant matrix • Aqueous binder • Commercial LiAlO_2
ANODE	• Improve dimensional stability • Develop continuous processing techniques • Optimize as electrolyte support structure • Develop copper-based anodes
CATHODE	• Resolve dissolution • Improve crush strength • Optimize pore matching
BUBBLE BARRIER	• Standardize fabrication techniques • Optimize location between electrodes • Define materials and microstructure • Evaluate dual porosity anode
CELL HARDWARE	• One piece design • Define anode-side materials • Define cathode-side materials • Define long-term dimensional stability.

(NFCS86-TB/RPE)



Figure 1. 1962 STACK PACKAGE

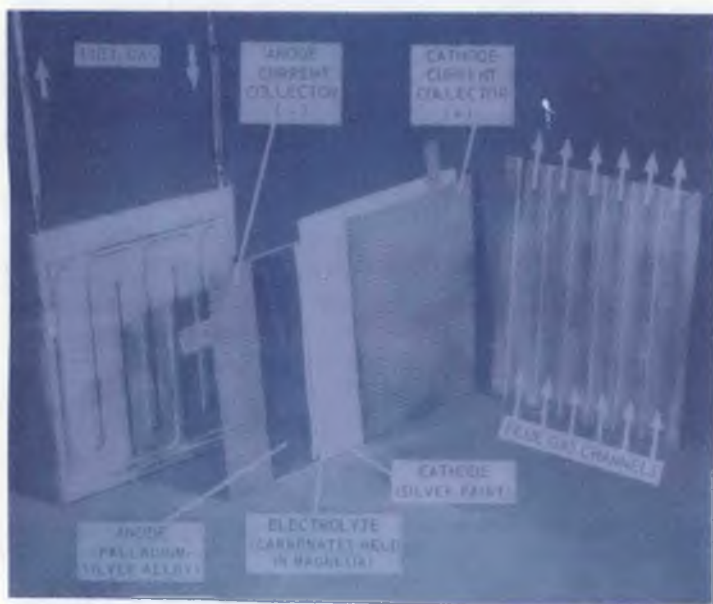


Figure 2. 1962 STACK BOILER PLATE COMPONENTS

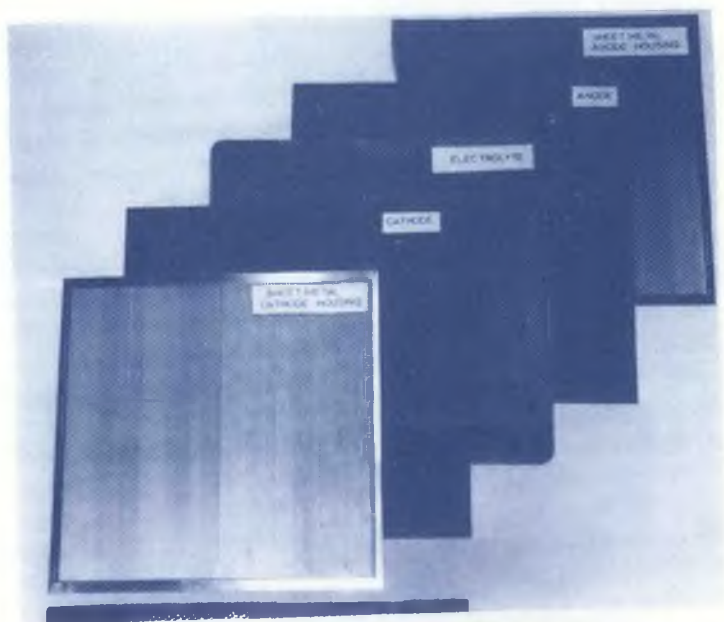


Figure 3. SHEET METAL COMPONENTS

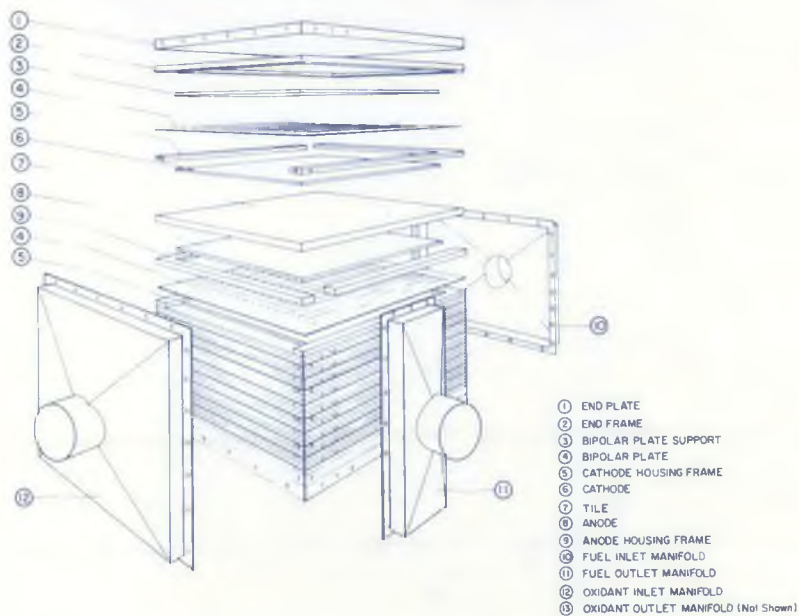


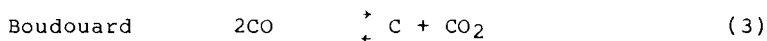
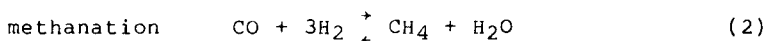
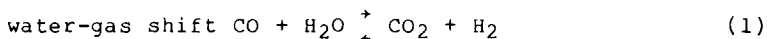
Figure 4. SHEET METAL STACK DESIGN

CARBON DEPOSITION IN MOLTEN CARBONATE FUEL CELLS

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Carbon deposits can form on molten carbonate fuel cell (MCFC) anode materials or inlet hardware from the carbon monoxide in the fuel mix. These deposits can block electrode pores, decreasing reactivity, or can completely clog the inlet and block the fuel flow. The usual approach for preventing carbon deposition is to add steam to the fuel. Steam addition requires heat to generate the high temperature steam and reduces cell operating efficiency due to fuel dilution. If we can limit steam addition to the minimum necessary to obtain compositions near the equilibrium carbon formation boundary while maintaining carbon free operation, we can attain an efficiency gain of two to three percent compared with normal operation.

We have investigated carbon deposition on various MCFC materials to obtain sufficient understanding of this process to guide the choice of conditions for efficient operation. We interpreted our experimental results by comparing them with equilibrium and partial equilibrium calculations of carbon boundaries and species concentrations. In this analysis the Gibb's phase rule specifies that three, and only three, independent reactions can be considered among the five independent components of the system, the fuel species H_2 , H_2O , CO , CO_2 and CH_4 . No detailed mechanisms are available to guide our choice of reactions, so we have chosen the three simplest, global reactions as our complete set. These reactions along with their common names are:



All three reactions are reversible, heterogeneous reactions. Rates of these reactions will depend upon the surface on which they occur. Equilibrium constants for the reactions are independent of the metal surface but depend upon the form of carbon deposited which may be determined by the metal surface.

Our experiments were performed at 925 K and at both 1 and 5 atmospheres total pressure. The materials we studied were smooth nickel and stainless steel, representative of inlet hardware, and both new and used nickel/chrome (Ni(Cr)) anode materials. We performed two types of experiments. Using simulated fuel mixes we determined whether carbon was formed for various compositions. We also performed experiments omitting components such as CH_4 , CO_2 or H_2O so that progress of reactions 1, 2 and 3 could be followed sensitively by detecting small amounts of these species formed. Details of these experiments are available in PSI report TR-398. In this abstract we will only summarize our results and conclusions.

Our measurements show that carbon deposition is determined largely by the kinetic behavior of the three reactions involved. A partial equilibrium carbon deposition boundary, neglecting reaction (2), seems to be a useful criterion for carbon fouling. This is true because on all surfaces tested we found the Boudouard reaction is faster than the water gas shift reaction which is much faster than the methanation reaction at MCFC conditions.

Carbon fouling problems are not expected on Ni(Cr) anode materials, especially after initial stages of operation, because rates for the water gas shift reaction on this material are adequate to stay close to partial equilibrium. In addition, the reaction of the fuel gas as it traverses the fuel cell electrode reduces the CO concentration, moving the gas mixture away from the carbon forming zone. Carbon fouling is most likely to occur on the smooth metallic surfaces of the inlet hardware where reaction rates for the water gas shift reaction are slow.

Carbon deposition can be suppressed by CO_2 addition rather than the usual H_2O addition even if the water gas shift reaction is slow. CO_2 can be added economically as anode gas recycle in an MCFC power plant.

Improved catalytic activity of any of the surfaces in an MCFC will reduce the possibilities for carbon fouling. Catalysts in the cell for internal reforming of methane should be especially effective because they enhance the methanation reaction so that full equilibrium carbon deposition boundaries apply as opposed to no methane, partial equilibrium boundaries. A high surface area metallic catalyst coating could be used on inlet hardware components as a solution to fouling in this likely problem region.

This work was supported by the U.S. Department of Energy through Morgantown Energy Technology Center under contract number DE-AC21-81MC16242.

MAGNESIUM OXIDE BASED INTERNAL REFORMING CATALYSTS FOR THE DIRECT MCFC

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Introduction

As direct utilization of methane in the direct molten carbonate fuel cells (DMCFC) is expected to offer higher efficiencies, ever increasing attention has been recently paid to search of catalysts (1,2) which could offer high activity together with satisfactory thermal and chemical resistance to the severe conditions of the cells. Further, as modeling of DMCFC (3) requires reliable kinetic data, the need of extensive experimentation on catalytic activity of candidate catalysts is strengthened.

In this work we report preliminary results of "out-of-the cell" experiments in the steam reforming of CH_4 . Kinetic data on some model Ni/MgO and Ni/ γ - LiAlO_2 catalysts are reported under reference conditions approaching extreme GHSV (up to 150.000 h^{-1}) and T lower than the baseline T (923°K). Emphasis is placed on a novel Ni/MgO formulation which takes advantages of unique characteristics of an "as-received" commercial MgO support (Ube # 500).

Experimental

A series of Ni/MgO (support S.A. = $35 \text{ m}^2/\text{g}$) and Ni/ γ - LiAlO_2 (support S.A. = $30 \text{ m}^2/\text{g}$) catalysts varying by the % of Ni have been prepared by the pore-filling procedure using Ni-acetylacetonate as the precursor. Unless otherwise stated (see Table 1), catalysts were activated at T (T) of 673°K (H_2 -2h) and further at 898°K (H_2 -1h). Catalytic experiments were carried out in a conventional flow micro-reactor (L = 300 mm; I.D. = 4 mm) suitable for integral and differential measurements. CH_4 , He and N_2 , regulated by a mass-flow controller, were bubbled into the water saturator, thermostatically controlled ($T = \pm 0.01^\circ\text{C}$). Catalytic activity measurements were made at atmospheric pressure and at temperature (T_R) ranging from 798° to 923°K at gaseous space velocity (GHSV) made to vary from 1,500 to $150,000 \text{ h}^{-1}$. The initial H_2/CH_4 volumetric ratio was set at 2.54.

Results and Discussion

The performance of model catalysts is compared (at the reference $T_R = 898^\circ\text{K}$) in Fig. 1 in terms of % conversion of CH_4 as function of the GHSV. The kinetic rate constants, evaluated according to a pseudo-first order kinetic model:

$$k = -\frac{1}{P_{\text{CH}_4}} \text{--- GHSV} \ln 1/(1 - \alpha)$$

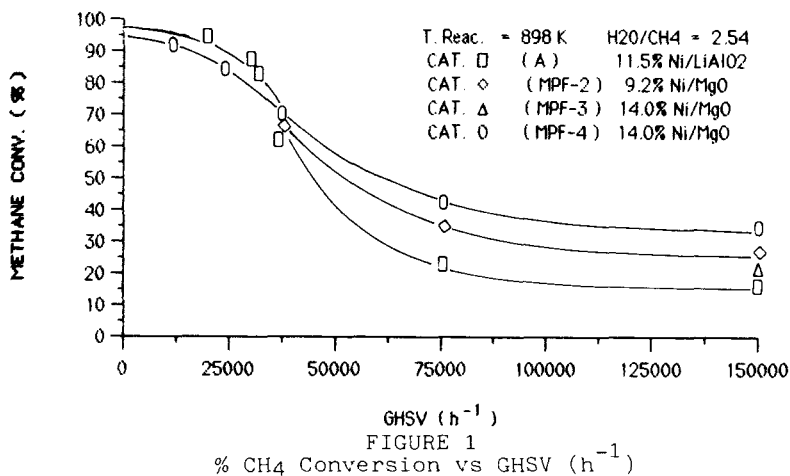
where α = conv.%, are reported in Table 1 for few exemplary specimens, under comparable conditions. As evident (Fig. 1), thermodynamic conversions are approached on both types of catalysts at any GHSV below 12.500 h^{-1} . Departure from equilibrium at any higher value proves undoubtedly that MgO-based catalysts are more active than the $\gamma\text{-LiAlO}_2$ based ones. Variations in the activation procedure (higher T_A) offer the possibility of increasing the catalytic activity of both catalysts but differences still remain in favour of MgO-based catalysts. Superior activity of MgO-based catalysts is further evident if kinetic constants are compared on the basis of the respective nickel metal surface areas (Table 1).

TABLE 1

KINETIC CONSTANTS FOR REFORMING OF CH_4 IN OUT-OF-THE
CELL CONDITIONS $T_R = 898^\circ\text{K}$, $P = 1 \text{ atm}$, $\text{H}_2\text{O}/\text{CH}_4 = 2.54$

	Catalyst	% Ni wt%	MSA m^2/gNi	Pretreat. $T_A^\circ\text{K}$	GHSV h^{-1}	Conv. %	Kinetic rate constant $\frac{\text{mole CH}_4 \text{ conv.}}{\text{g}_{\text{cat}} \cdot \text{sec atm}}$
MPF-2	Ni/MgO	9.6	87	s.p.	37.500	67.5	297
MPF-2	Ni/MgO	9.6	n.d.	$T_A = 998^\circ\text{K}$	37.500	80.0	352
MPF-2	Ni/MgO	9.6	87	s.p.	150.000	26.3	463
MPF-3	Ni/MgO	14	21.2	s.p.	150.000	17.0	300
MPF-4	Ni/MgO	14	n.d.	s.p.	150.000	33.0	585
A	Ni/ $\gamma\text{-LiAlO}_2$	11.5	46.6	s.p.	30.000	87	246
A	Ni/ $\gamma\text{-LiAlO}_2$	11.5	46.6	s.p.	150.000	12	211
A	Ni/ $\gamma\text{-LiAlO}_2$	11.5	n.d.	$T_A = 998^\circ\text{K}$	150.000	21	370

* s.p. = standard procedure.



Values of the specific kinetic constants greater than $500 \mu \text{ moles CH}_4 (\text{conv}) \text{ g}^{-1} \text{ sec}^{-1} \text{ atm}^{-1}$ are in fact obtained in case of MgO-based catalysts even at $T = 898^\circ \text{K}$; these values well fulfill the expectation of a long service in DMCF (4). It is anticipated that the superior activity of MgO-based catalysts comes as a result of a different spatial arrangement of constituents Ni active sites, as combined RXD and TPR measurements seem to indicate. With reduction of the Ni precursors (by TPR) occurring on $\gamma\text{-LiAlO}_2$ at a much faster rates and lower T than in case of MgO-based catalysts it is stressed that the crux of the problems is the nature of the metal support interactions. Better understanding of these characteristics is a prerequisite for an improvement of present formulations also in view of a screening of catalysts which saves in the time-consuming stability tests under "in-cell" conditions.

Conclusions

Catalytic activity experiments in the out-of-the cell steam reforming of CH_4 have demonstrated that, under comparable conditions, Ni-MgO-based catalysts are, in general, more effective than Ni $\gamma\text{-LiAlO}_2$ based catalysts. Comparison emphasizes differences at GHSV as high as $150,000 \text{ h}^{-1}$ and this allows determination of kinetic rate constants approaching differential conditions. Superior activity of MgO-based catalysts might be a consequence of a different

spatial arrangements of Ni in the support lattice and this adds in qualifying this class of catalysts for further experimentation.

Aknowledgment

Work performed under contract from ENEA (Italy).

References

1. B.S. Baker, S.D. Burn, C. Lee, M. Maru and P. Patel. "Internal Reforming for Natural Gas Fueled Molten Carbonate Fuel Cells". Final Report for GRI Contract, N. 5080-344-0302, Energy Research Corp. Danbury, CT, USA.
2. E.H. Camara and E.T. Ong. "Molten Carbonate Fuel Cell Component Development". Fuel Cell Seminar 1983. Orlando Florida, USA.
3. G. Wilemski, H.G. Ghezal-Ayagh, P.S. Patel, M.C. Maru "Modeling of Internal Reforming Direct Fuel Cell". Fuel Cell Seminar 1985. Tucson, Arizona, USA.
4. H.C. Maru. Quarterly Progress Report. DOE Project DEA C03-76 (ET-11304), ERC, Danbury, CT.

ELECTRONIC DEFECTS IN LiFeO_2

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LiFeO_2 is under development as an alternative cathode in molten carbonate fuel cells. It is chemically stable, has low solubility, and does not migrate under fuel cell conditions. In the doped state, LiFeO_2 has been produced with resistivities of 10 $\Omega\text{-cm}$ in realistic cathode gases; under similar conditions, undoped LiFeO_2 has a resistivity of $\sim 300 \Omega\text{-cm}$. While the doped material appears to be adequate for fuel cell use, further improvement is being pursued. A better understanding of the details of the conduction mechanisms of the material would aid in this endeavor.

It is known, from our previous studies, that the resistivity, ρ , of undoped LiFeO_2 is sensitive to reaction gas conditions (1). Therefore, it is reasonable to assume that small changes in stoichiometry have occurred. Conductivity ($1/\rho$) is then caused by electronic defects which result from equilibration with the fuel cell cathode environment. With LiFeO_2 , the problems of dealing with a ternary oxide must be considered. Smyth (2,3) and Schmalzried (4) in their discussions of the nonstoichiometry of ternary oxides, point out that in addition to temperature and oxygen partial pressures (variables relevant for binary oxide studies) another variable, such as the activity of one of the constituent binary oxides, must be specified for complete thermodynamic definition of the system. Because of the working environment of a carbonate fuel cell cathode, the lithia activity is the most reasonable additional specified variable. It is apparent that the lithia activity is a function of electrolyte melt and cover gas compositions, especially the p_{CO_2} and $p_{\text{H}_2\text{O}}$ of the cover gas. This study seeks to identify the defect structure and nonstoichiometries of undoped LiFeO_2 prepared in air and in typical cathode gas using a variety of tests including conductivity, Seebeck, and thermogravimetric measurements in controlled gas environments.

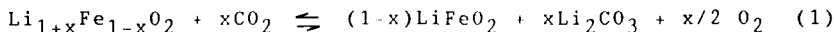
EXPERIMENTAL PROCEDURES

All samples of undoped LiFeO_2 , prepared for testing, were synthesized by a standard procedure to assure appropriate stoichiometry. Briefly, the procedure is as follows. A fine powdered Fe_2O_3 is mixed with stoichiometric Li_2CO_3 plus about 50% excess $\text{Li}_2\text{CO}_3\text{-K}_2\text{CO}_3$ eutectic. The mixture is reacted at the temperature, gas composition and pressure under study. After synthesis, the reaction products are water washed to remove excess carbonates and are air dried. X-ray diffraction analysis is performed to identify the phase(s) formed. Sintered pellets, $\sim 2.5 \text{ cm dia} \times 0.16 \text{ cm thick}$ are made for resistivity measurements by the van der Pauw technique (5) and for Seebeck coefficient measurements. Thermogravimetric measurements are made using the washed and dried reaction product held in a gold-lined Al_2O_3 cup with a Cahn microbalance.

RESULTS AND DISCUSSION

To gain insight into semiconductor type and therefore defect structure, the effect of cover gas composition on resistivity is studied. Figure 1 is a plot of the resistivity at 650°C of undoped LiFeO_2 prepared in air as a function of time and cover gas. The data show a decrease in resistivity with an increase in p_{O_2} ; this behavior is an indication of a p-type semiconductor. This suggests the presence of Fe^{4+} in the material; if conduction were due to Fe^{2+} , increases in p_{O_2} would cause an increase in resistivity. Fayard (6), in an investigation of crystalline forms of LiFeO_2 , suggested nonstoichiometric LiFeO_2 having a lithium excess ($\text{Li}/\text{Fe} > 1$). Anderson (7) further suggested a lithium substitution for iron to form the lithium excess compound and, through chemical analysis, showed Fe^{4+} was formed. As stated earlier, our studies have shown that resistivity of undoped LiFeO_2 is affected by reaction gas conditions, i.e., a one-hundred fold increase in resistivity as compared to air prepared LiFeO_2 is observed in undoped LiFeO_2 prepared in a 0.3 atm CO_2 -balance air environment. These results also suggest that in low p_{CO_2} , a lithium-rich compound is formed. At higher p_{CO_2} , the synthesis molten salts (Li_2CO_3 and Li_2CO_3 - K_2CO_3 eutectic) would equilibrate with the cover gas causing a change in the lithia activity, resulting in a less lithium-rich compound. Because of the response of the resistivity with changing p_{O_2} as well as p_{CO_2} , it appears that air-prepared undoped LiFeO_2 has both cation, Li/Fe ratio, and oxygen nonstoichiometry. However, this type of measurement cannot describe the LiFeO_2 system completely.

Seebeck measurements give direct information on semiconductor type. A positive coefficient is indicative of a p-type and a negative coefficient of an n-type. Figure 2 is a plot of Seebeck coefficient as a function of temperature and cover gas. All undoped LiFeO_2 tested exhibited a positive Seebeck coefficient at lower temperatures. This indicates p-type conduction and therefore Fe^{4+} . However, an n-type conduction is also seen in some situations. The data show that undoped LiFeO_2 , air prepared/ CO_2 measured, and CO_2 prepared/air measured both change from p- to n-type conductors. Because these transition temperatures of conduction type are low ($\sim 650^\circ\text{C}$) and nearly identical, it is likely that the change is due to a similar phenomena, i.e., Li_2O and/or O_2 loss. In air prepared/air measured LiFeO_2 no similar behavior occurs; however, the Seebeck coefficient is seen to begin decreasing at 850°C , suggesting a change in stoichiometry. The difference in Seebeck behavior between air prepared/air measured LiFeO_2 and CO_2 prepared or CO_2 measured material can be viewed as the result of



which governs the excess lithium incorporation and/or lithium excess removal. Supporting evidence for nonstoichiometry due to oxygen excess must be determined by other methods.

Thermogravimetric measurements were made in an effort to determine the number density of the defects resulting from lithium and/or oxygen nonstoichiometry in LiFeO_2 . Initial efforts were focused on ascertaining the degree of lithium excess. A series of measurements on CO_2 prepared LiFeO_2 showed only a negligible total mass change (<0.2 mg) on a sample weighing ~ 250 - 300 mg, indicating very little or no lithium excess. Figure 3 shows the total mass change of an undoped, air prepared sample of LiFeO_2 , initially weighing ~ 300 mg, measured at 650°C , first in high p_{CO_2} (~ 0.01 atm) and then in low p_{CO_2} (~ 0.0003 atm) as a function of time. The data show that a significant increase in mass occurs in high p_{CO_2} with ~ 35 h required for equilibrium. The corresponding decrease in mass in low p_{CO_2} is in good agreement with the weight gain. From these data, a value of $x \approx 0.014$ was determined for nonstoichiometric $\text{Li}_{1+x}\text{Fe}_{1-x}\text{O}_2$. The oxygen nonstoichiometry is still under study. Figure 4 is a plot of the least squares fit of total mass change of air prepared LiFeO_2 as a function of p_{O_2} for the isotherms 650 , 700 , and 750°C . The analysis of these data has not yet been completed, but it is apparent that at any given p_{O_2} an increase in mass occurs with increasing temperature, indicating an uptake of O_2 .

The studies on undoped LiFeO_2 to date have provided an understanding of the conduction mechanisms and of the effect of reaction environment on the stoichiometry of the material. The semiconductor type and its region of influence as well as the degree of cation nonstoichiometry have been assessed while that of oxygen nonstoichiometry is under way. It should be possible to obtain the defect equilibrium constants from the p_{O_2} thermogravimetric measurements and accordingly the ΔH and ΔS of the defect reaction.

ACKNOWLEDGMENT

Work supported by the U.S. Department of Energy, Morgantown Energy Technology Center, Fuel Cell Projects Section under Contract No. W-31-109-ENG-38, and performed under the direction of W. J. Huber.

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REFERENCES

1. N. Q. Minh, G. H. Kucera, and J. L. Smith, Proc. of the Fifth Int. Symp. on Molten Salts, M. L. Saboungi-Blander, et al., Eds., The Electrochemical Society, Pennington, NJ (1986) p. 597.
2. D. M. Smyth, J. Solid State Chem., 16, 73 (1976).
3. D. M. Smyth, J. Solid State Chem., 20, 359 (1977).
4. H. Schmalzried, Prog. Solid State Chem., 2, 265 (1965).
5. L. J. van der Pauw, Philips Res. Rep., 13(1), 1 (1958).
6. M. Fayard, Ann. Chim. (Paris), 6, 1279 (1961).
7. J. C. Anderson and M. Schieber, J. Phys. Chem. Solids, 25, 961 (1964).

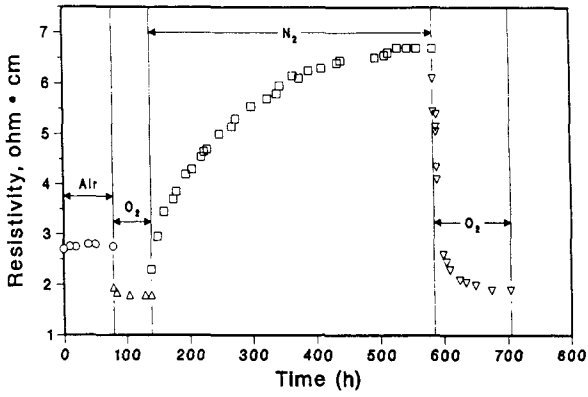


FIGURE 1

RESISTIVITY OF UNDOPED, AIR PREPARED LiFeO_2 AT 650°C .

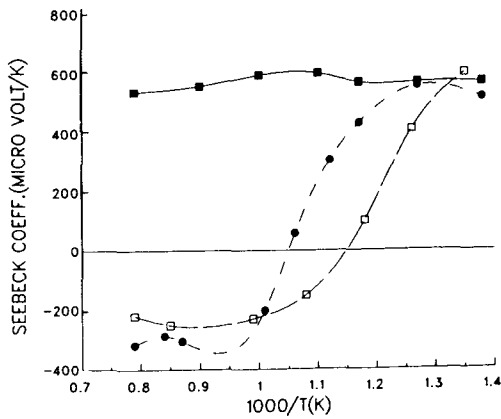


FIGURE 2

SEEBECK COEFFICIENT OF UNDOPED LiFeO_2 (■ AIR PREPARED/AIR MEASURED, □ CO_2 PREPARED/AIR MEASURED, ● CO_2 PREPARED/ CO_2 MEASURED).

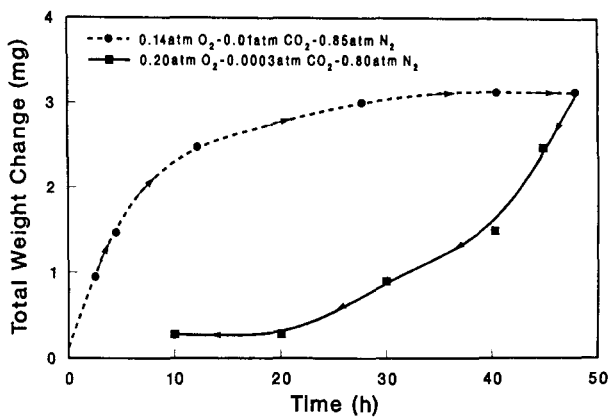


FIGURE 3

THERMOGRAVIMETRIC ANALYSIS AT 650°C OF
UNDOPED LiFeO_2 PREPARED IN AIR.

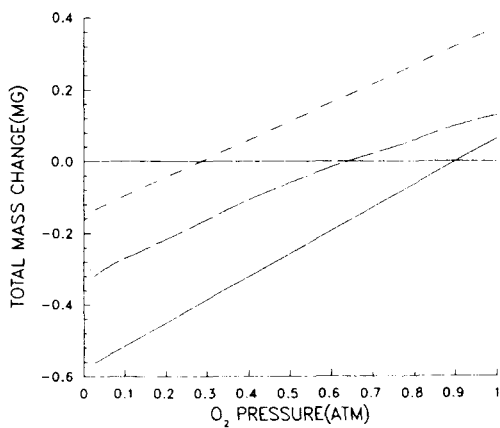


FIGURE 4

MASS CHANGE OF UNDOPED LiFeO_2 (— 650°C,
— — — 700°C, - - - 750°C).

PHYSICAL AND CHEMICAL CHARACTERIZATION
OF GAMMA-LITHIUM ALUMINATE
FOR USE IN MOLTEN CARBONATE FUEL CELLS

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INTRODUCTION

Lithium aluminate, a lithium aluminum oxide having the formula LiAlO_2 , has found application as an electrolyte support medium in molten carbonate fuel cells^{1, 2}. This compound can be prepared from the calcination of various lithium and alumina sources³⁻⁵.

Three crystal modifications of LiAlO_2 have been characterized: α , β , and γ . Both α and β - LiAlO_2 undergo an irreversible transformation to γ - LiAlO_2 in the presence of $\text{Li}_2\text{CO}_3/\text{K}_2\text{CO}_3$ (62 mol % $\text{Li}_2\text{CO}_3/38$ mol % K_2CO_3) at 650°C and 700°C, respectively⁵. The phase changes are accompanied by a change in particle morphology and a decrease in surface area. From a thermodynamics standpoint, γ - LiAlO_2 is the most desirable crystalline form for MCFC applications.

Foote Mineral Company has commercialized two γ - LiAlO_2 products for specific application in MCFC technology: a high surface area (8-12 m^2/g) and a low surface area (0.5-1.0 m^2/g) product. High-surface area γ - LiAlO_2 is used in MCFC matrices primarily for electrolyte retention. Low surface area γ - LiAlO_2 can be viewed as a larger particle size inert ceramic material to be added to the electrolyte matrix for strength and crack attenuation. Mixtures of high and low surface area γ - LiAlO_2 provide a broader range of particle sizes to allow better packing and forming characteristics.

PHYSICAL/CHEMICAL PROPERTIES

Physical and chemical properties for high and low surface area γ - LiAlO_2 are summarized in Table I. S.E.M. photographs of the high and low surface area products are shown in Figures 1 and 2, respectively. Particle size distribution curves for these products are given in Figures 3 and 4. High surface area γ - LiAlO_2 consists of smaller particles and a narrower particle size distribution when compared to low surface area γ - LiAlO_2 .

Properties of ceramic bodies made from various blends of high surface area and low surface area γ - LiAlO_2 have been determined. The results are given in Table II. Although the firing temperature used (1200°C) is well in excess of MCFC operating temperatures, the relative effect of various LiAlO_2 blends on shrinkage, strength, and porosity can be used for comparison. Ceramic bodies made from high surface area γ - LiAlO_2 exhibit the highest compressive strength, but also have the greatest shrinkage upon firing. Addition of low surface area γ - LiAlO_2 (30%) appears to decrease shrinkage while maintaining a high structural strength and porosity.

REFERENCES

1. Benjamin, T. G. and Camara, E. H., "The Fuel Cell: Key to Practically Unlimited Energy", Foote Prints, Vol. 48, No. 2, 1985.
2. Maru, H. C., Paetsch, L., and Pigeaud, A., "Review of Molten Carbonate Fuel Cell Technology", Proc. Symp. on Molten Carbonate Fuel Cell Technology, The Electrochem. Soc., Vol. 84-13, p. 20, 1984.
3. Kinoshita, K., Sim, J. W., and Ackerman, J. P., "Preparation and Characterization of Lithium Aluminate", Mater. Res. Bull., Vol. 13, p. 445, 1978.
4. Kinoshita, K., Sim, J. W. and Kucera, G. H., "Synthesis of Fine Particle Size Lithium Aluminate for Application in Molten Carbonate Fuel Cells", Mater. Res. Bul., Vol. 14, p. 1357, 1979.
5. Kinoshita, K., "Electrolyte Structures for Molten Carbonate Fuel Cells", DOE/EPRI workshop on Molten Carbonate Fuel Cells, WS-78-135, p. 4-5, 1979.

TABLE I

Physical and Chemical Properties of High and Low Surface Area -LiAlO_2

	High Surface Area LiAlO_2	Low Surface Area LiAlO_2
Typical Chemical Analysis:		
Li_2O	22.5%	22.5%
Al_2O_3	77.0%	77.0%
Typical Physical Analysis:		
Phase Composition	95% gamma 5% alpha	97% gamma 3% alpha
Surface Area (B.E.T.)	8-12 m^2/g	0.5-1.0 m^2/g
Particle Size:	97% -325 mesh	87% -325 mesh
Bulk Density:		
Free Fall	12 lbs./ft. ³	35 lbs./ft. ³
Packed	30 lbs./ft. ³	90 lbs./ft. ³

TABLE II

Properties of Various Blends
of High Surface Area (8-12 m²/g) and
Low Surface Area (0.5-1.0 m²/g) -LiAlO₂

<u>Composition</u>		<u>Densities (lbs/ft.³)</u>		<u>Percent</u>	<u>Properties of Fired</u>	
<u>% High</u>	<u>% Low</u>	<u>Green</u>	<u>Fired</u>	<u>Shrinkage</u>	<u>Compressive</u>	<u>Apparent</u>
<u>Surface</u>	<u>Surface</u>	<u>Compact</u>	<u>Compact</u>	<u>Upon</u>	<u>Strength (psi)</u>	<u>Porosity (%)</u>
<u>Area</u>	<u>Area</u>	<u>(3800 psi)</u>	<u>(1200 C)</u>	<u>Firing</u>		
100	--	62	102	15.9	9600	40.0
70	30	72	93	9.04	5600	44.4
50	50	79	96	7.88	3000	40.3
30	70	89	110	7.63	3300	30.1
--	100	103	113	3.61	4000	28.6

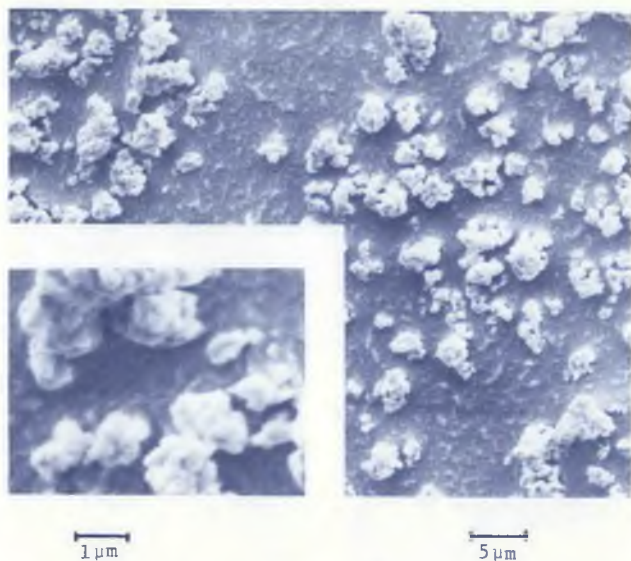


Figure 1. S.E.M. Photographs of High Surface Area γ -LiAlO₂

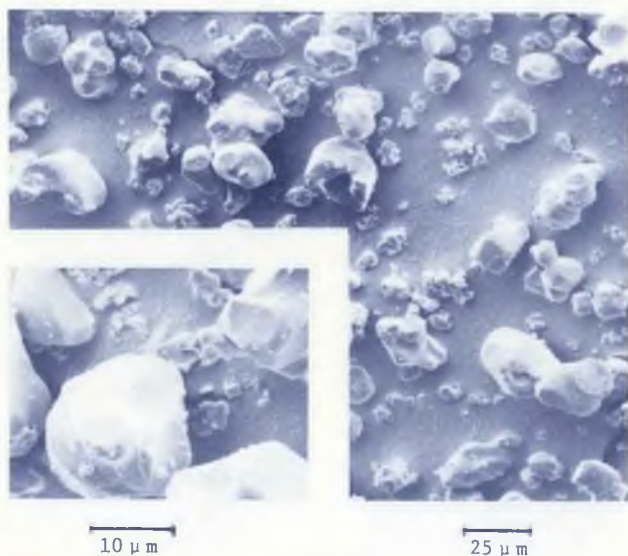


Figure 2. S.E.M. Photographs of Low Surface Area γ -LiAlO₂

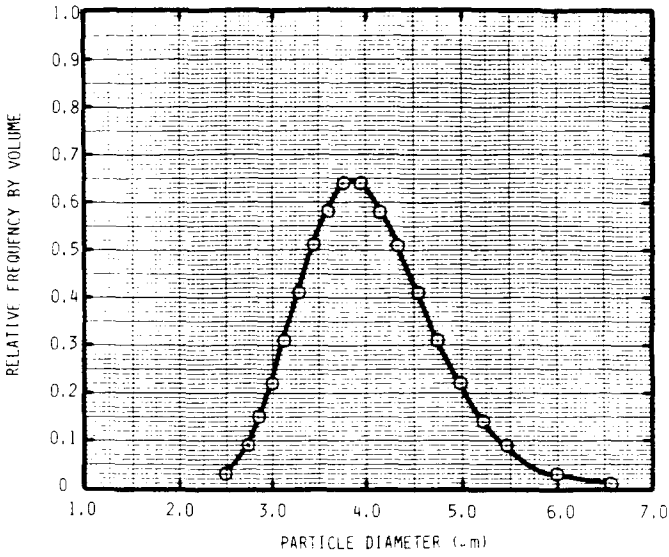


Figure 3. Particle Size Distribution for High Surface Area γ -LiAlO₂

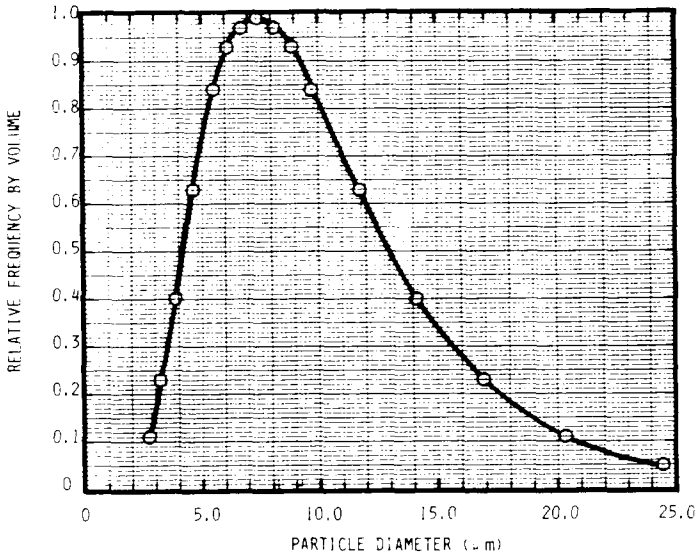


Figure 4. Particle Size Distribution for Low Surface Area γ -LiAlO₂

MATERIAL STUDIES ON MOLTEN CARBONATE FUEL CELL

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INTRODUCTION

Government Industrial Research Institute, Osaka (GIRIO) started studies on cell materials of molten carbonate fuel cell (MCFC) from 1981 in the Moonlight Project.

At present, our surveying efforts of electrode and electrolyte matrix materials are continued, and the physical properties data such as melting point, electric conductivity, vapor pressure etc. are being accumulated for binary or ternary systems of carbonate electrolytes.

Our activities mentioned above are introduced and some recent results are shown in this paper.

SURVEY CELL MATERIALS

We are surveying cell materials by means of immersion method into molten carbonate. Fe-based or Ni-based alloys and electric conductive ceramics for electrodes, and non or ionic conductive ceramics for electrolyte matrix were investigated. Over a hundred kinds of materials have been surveyed so far. In order to simplify to analyze a contribution of components in Fe-based alloys to an anti-corrosion characteristic, we fabricated some sample rods (3x4x25mm) composed of one additive such as Si, Al. or Cr as shown in TABLE I. Corrosion tests were carried out in three phases; that is, in atmosphere of $1/2 \text{ CO}_2/\text{O}_2$ (denoted by A), in molten carbonate ($\text{Li}_2\text{CO}_3/\text{K}_2\text{CO}_3$, 62/38mol%;L) and at interface between the gas and the liquid(I). The corrosion rate or penetration rate(P) was estimated from weight change following Eq.1.

$$P = X / (dxS) \quad (1)$$

where X, d and S denote weight change, density and surface area of the rod, respectively. The results are shown in FIGURE 1. It can be seen that an addition of Cr is effective clearly for anti-corrosion. Corrosion products on each specimen was investigated by SEM photograph and X-ray analysis.

PHYSICAL PROPERTIES OF ELECTROLYTE

The physical properties data of binary and ternary systems of molten carbonate were being accumulated. In order to obtain less corrosive molten carbonate, we are trying addition of alkaline earth metal carbonate such as CaCO_3 , BaCO_3 , and SrCO_3 to conventional binary system (Li_2CO_3 - K_2CO_3). The phase diagram of melting point of ternary systems, CaCO_3 - Li_2CO_3 - K_2CO_3 and BaCO_3 - Li_2CO_3 - K_2CO_3 are shown in FIGURE 2 and FIGURE 3, respectively. Conductivity measurement was also carried out for ternary system such as BaCO_3 - Li_2CO_3 - K_2CO_3 . The result is shown in FIGURE 4.

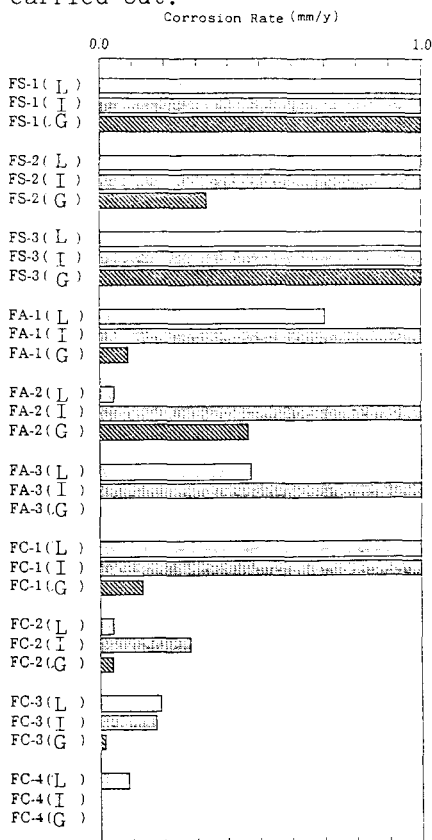
CELL TESTING

Some materials were chosen as candidate materials for cathode, especially. At present, fabrication techniques for porous electrode are being examined. And cell testing using these electrodes is also being carried out.

FIGURE 1

Results of Corrosion Tests of
Binary Fe-based Alloys.

L:Liquid Phase
I:Interface
G:Gas Phase



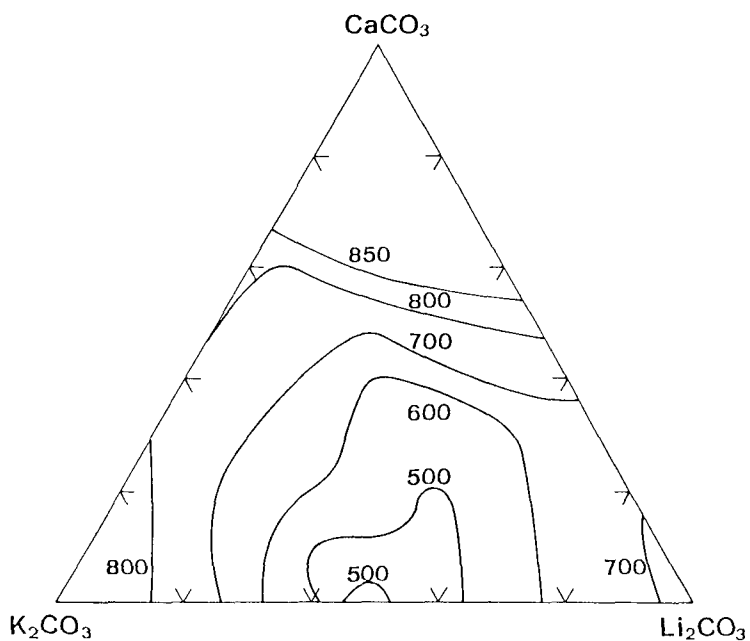


FIGURE 2 Phase Diagram of Melting Points of Ternary System, CaCO_3 - Li_2CO_3 - K_2CO_3 .

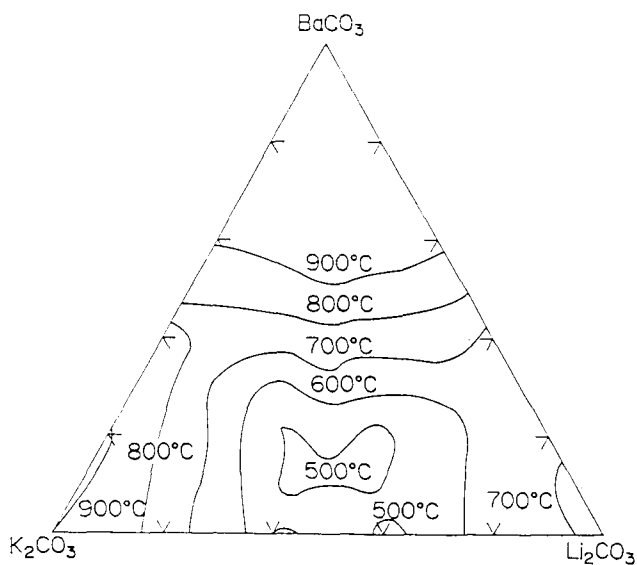


FIGURE 3 Phase Diagram of Melting Points of Ternary System, BaCO_3 - Li_2CO_3 - K_2CO_3 .

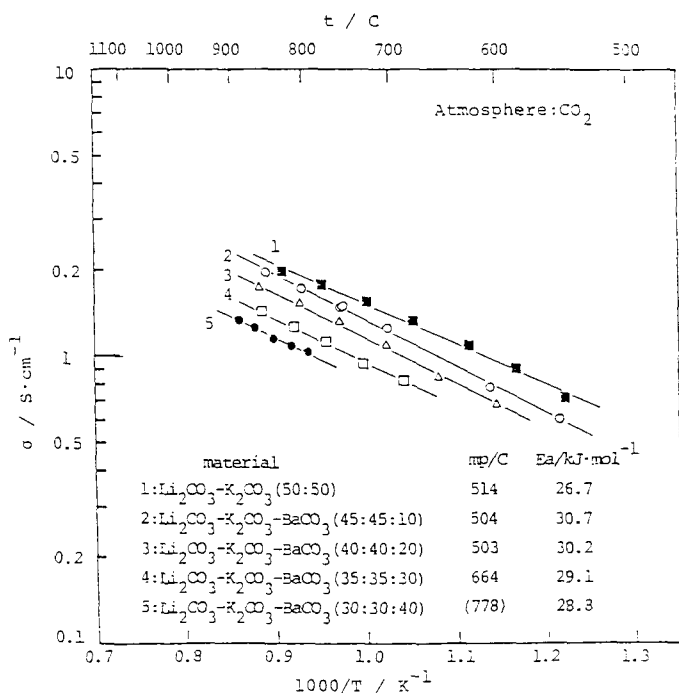


FIGURE 4 Temperature Dependence of Conductivities of Ternary System, BaCO₃-Li₂CO₃-K₂CO₃.

TABLE 1 Chemical Composition of Binary Fe-based Alloys.

記号	C	Si	Mn	S	Cu	Cr	Al	Mg	Ca	N
FS 1	0.0031	<u>5.83</u>	0.0011	0.0006	0.0014	<0.001	0.002	<0.0002	0.0002	0.0008
FS 2	0.0037	<u>13.33</u>	0.0010	0.0007	0.0011	0.001	<0.001	<0.0002	0.0004	0.0007
FS 3	0.0034	<u>22.10</u>	0.0018	0.0003	0.0010	<0.001	0.002	<0.0002	<0.0002	0.0003
FA 1	0.0016	<0.005	0.0070	0.0013	0.0016	<0.001	<u>1.58</u>	<0.0002	0.0002	0.0026
FA 2	0.0016	0.006	0.0028	0.0012	0.0018	0.001	<u>3.37</u>	<0.0002	<0.0002	0.0017
FA 3	0.0028	0.010	0.0014	0.0010	0.0021	0.001	<u>13.31</u>	0.0003	<0.0002	0.0021
FA 4	0.0036	0.022	0.0021	0.0008	0.0029	<0.001	<u>22.58</u>	0.0045	<0.0002	0.0023
FC 1	0.0019	0.007	0.0005	0.0016	0.0014	<u>1.32</u>	0.001	<0.0002	0.0004	0.0088
FC 2	0.0046	0.006	0.0008	0.0016	0.0015	<u>12.32</u>	0.002	<0.0002	0.0004	0.0052
FC 3	0.0027	0.021	0.0008	0.0016	0.0014	<u>24.51</u>	0.004	<0.0002	0.0006	0.0121
FC 4	0.0063	0.014	0.0010	0.0016	0.0014	<u>44.32</u>	0.002	<0.0002	0.0028	0.0168

DEVELOPMENT OF PHOSPHORIC ACID FUEL CELL TECHNOLOGY

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INTRODUCTION

Phosphoric acid tends to be driven out of the due positions and to lose the desirable distribution form among the cell constituents during the cell operation. Although all the driving forces of the phosphoric acid to move are not clearly known, the routes are known with their weights of importance. Some routes are via electrode backing substrates. Phosphoric acid, in the form of microstream, flows from the catalyst layers to the separator through the backings. In order to prevent the phosphoric acid stream from occurring, wetproofing treatment of the backing substrate is carried out.

In the wet process of manufacturing electrodes, backing substrate is coated with catalyst pastes. Wetproofing of the substrates influences the surface roughness of the catalyst layer in the substrate side and the gas diffusion, and the counter diffusion of water vapour also, with the formation of phosphoric acid film near the electrode surface in the substrate.

The authors intend to make clear in this paper, the effects of wetproofing on cell performance.

Wetproofing Procedure

Substrate, consisting of carbon fibres and binder, was coated with diverse fluoropolymers and baked at diverse temperatures. The carbon fibre is of petroleum pitch origin, about $14\mu\text{m}$ in diameter, interplanar spacings of C(002) being 0.3490nm . Total pore volume of the untreated substrate is 76% of apparent bulk volume and median pore diameter is $64\mu\text{m}$. Aqueous dispersions of fluoropolymers, containing surface active agent, are diluted and sprayed or otherwise are conditioned with some viscosity increasing agents followed by reverse roll coating.

Effects of wetproofing on phosphoric acid transfer

Fig.1 shows phosphoric acid absorption of separator through wetproofed substrate at 200°C . 300mg PTFE is sprayed on each cm^2 of the substrate followed by baking at 375°C . Amount of absorbed phosphoric acid is estimated by weighing each component. In earlier period of time, the weight of the substrate increases, while no weight gain of the separator is observed. After some period of time, weight gain of the separator starts, which corresponds to the time the front of phosphoric acid passes the interface

of these separator and the substrate. Essentially similar shapes of curves were obtained in the cases of FEP (poly tetrafluoroethylene hexafluoropropylene) and PTFE, of spraying and reverse roll coating, of diverse coating amounts of fluoropolymers, of diverse baking temperatures, especially of uncoated substrate. However, the

weight gain of

less wetproofed substrate is larger, accordingly induction period of weight gain of the separator shorter. It implies

that it is very difficult to cut perfectly the stream of phosphoric acid in the substrate by wetproof treatment alone. It is well known that the cross section of carbon fibre shows the radial or the onion structure, the former predominant.

Interlamellar spacings grow in the calcination process of substrate manufacturing.

The structure appears at a low calcination temperature below 1000°C. Particle size of fluorocarbon polymers in the dispersion is too large to enter the

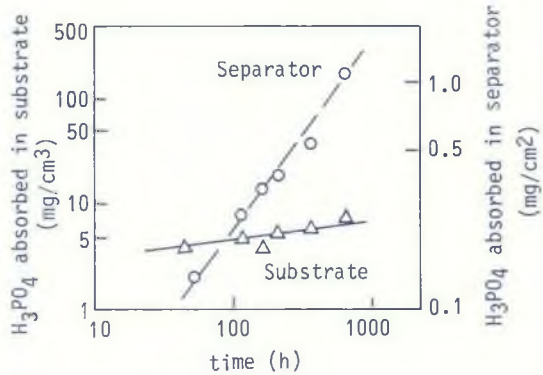


Fig.1 H_3PO_4 transfer to separator through substrate

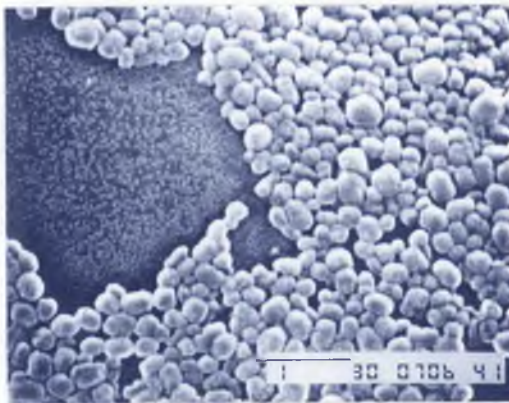


Fig.2 Secondary electron image of carbon fibre surface treated with PTFE dispersion, still unbaked

1μm

interlamellar spacings and the inner surface of carbon fibres remains hydrophillic. As is shown in Fig.2, fluorocarbon polymer particles form a monolayer on the outer surface of carbon fibre. Similar phenomenon is often noticed under an optical microscope when dispersing liquid added to de-agglomerate secondary particles is drying. Element particles flow to drying site and there form a mosaic monolayer. The monolayer has inevitably a vacancy at the final drying area, which is shown in Fig.2. Even after baking, the vacancy is left hydrophillic owing to the poor throwing power of the fluoropolymers. It is also difficult to cover with the polymer the ends of carbon fibres. The residual amount of phosphoric acid transfer is probably due to the uncovered surface region of the carbon fibres. We can only make small the stream of phosphoric acid by wetproofing of the substrate. For example, carbon paper substrate, 0.4mm thick, of anatomized cell after a long period of operation contains about 0.5 to 1.0 mg/cm² of phosphoric acid. This amount of phosphoric acid is thought to correspond mainly to that trapped in internal vacancy in carbon fibres.

Effect on electrical contact resistance

Contact resistance between separator and substrate increases at any rate through the formation of wetproofing

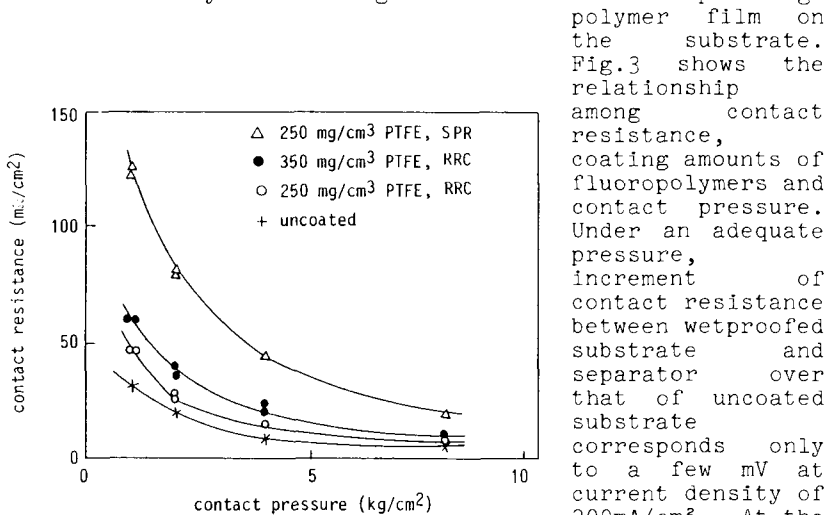


Fig.3 Electrical contact resistance between separator and substrate

carbon fibres. Difference between spraying and reverse roll coating is based on the depth profile of distribution of PTFE in the substrate.

Effect on gas permeability

Fluoropolymer has its own volume. For example, 10mg PTFE per cm^2 of substrate corresponds to about 4.6 μl loss of pore volume per cm^2 . In addition it makes sometimes films and blocks among carbon fibres depending on wet proof treatment procedures. Distribution and film thickness of phosphoric acid in the electrodes depends also on wetproofing of the substrates. Roughness of the surface of catalyst layer on the substrate side depends on the hydrophobicity of the substrate.

Gas permeability can directly be determined. On the other hand, H_2 and O_2 gains are measures of it. Fig.4 shows gas permeability directly measured in the dry versus hydrophobicity. Gas permeability decreases with amount of fluoropolymers. The differences of the effects on the basis of kinds of fluoropolymer and coating process can easily be accounted for from the view point of throwing power. When the substrate is wetted with phosphoric acid, additional decrease of gas permeability would take place. Fig.5 shows that the effect of phosphoric acid is negligibly small in normal conditions of cell operation.

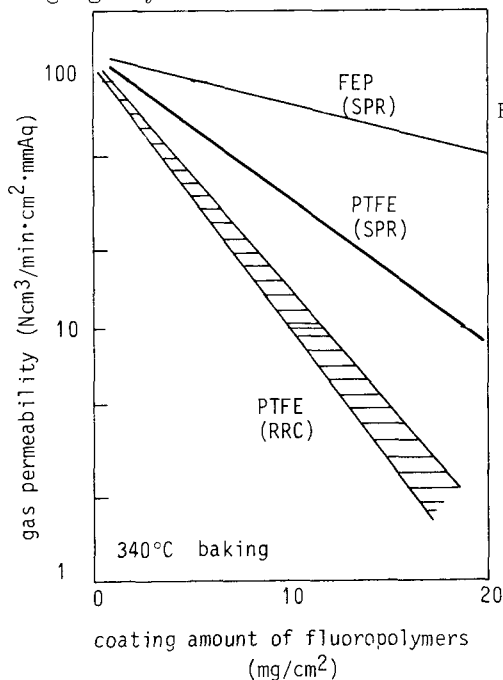


Fig.4 Effect of hydrophobicity on gas permeability of substrate

SPR : spray
RRC : reverse roll coating

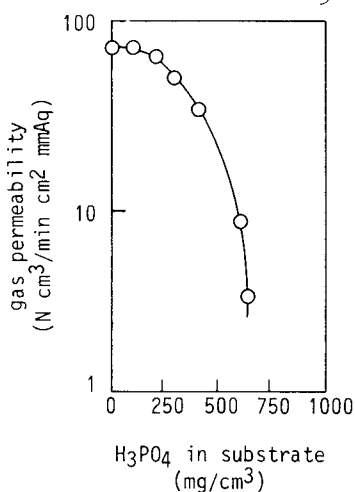


Fig.5 Effect of phosphoric acid in uncoated substrate on gas permeability

The effect of wetproofing of substrate on efficiency of the electrode depends on gas permeability of the electrode in the working state with complicated factors in it.

In Fig.6 is shown the relationship between limiting current of cathode half cells and the gas permeability.

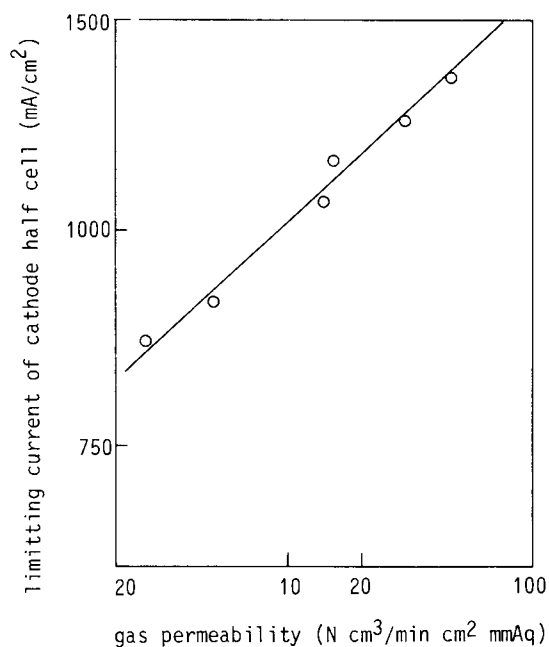


Fig.6 Relationship between limiting current and gas permeability of cathode

According to theoretical calculations, diffusion polarization is comparable to the others and is dependent mainly on the tortosity of gas passage to the phosphoric acid film covering the reaction sites. In Fig.7 are plotted O_2 gains of single cells with cathodes using substrates of diverse coating amounts of PTFE.

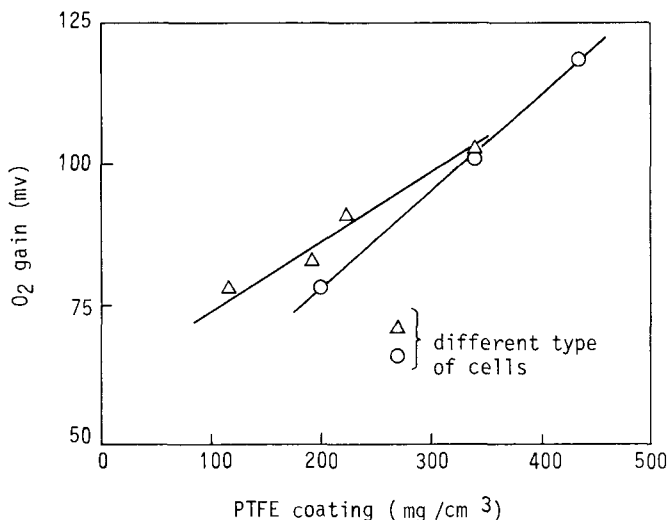
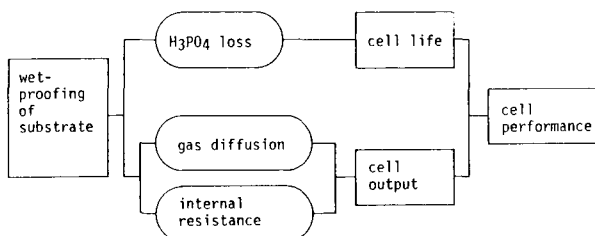


Fig.7 O_2 gains versus hydrophobicity of cathodes

O_2 gain is sum of the effect on gas permeability of the substrate and of that of the catalyst layer formed on the substrate.

Summary

Wetproofing of substrate affects cell performance, as is shown in the diagram below. It acts on cell life and output inversely, each effect innegligibly large. The authors made clear the details of the effects through physical properties of cell components.



HYDROGEN STORAGE OPTIONS FOR FUEL CELLS

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Hydrogen/oxygen fuel cells can be used in a variety of commercial, military, and aerospace applications where the hydrogen must be stored. Applications include:

- o Terrestrial vehicles
- o Underwater vehicles
- o Military installations
- o Standby or emergency installations
- o Spacecraft

For some of these applications, it is preferable to store hydrogen in a form that is more easily accessible than as a cryogenic liquid, a pressurized gas, or to reform a hydrocarbon. Chemical storage and storage as hydrides become very attractive for some of these applications. The storage method selected for any specific application will depend on the relative importance of such factors as system weight, system volume, cost, rechargeability, and thermal considerations.

Hydrides are an attractive method for storing hydrogen. It is possible with hydrides to store hydrogen in a smaller volume than for liquid hydrogen. This process results in the generation of heat as the hydride is formed, so heat must be supplied to remove the hydrogen. Pressure is also an important factor in this process. Early efforts to develop hydrides for secondary batteries resulted in a gradual physical deterioration of the hydride material due to volume changes. Modification has been made to the composition of the materials to correct that deficiency. There are four major crystalline compound types:

<u>Compound Type</u>	<u>Examples</u>
A ₂ B	Mg ₂ Ni; Mg ₂ Cu
AB	TiFe; TiFe _{0.9} Mn _{0.1} ; TiFe _{0.8} Ni _{0.2}
AB ₂	ZrFe ₂ ; TiCr ₂ ; TiV _{0.6} Fe _{0.15} Mn _{1.25}
AB ₅	LaNi ₅ ; Mischmetal-Ni ₅ ; Mischmetal-Ni _{4.15} Fe _{0.85}

The greatest amount of hydrogen stored in hydrides appears to be with the use of amorphous materials, as opposed to the more common crystalline materials. Up to three weight percent of hydrogen can be stored for operation at room temperature, and even greater amounts are obtainable using high temperature extraction.

Chemical storage of hydrogen also has good promise for some applications. Candidate chemicals include VH₂, ZrH₂, ZrNiH, NH₃, NaBH₄, and Fe + HCl. Crystalline aluminosilicates, referred to as zeolites, can also store hydrogen by insertion into molecular-scale channels and cavities. Another approach is storage of hydrogen in glass microspheres, typically 5 to 200 microns in diameter with wall thicknesses in the range of 0.25 to 5.0 microns. Hydrogen can be stored at very high pressure, on the order of 800 atmospheres, with a theoretical capacity of 11% by weight. The hydrogen is recovered by heating the spheres to about 225°C, whereupon the hydrogen diffuses out through the walls of the spheres. Still another method is absorption on high surface area activated carbons, typically at liquid nitrogen temperature. Up to 7 wt. % of hydrogen can be stored at 600 psig.

DESIGN AND ECONOMICS OF LARGE FUEL CELL POWER PLANTS

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INTRODUCTION

Fuel cells, in general, can provide a number of benefits relative to state-of-the-art energy conversion technologies. Among these are (1) modularity (which provides the opportunity to minimize risks associated with capacity expansion planning without losing the benefits of scale economies), and (2) excellent part-load performance. In addition, fuel cells are environmentally benign. However, unless fuel cell systems are competitive with alternative technologies net of these benefits, the market potential for fuel cells will be limited to some unique applications.

At Argonne National Laboratory we recently assessed the economics of fuel cell power plants for 575 MW utility central stations. The results are discussed by M. Krumpelt elsewhere in this volume. Initially we based our assessment on fuel cell systems taken from the literature. It became apparent that the cost of the initial set of fuel cells plus the replacements represented a large share of the system cost, and in fact made the fuel cell systems more costly than the competing technology. We suspected that the systems had been designed assuming high efficiencies were synonymous with good economics, but no attempts had been made to determine the most economical combination of fuel cells, combustion turbines, and steam turbines.

In this extended abstract, we discuss two new system designs for phosphoric acid and molten carbonate fuel cells. Both designs were developed cascading the flow of energy through the fuel cells, combustion turbine and steam turbine. By varying the utilization of fuel in the fuel cells and the current density, the distribution of power among the prime movers is being changed, and effects of those changes analyzed.

A decrease in fuel utilization improves the fuel cell performance because the average hydrogen and oxygen concentration in the fuel cells will be higher. An increase in current density has two effects. First, the specific cost of the fuel cell decreases because power output increases for a given cell area. Second, additional thermal energy is released in the cells which can then be recovered resulting in a larger capacity bottoming section.

The general approach for evaluating and developing cost-effective fuel-cell systems is to optimize them for minimum cost of electricity (COE) through integrated thermodynamic simulation and cost analysis using our SALT code¹. The essence of the analyses is to determine the most cost effective configurations and flow of energy within power systems that are represented schematically in Fig. 1. As shown, any change in the energy flows within the system can affect the net energy output which can range from about 40 to 55% of the energy input. Further, because specific costs of each component are different, the specification of the energy flows will affect total system capital cost and COE. During the optimization, the energy flows were redistributed in such a way to provide the minimal COE.

PAFC DESIGN

The starting point for the PAFC reference design was the recent study by Kinetic Technology International (KTI)⁴. However, after a brief evaluation of alternative gasification technologies, we chose to use an oxygen-blown Texaco gasifier rather than either the Wellman-Galusha or Kohlegas Nordheim (KGN) gasification technology used in the KTI study.

The process flow diagram for the PAFC design is presented in Fig. 2. As shown, the coal slurry is converted to a hydrogen-rich synthesis gas in an oxygen-blown Texaco gasifier. The hot raw synthesis gas is cooled through a series of boilers and heat exchangers to the inlet temperature required for the Selexol acid gas removal (AGR) unit. The high temperature shift conversion which employs a conventional low temperature shift sulfur tolerant catalyst is upstream of the Selexol unit. Also, the high-temperature shift (the first of three stages of shift to reduce CO concentration to less than 1 mol% required by the PAFC) is accomplished without steam injection as there is sufficient steam in the synthesis gas from a Texaco gasifier to shift about one-third of the CO to CO₂.

In the AGR unit, sulfur and ammonia are removed to ppm levels as also required by the PAFC. Elemental sulfur is recovered in the CLAUS unit followed by combustion of the tail-gas in the SCOT unit. Typically, an oxide guard bed will be employed between the AGR and PAFC anode inlet to protect the PAFC in the event of high sulfur carryover. The clean gas is then reheated prior to expansion. Shifting of the CO down to less than 1 mol% is accomplished by the intermediate and low-temperature shift converters. The depleted fuel leaving the fuel cell is combusted in the cathode exhaust stream, then the combined flow is expanded in the gas turbine which drives the compressors for the PAFC oxidant requirements prior to exiting the plant stack.

The fuel cell stacks are water-cooled and heat is recovered to produce medium-pressure steam for the integrated steam cycle.

This flowsheet is essentially an ANL design with many design features taken from various literature sources. However, we have departed from the traditional practice in two areas: shifting and fuel utilization.

Shifting of CO requires a considerable amount of H₂O. The H₂O is conventionally supplied in the form of steam, which could otherwise have been used to drive the steam turbine. In our design, no steam is diverted from the turbine at all.

The shift reactors are located at points where other H₂O is already present in sufficient quantity (high temperature shift) or where hot water rather than steam may be injected. To preheat the water, very low quality heat is used which would otherwise not be recovered.

In addition to the new "shifting" approach and reduced fuel-cell fuel utilization, as we discussed before, we improved the performance of PAFC power plant design by superheating steam from the cooling system prior to entering the steam turbine and by increasing the inlet temperature before the gas turbine.

MCFC DESIGN

A common design feature in all the literature designs for MCFCs is a direct transfer of the depleted fuel from the anode exit to the cathode inlet (as in the GE design, for instance)³. The reason, no doubt, is to supply the cathode with carbon dioxide which is needed in the cell reaction. In addition, the increased flow rate through the cathode is needed for the purpose of fuel cell cooling.

From a system's standpoint, such direct coupling of the anode and cathode streams is far from optimal, because the heat from combusting the residual fuel could be used more efficiently in a gas turbine. Furthermore, the heat generated in the fuel cell should be cascaded first through a gas turbine followed by steam generation.

The advanced MCFC design is shown in Fig. 3. The gasification and clean-up section up to the point of entering the fuel cell anode side remains unchanged from the design described by GE.³ Leaving the anode, the depleted fuel passes through a heat exchanger which is needed to bring the fresh fuel to the required inlet temperature of the fuel cell, and is then oxidized by the cathode exit gas. The resultant combustion gas is directed immediately to the gas turbine, which rotates an electric generator and the air compressors.

After passing the gas turbine, the now decompressed but still fairly hot gas is used to preheat air, and then to generate steam in a series of superheaters, boilers, and economizers. At this point, the stream is split. One part exits the system through the stack. The other part, after additional cooling, is recirculated to supply carbon dioxide to the air stream and to increase the cathode flow rate. Thus, the combustion gas with CO_2 is returned to the cathode, but without sacrificing the efficiency of the gas turbine, and without having to cool the fuel cell by recirculating cathode gas through steam generators.

The three section steam turbine consists of high-, intermediate- and low-pressure turbines. The high-pressure steam turbine provides a needed amount of steam to be mixed with the clean fuel gas in order to prevent carbon deposition. After the high-pressure turbine, steam flows through the intermediate- and low-pressure turbines. If necessary, a certain amount of water in the steam can be removed between these two turbines to ensure an acceptable steam quality at the end of turbine expansion process.

After a steam condenser, the condensate flow merges with make-up water and passes through the economizer. Then, the feed water merges with water coming down from the steam separator (drum) and splits into two parts. One part boils in the boiler of the gasification system, the other part in the boiler of the bottoming section. Both steam flows merge again in the separator (drum) from where the saturated steam is directed to the superheater and then to the steam turbines.

So far, we have not mentioned one new component required in the design. It is the heat exchanger in the CO_2 return loop. Before mixing with air and recompression, the gas needs to be cooled. Because it is a gas-to-gas heat exchanger, it will be fairly large. We estimated that its cost accounts for about 0.7% of system COE.

PARAMETRIC ANALYSIS AND OPTIMIZATION

As mentioned, two major parameters were analyzed and optimized for PAFC and MCFC systems: fuel cell fuel utilization, and current density. For brevity the results of the analysis will be discussed for the MCFC system only. In order to determine the efficiency and COE of the new design for different fuel utilizations and current densities it is necessary to define the performance of the fuel cell under those conditions. Molten carbonate fuel cells have been modeled by Wilemski⁴. His code computes polarization curves for a variety of flow conditions, such as cross-, counter-, and co-flow, and for either constant flows or constant utilizations. Predicted cell potentials are given in Fig. 4.

Using the data from Fig. 4, we optimized the system and found the values of fuel-cell fuel utilization and current density at which COE is minimized. Figure 5 shows a plot of the COE versus fuel utilization in the fuel cell. The plot shows a dramatic decrease of the COE as the fuel utilization (FU) decreases. At a current density of 1800 A/m², which is typical for MCFC systems in the literature, the COE is still not at a minimum at our lowest FU of 45%, but is several mill/kWh below the COE of the literature system. Very clearly, a fuel utilization of 85% as commonly proposed for central station power plants is not cost effective.

Figure 6 shows the COE versus current density for five different fuel utilizations. The optimum current density is about 4000 A/m² in the ANL design.

Figure 7 shows contributions to the total system output from the fuel cells and bottoming sections. As expected, the contribution of the fuel cell to the total power output declines with lower FU, while the gas and steam turbine outputs increase. For the low FU conditions that are favored economically, the gas turbine capacity exceeds that of the fuel cells in all cases.

The optimum fuel utilization will vary with fuel cell stack cost.² All the above data were obtained for our "reference" assumption of \$22/ft² plus contingencies, which corresponds to \$300/m². Lower stack costs shift the minimum to higher fuel utilizations.

CONCLUSIONS

To put the results of the optimized fuel cell systems in perspective, we list the main characteristics in Table 1 together with numbers representing the conventional designs. The latter were obtained by simulating the PAFC₂ and MCFC flowsheet in Figs. 2 and 3 for 85% fuel utilization and 2000 A/m² current density.

The COE data for the "conventional" designs indicate that the two fuel cell systems would be contenders for future base-load utility applications, but only if a utility attaches additional value to the so-called intangibles such as environmental acceptability, modularity, etc.

However, for the advanced designs the COE of the MCFC system is lower than that of the Combined-Cycle by 3 mills/kWh. The PAFC system almost breaks even with the combined cycle and will have an economic advantage at locations where intangibles impact the economics.

Perhaps the single most important conclusion to be drawn from our study is that fuel cells are most competitive in central station applications when

operated at low fuel utilization and providing a smaller percentage of the total electrical capacity of the plant.

Table 1. Technical and Economic Summary of Fuel-Cell and Combine-Cycle Central Station Power Plants (575 MW(e), 1984 dollars)

	PAFC	MCFC	Combined-Cycle Power Plant
Cost of Electricity, mills/kwh			
• "Conventional" Designs	61.7	55.4	48.9
• Advanced Designs	55.6	48.7	50.9*)
Specific costs, \$/kW**)			
• "Conventional" Designs	2890/2260	2440/1980	1620
• Advanced Designs	2110/1920	2260/2100	—
Efficiency, %			
• "Conventional" Designs	42.2	47.7	37.2
• Advanced Designs	37.9	44.1	—
Current Density, A/m ²			
• "Conventional" Designs	2000	2000	—
• Advanced Designs	4800	4000	—
Fuel Utilization, %			
• "Conventional" Designs	85	85	—
• Advanced Designs	45	55	—

*) With reduced SO₂ and NO_x emission equal to that of PAFC and MCFC.

**) Total cost/cost without fuel-cell replacement component.

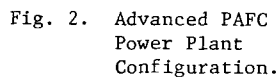
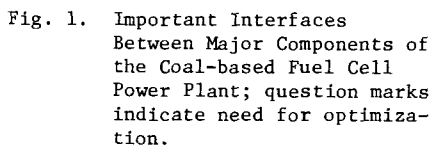
ACKNOWLEDGEMENT

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REFERENCES

1. "The System Analysis Language Translator (SALT): User's Guide, H. K. Geyer and G. F. Berry, Argonne National Laboratory, ANL/FE-85-3, 1985.
2. "Site-Specific Assessment of a 150-MW Coal Gasification Fuel Cell Power Plant," Kinetics Technology International Corporation, EPRI, EM-3162, 1983.
3. "Development of Molten Carbonate Fuel Cell Power Plant," General Electric Company, FC-17019-82-14, 1982.
4. "Molten Carbonate Fuel Cell Performance Model Update: Final Report," G. Wilemski, et al., Physical Sciences, Inc., DOE, DOE/FE/15078/1742, 1985.



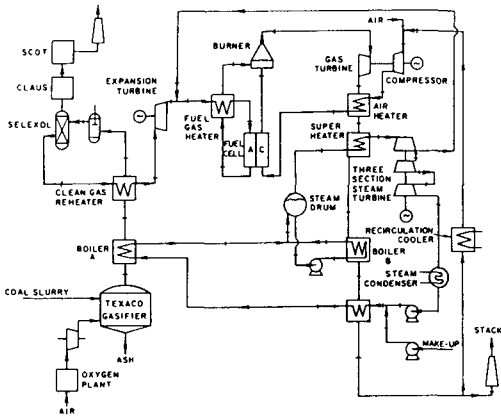


Fig. 3. Advanced MCFC Power Plant Configuration.

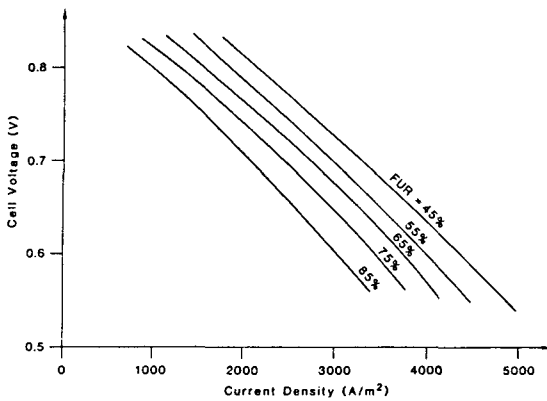


Fig. 4. MCFC Voltage vs Current Density for Various Fuel Utilizations.

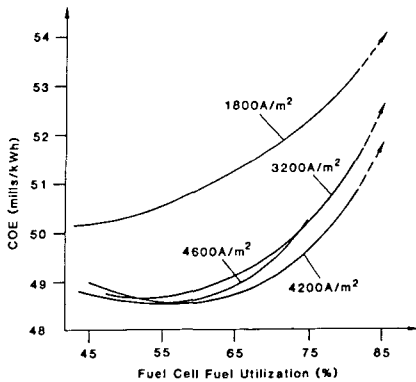


Fig. 5. Cost of Electricity vs Fuel Utilization.

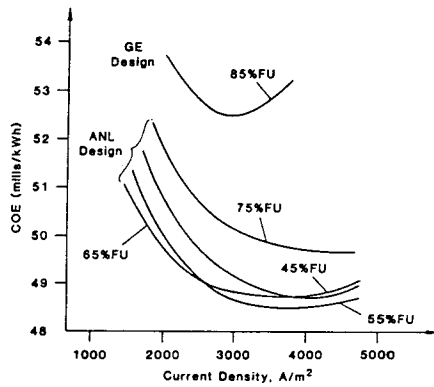


Fig. 6. Cost of Electricity MCFC Plant vs Current Density.

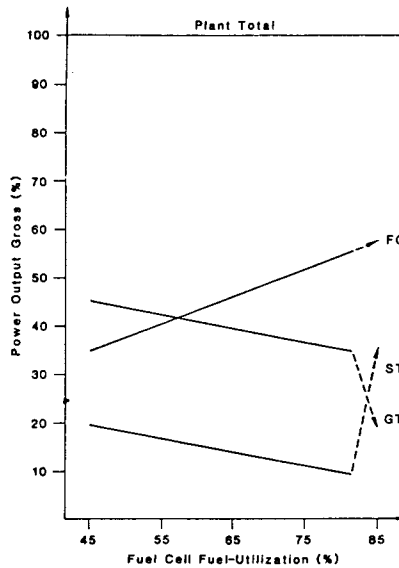


Fig. 7. Power Distribution of MCFC Power Plant vs Fuel Utilization.

PRELIMINARY DESIGN OF COAL GASIFIER/PHOSPHORIC ACID FUEL CELL POWER PLANTS ON AN ELECTRONIC SPREADSHEET

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The objective of this study is to identify the most promising integrated coal gasifier (CG)/PAFC design and its optimal operating conditions. Many system studies have been conducted separately on both coal gasification with associated contaminant control, and phosphoric acid fuel cells (PAFC) to determine the performance and economics of each. There are very few studies that have been combined both systems.

A spreadsheet-created process flowsheet simulation model using a personal computer is very user-friendly and has an advantage of interaction, especially during the preliminary system synthesis work. Material and energy balances for each component (unit operation) in the CG/PAFC system are formulated on a spreadsheet. Then a power plant system is synthesized by coordinating and integrating unit operation models. The interactive feature will allow the designer to review the calculation, make decisions based on the preliminary results, and quickly correct mistakes or faulty assumptions.

The system or "single-staged" approach is applied in this study. Thermodynamic balances are used to set up algebraic equations, then one can calculate the physical and chemical properties of the streams for one operating condition, such as the mean temperature and pressure.

Conceptual Designs of CG/PAFC Powerplant for Cogeneration

Conceptual designs for seven CG/PAFC integrated systems for cogeneration application have been completed. A reference system using methane as the fuel is also developed.

For each design the input quantity of coal is about the same amount (288 TPD). The criterion for the design is to produce the maximum amount of electricity. The developed systems cogenerate 20-28 MW electric power and 8-28 MW 50 psig steam. For comparison, a steam turbine is assumed to convert the thermal energy in each system into electric energy.

The coal gasifiers integrated in to these designs are listed in the order of the status of commercialization (from most developed to the least) as follows: Wellman-Galusha (W-G) air-blown, Koppers-Totzek (GKT) oxygen-blown, Texaco oxygen-blown, High Temperature Winkler (HTW) oxygen-blown, Westinghouse oxygen-blown, Kohlegas Nordrhein GmbH (KGN) air-blown, and TRW Catalytic Hydrogen Process (CHP). The typical material and energy balances for the selected CGs, which are reported in References 1, 2, 3, and 4 are used in this study.

Cold gas cleanup is considered in the design because of its ability to clean ammonia to 0.1 to 1.0 ppm, which PAFC can

tolerate, in the fuel stream. The physical absorption process such as Selexol with CLAUS and SCOT units is selected for the high pressure coal derived gases (e.g., gases from Texaco and Westinghouse CGs). The liquid-phase oxidation (Stretford) process is used for cleaning the low to median pressure (16 to 160 psia) coal derived gases. An iron oxide guard bed is used in the methane-fueled/PAFC reference design for the same purpose.

International Fuel Cells' (IFC) water-cooled PAFC stack is used in the design. The operating conditions are fixed at IFC's 11 MW powerplant rated conditions. A semi-empirically based parametric relationship was used to calculate current density (CD)-voltage characteristics.

One of the designs, which was integrated KGN CG with the PAFC powerplant, is shown in Figure 1.

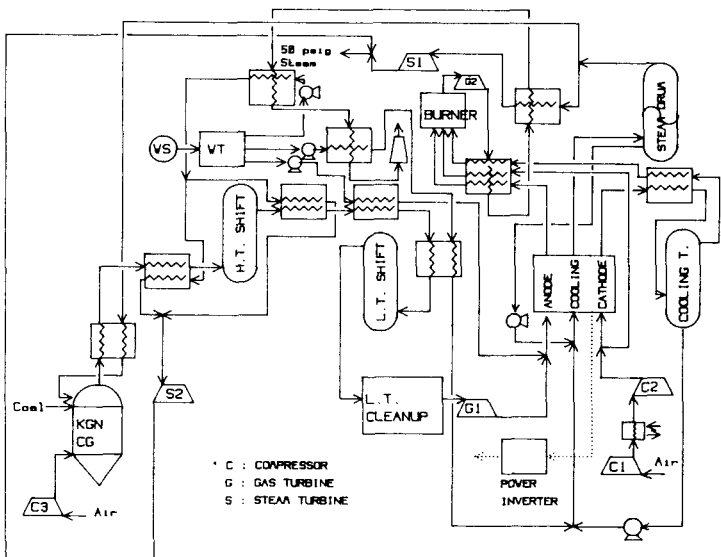


Figure 1 KGN/PAFC Integrated System Diagram

The capital cost, operating cost, and cost of electricity (COE) models are also developed on a separate spreadsheet. Real constant 1984 \$ dollars are used in all of the studies. The COE estimating methodology used in this analysis is consistent with the 1982 EPRI TAG for calculating the 30 year levelized revenue requirements. The COE (mills/kWh) depends on many assumptions - debt rate, inflation rate, tax rate, etc. Such

an explicit table calculation is ideal for using a spreadsheet. Figure 2 compares efficiencies and COEs for CG/PAFC integrated systems with a methane-fueled PAFC system as a reference. Two methane costs (\$6 and \$3.5/mm Btu) are considered for the reference design. These preliminary results show that the air-blown CG/PAFC systems have a higher efficiency (for KGN CG) and a lower COE (for W-G and KGN CGs), which results from the low power consumption and low cost of air compression relative to the oxygen plant. The reference design results in the lowest capital investment, but the resulting COE depends heavily on the price of methane.

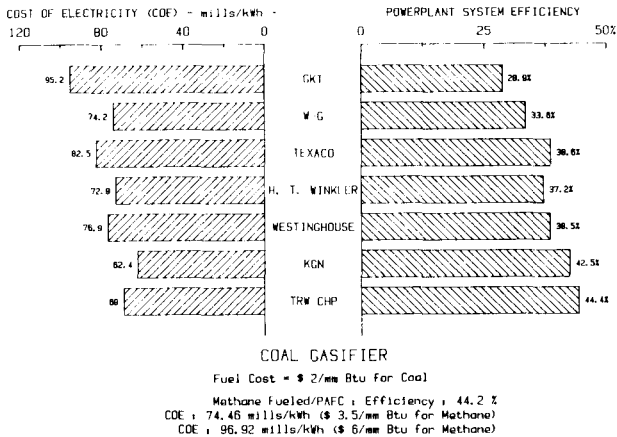


Figure 2 Comparisons of Efficiencies and COEs for CG/PAFC Integrate Powerplant Systems

The recommended CG for a CG/PAFC system contains the following conditions:

1. air-blown.
2. operating pressure is at a minimum of 25% higher than the operating pressure for the PAFC. It has an advantage to operate the CG at close to the minimum pressure.
3. operating temperature should be higher than the boiling points of oils and tars (1200°F) and with an operating pressure that will produce high hydrogen-content and low methane-content (in the order of 5%) raw gases.

Trade-off and Sensitivity Analyses of Fuel Utilization Ratio and Operating Current Density for the PAFC

In the previous section the operating conditions for the PAFC are fixed to the present values reported by IFC. But the capital cost and the efficiency are proportional to the fuel

utilization ratio (FUR), which is defined as the energy ratio of consumed hydrogen to total input fuel. To consume all the fuel in the PAFC is one of the limiting conditions, but it suffers very high capital cost for the powerplant. Another limiting condition is with all the fuel burned in the bottoming cycle, which decreases both the capital investment and the system efficiency. The simulation and economic models of a generic PAFC/bottoming cycle subsystem (Figure 3) is developed to study the effect of the FUR on the electric generation efficiency and COE. Various fuel compositions from several fuel processors (including the CG and shift converters) are used as input data.

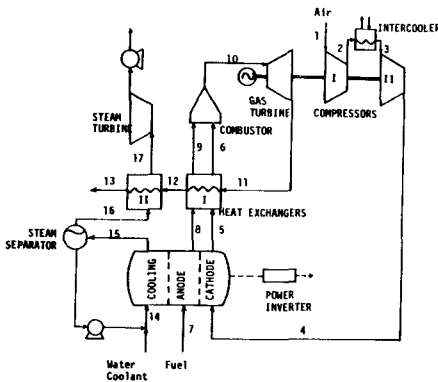


Figure 3 Generic
PAFC/Bottoming Cycle
Subsystem Flow Diagram

A spreadsheet application result is shown in Figure 4 for the KGN CG produced coal gases. Table 1 lists the values of FUR at which the maximum allowable firing temperature of gas turbine (2000 °F), the maximum efficiency, and the minimum COE for six kinds of CG produced coal gases are reached.

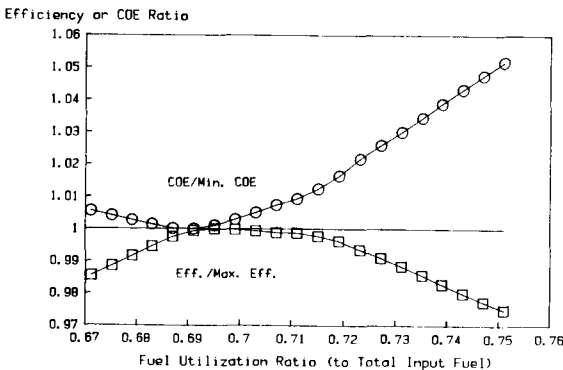


Figure 4 Efficiency
and COE Ratios vs FUR
of PAFC (KGN CG
Produced Coal Gases)

PAFC Input Fuel Compositions : Methane : 0.0274,
Carbon Monoxide: 0.006, Carbon Dioxide: 0.2447,
Steam: 0.0336, Hydrogen: 0.3625, Nitrogen: 0.326

CGs	W-G	GKT	Texaco	HTW	W	KN
Oxidant Used	Air	Oxygen	Oxygen	Oxygen	Oxygen	Air
PAFC Input Fuel Composition						
CH ₄	0.0149	0	0.0025	0.0199	0.0417	0.0274
CO	0.0171	0.0195	0.0212	0.0162	0.0207	0.0059
CO ₂	0.2453	0.4214	0.3777	0.3910	0.3865	0.2447
H ₂ O	0.0144	0.0146	0.0229	0.0148	0.0172	0.0336
H ₂	0.3746	0.5335	0.5701	0.5533	0.5250	0.3625
N ₂	0.3338	0.0110	0.0056	0.0048	0.0090	0.3259
Fuel Flow Rate (lb-mole/hr.)	3970	2817	2833	2711	2564	3903
FUR @						
(1) Max. Firing T (2000 °F)	0.72	0.75	0.76	0.76	0.76	0.72
(2) Max. Efficiency	0.70	0.73	0.74	0.74	0.74	0.70
(3) Min. COE	0.69	0.72	0.74	0.74	0.74	0.69
Improvements with Optimal FUR (%)						
Efficiency	0.81	6.18	5.08	0.08	5.91	0.84
COE	2.18	9.11	7.66	0.30	2.96	0.27

Table 1 Improvements with Optimal Fuel Utilization Ratio

The following conclusions can be drawn from this trade-off study.

- (1) The optimal FURs for the minimum COE can be grouped into two categories, 0.69 for air blown CGs and 0.735 for oxygen blown CGs.
- (2) The values of FUR for the minimum COE and the maximum electrical efficiency are close.
- (3) The maximum allowable firing temperature of the gas turbine is almost always reached in the optimal solution.

A higher operating current density (300 ASF instead of 200 ASF in the previous study) was used in the trade-off analysis of the generic PAFC/bottoming cycle subsystem. The input coolant conditions were adjusted to meet the operation requirement (i.e., 405 °F operating temperature). This adjustment included a higher coolant flow rate, and a lower coolant input pressure and temperature compared to the conditions needed in 200 ASF operation. The values were calculated from the engineering model for an IFC stack which was developed previously. The results show that the saving of a minimum COE, when the optimal FUR being used, is about 3.6% compared to that for a 200 ASF current density operation. The values of the optimal FUR at 200 ASF and 300 ASF are close.

References

1. Synthetic Fuels Associates, Inc., "Coal Gasification Systems: A Guide to Status, Applications and Economics," EPRI Report AP-3109, June 1983.
2. Kinetics Technology Intl. Cor., "Site-Specific Assessment of a 150-MW Coal Gasification Fuel Cell Power Plants," EPRI Report EM-3162, Nov. 1983.
3. Physical Sciences Inc., "Advanced Coal Gasifier - Fuel Cell Power Plant Systems Design," NTIS No. 83N33317, Jan. 1983.
4. Jet Propulsion Laboratory, "Systems Analysis of Advanced Technology Coal-Based Power Plants," JPL D-1867, March 1985.

PERFORMANCE AND CORROSION RESISTANT SUPPORTS FOR ACID FUEL CELLS

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A review of ERC's experience on alternate catalyst supports for atmospheric and pressurized phosphoric acid fuel cells is presented. Equivalent performance was demonstrated for graphitized and nongraphitized carbon black supports as shown in Figure 1, although the corrosion rates are at least two orders of magnitude different. The most corrosion resistant material tested to-date is a 2700°C heat treated carbon black from Cabot Corporation known as Black Pearls 2000. A comparison of typical corrosion rates is shown in Figure 2.

Performance measurements at various potentials and pressures have been performed to assess the effect of changes in corrosion rate. Operation in the range of 700mV and 850mV and 1 atm to 120 psia revealed no basic difference in the performance loss behavior even though the carbon catalyst support had very different apparent corrosion rates. A loss in activity was observed for all materials. Apparently there is a loss which is for all materials. Apparently there is a loss which is unrelated to diffusion and corrosion resistance of the carbon support. A typical loss behavior is shown in Figure 3.

ACKNOWLEDGMENT:

This work was supported in part by DOE under NASA contract DEN3-290 (under a subcontract from Westinghouse).

Operating Conditions: 190°C, 4.7 atm, 83% fuel (H_2) and 50% oxidant (air) utilization

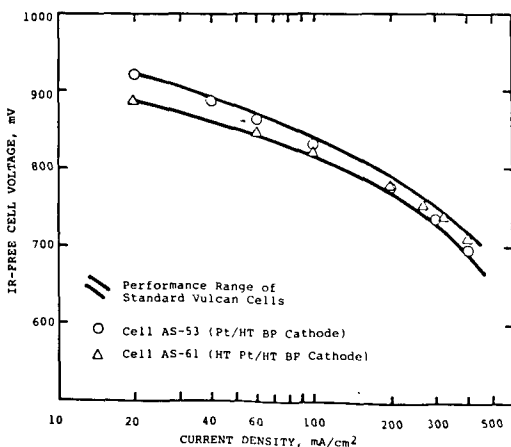


Figure 1 Polarization of Heat-Treated Black Pearls Cathodes

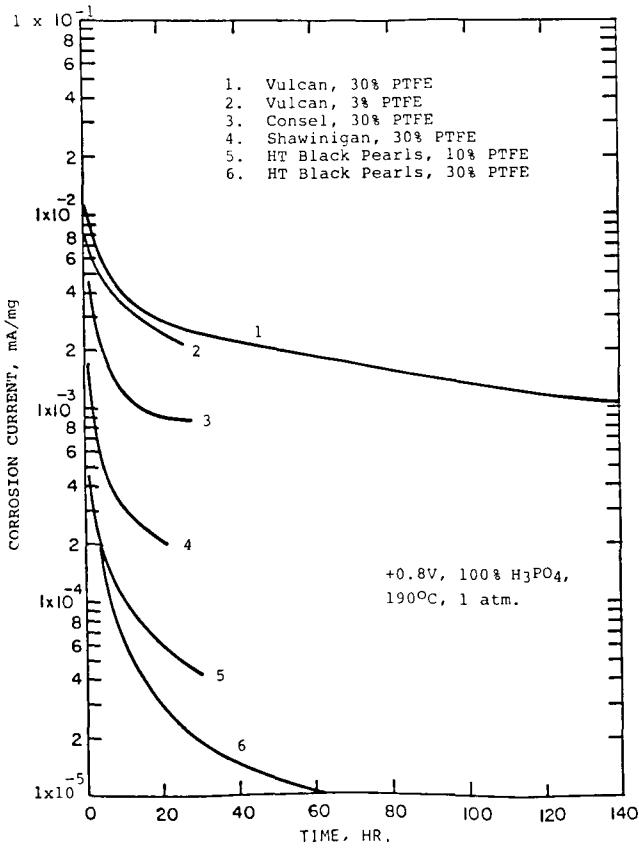


FIGURE 2 Corrosion Characteristics of Various Carbon Support Materials

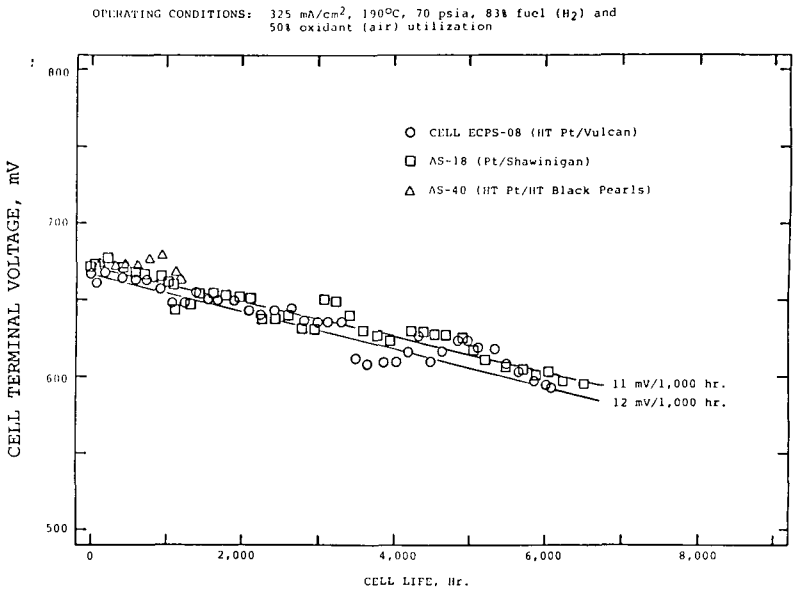


FIGURE 3 PERFORMANCE OF VULCAN,
SHAWINIGAN, AND BLACK PEARLS CATHODES AT PRESSURE

DEVELOPMENT OF A MEMBRANE ALKALINE FUEL CELL FOR CAUSTIC CONCENTRATION IN THE CHLOR-ALKALI INDUSTRY

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The objective of the PSI/Department of Energy cooperative agreement, "Application of Fuel Cells to Chlorine-Caustic Technology," is to demonstrate the feasibility of improving the efficiency of the chlorine/caustic soda production process. Due to the magnitude of this industry, efficiency improvements have a significant impact on the nation's energy usage. The daily production of chlorine in the U.S., 50,000 tons (1), translates into an equivalent energy consumption by the chlor-alkali industry of 287,000 bbl of oil daily.

Previously (2,3), we presented the results of an energy and economic analysis of three cases: 1) conventional membrane electrolysis cell technology; 2) membrane electrolysis cell technology incorporating phosphoric acid fuel cells; and 3) membrane electrolysis cell coupled with a membrane alkaline fuel cell reactor (PSI system). In case 1, the by-product hydrogen from the electrolysis cell is used in the evaporators to concentrate the caustic soda from 30 wt% to 50 wt%. For case 2, the by-product hydrogen from the electrolysis cell is used to generate electric power in the phosphoric acid fuel cells. Case 2 resulted in 6% energy savings compared to Case 1.

In the PSI system (see Figure 1), the dilute sodium hydroxide (~ 30 wt%) from the membrane electrolysis cell is split and

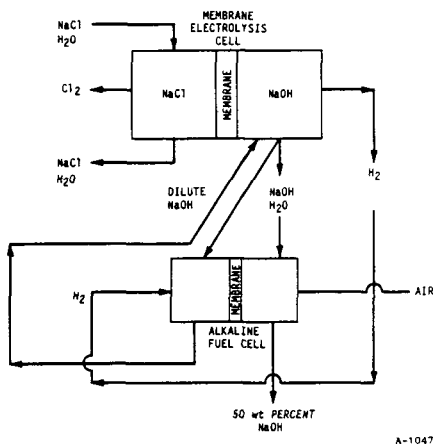


Figure 1. Process flow diagram of the PSI coupled membrane electrolysis cell/membrane alkaline fuel cell reactor

goes into the alkaline fuel cell which contains a cation selective membrane separating the anode and cathode chambers. By-product hydrogen produced in the membrane electrolysis cell is used as fuel at the anode of the fuel cell and oxygen from air is the oxidant. Due to the presence of the cation selective membrane, the electrochemical reactions concentrate the caustic soda in the catholyte and dilute the caustic soda in the anolyte. The sodium hydroxide catholyte leaves the alkaline fuel cell at ~ 50 wt% and the anolyte leaves at 21 wt%. The anolyte is recycled back to the cathode side of the electrolysis cell. Thus the alkaline fuel cell serves two functions: 1) to concentrate caustic and 2) to generate electrical power. The most significant advantage of the PSI system over current technologies is that caustic concentration is carried out in the fuel cell without any need for external energy input. Additionally, the alkaline fuel cell provides an efficient way to use the by-product hydrogen to cogenerate electricity.

To date, we have studied Nafion 901® and seven developmental membranes (DuPont) under conditions relevant to the PSI system. Initial screening in 30 wt% anolyte/catholyte and 25 wt% NaOH anolyte/40 wt% NaOH catholyte has indicated DuPont development membrane A1 to be the most promising.

We considered different modes of operation of the membrane alkaline fuel cell. As shown schematically in Figure 2, co-flow and counter-flow schemes result in different types of anolyte/catholyte environments for the membranes. In the co-flow scheme the 30 wt% caustic enters at one end of the concentrator cell and the 20 and 50 wt% caustic solutions exit

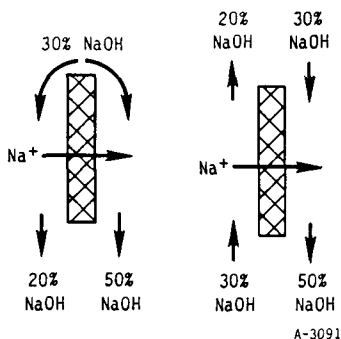


Figure 2. Schematic of co- and counter-flow concepts for the membrane alkaline fuel cell concentrator

*Nafion is a registered trademark of the E.I. DuPont deNemours and Company.

at the other end. In the case of the counterflow scheme, the caustic streams enter and exit from opposite ends of the concentrator. In order to determine the effect of the co-flow versus the counter-flow scheme on membrane performance, a test matrix covering 30 to 50 wt% of NaOH catholyte and 20 to 40 wt% NaOH anolyte was designed. Membrane A1 was evaluated under the conditions of this test matrix(4,5). A systems study has verified the ability of the membrane alkaline fuel cell to concentrate the caustic soda to 50 wt% using the experimentally determined membrane properties.

From these tests, we determined that the membrane alkaline fuel cell concentrator performance is better under co-flow conditions than counterflow conditions. In Figure 3 we present membrane voltage drop data for three co-flow conditions along with the hydrogen-air alkaline fuel cell performance data of the Institute for Hydrogen Systems (6).

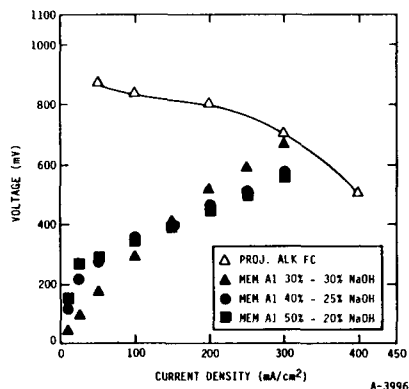


Figure 3. Alkaline fuel cell polarization and membrane polarization under conditions of co-flow conditions

The intersection of the membrane voltage drop data with the IHS alkaline fuel cell performance data represents the operating current density which would result in zero net power from the fuel cell. At higher current densities, external power is required by the membrane alkaline fuel cell. At lower current densities, power is generated by the membrane alkaline fuel cell. The optimal operating current density of the membrane alkaline fuel cell concentrator is defined by a tradeoff of energy power production and capital considerations. At low current densities, the electric power output which may be used in the electrolysis cell is increased but the membrane alkaline fuel cell area (and hence capital cost) required to concentrate a given amount of caustic soda is also increased. Conversely, at high current densities the

capital cost is decreased but the electric power output is also decreased. At current densities of $\sim 200 \text{ mA/cm}^2$ our system delivers 300 mV of d.c. electricity.

To date, we have demonstrated the performance of an advanced cation exchange membrane in the electrolyte environment relevant to the PSI system. We are currently evaluating electrocatalyst materials in the catholyte environment and, in future research efforts, we will evaluate membrane and electrode performance stability. Finally, we will demonstrate the system performance in a bench scale ($\sim 60 \text{ cm}^2$) process development unit.

Acknowledgment

The authors gratefully acknowledge the support of the U.S. Department of Energy, Office of Industrial Programs, and Mr. W. Sonnet for support under Contract No. DE-FC-07-84ID12495. Additionally, the efforts of Dr. L. Burton of DuPont are gratefully acknowledged. Helpful discussions with G. Wilemski, D. Ham and A. Boni are also gratefully acknowledged.

REFERENCES

1. D.E. Hall and E. Spore, "Report of the Electrolytic Industries for the Year 1984," J. Electrochem. Soc. 132(7), 252C-285C, 1985.
2. A. Gelb, A. Garman, D. Bloomfield, and H. Piperopoulou, "Application of Fuel Cells to Chlorine-Caustic Technology," 1985 National Fuel Cell Seminar Abstracts, Courtesy Associates, Inc., Washington, DC, Tuscon, AR, May 19-22, 1985.
3. A. Gelb and E.J. Taylor, "Application of Fuel Cells to Chlorine-Caustic Technology," Proceedings of the Symposium on Separation Processes, AIChE, Seattle, WA, 1985.
4. E.J. Taylor, R. Waterhouse, J. Campbell, and A. Gelb, "The Development of a Membrane Alkaline Fuel Cell Reactor for Energy Conservation in the Chlor-Alkali Industry," Proc. Symposium on Land Leveling and Energy Conservation in Industrial Processes, Chin (ed), The Electrochemical Society, Boston, MA, 1986.
5. E.J. Taylor, R. Waterhouse, A. Gelb, "Applications of Fuel Cells to Chlorine-Caustic Technology," 21st IECEC, 1986.
6. K. Tomantschger, S. Srinivasan, R. Findley, J. Joanes, F. McClusky, A. Reid, K. Kordesch, "Development of a 500-watt Bipolar Alkaline Fuel Cell," Proceedings of the 20th Intersociety Energy Conversion Conference, Society of Automotive Engineers, Warrendale, PA, 1985.

DEVELOPMENT OF POLYMER FUEL CELLS
FOR
CANADIAN DEPARTMENT OF NATIONAL DEFENCE

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Introduction

Ballard Technologies Corporation (BTC) is developing solid polymer electrolyte fuel cell or Polymer Fuel Cell (PFC) technology in conjunction with the Canadian Department of National Defence. The work began in January 1984.

During Phase I (Technology Acquisition), BTC acquired state-of-the-art PFC technology for Canada. The technology was demonstrated in single cells and stacks with power outputs up to 280 W.

The overall objective of the development program is to develop low cost PFC technology in Canadian industry capable of meeting a number of military and civilian applications. BTC's intention is to develop this technology with the goal of manufacturing and selling PFC power plants for military and civilian requirements worldwide.

Previous analysis by the Canadian Defence Research Establishment Ottawa (DREO) indicated that PFC technology could meet most potential defence applications for fuel cells such as portable field generators and propulsion for submarines. In addition, this type of fuel cell technology would also be suitable for a number of civilian applications such as portable generators for cottage, boat and industrial use as well as the prime power source for hybrid electric vehicles and other transportation applications.

Successful deployment of Polymer Fuel Cells depends on cost reduction and/or increases in power density together with the ability to operate on practical fuels and oxidants such as reformed methanol and air.

The majority of powerplant cost resides in the power section or fuel cell stack. Cost can be reduced through the use of low cost membranes, low cost catalyst loadings and/or the ability to operate at high power density.

Phase I ran from January 1984 to March 1986. Phase II (Technology Improvement) will run from April 1986 to March 1987. The following briefly describes what was achieved during Phase I and Phase II up until about July 1986.

Phase I - Technology Acquisition

The objectives of Phase I were to acquire state-of-the-art PFC technology, demonstrate cost reduction and operation on CO containing fuel gas, identify suitable low cost membranes as alternatives to high cost Nafion and, deliver three 50 to 100 W PFC stacks. BTC met or exceeded all objectives.

Work performed during Phase I included the development of the Membrane/Electrode Assembly (MEA) and associated single cell, stack and test station hardware.

Nafion membrane and Pt catalyzed porous carbon electrodes form the baseline MEA. Baseline catalyst loadings are 4 mg Pt/cm² for each electrode or 8 mg Pt/cm² total. About 300 MEAs were built during Phase I.

Low current density (LCD) and high current density (HCD) hardware were developed. LCD refers to hardware which operates at less than about 250 mA/cm². HCD refers to hardware which is capable of operating up to 1000 mA/cm².

The LCD hardware has Plexiglas end plates and uses O-ring sealing. There is no provision for controlled temperature operation. The cell operates under atmospheric pressure at a temperature of about 55°C. The cell is fed dry gasses and employs passive water removal via polypropylene wicks. The anode cell plates are grooved non-porous graphite while the cathode plates are grooved porous carbon. Active cell area is 31 cm².

The HCD hardware has aluminum endplates, uses spray-on silicone gasket sealing and is designed to be expandable to a multicell stack. Controlled temperature operation is provided by water circulated within the cell. The cell has operated under pressures up to 100 psig and temperatures up to 100°C. The cell is fed dry gasses which are internally humidified by water vapor transport across a membrane. The humidification water comes from cooling water circulated within the cell. Product water is removed with the excess oxidant stream. The cell plates are computer numerical control (CNC) machined graphite. A plastic pneumatic piston in one endplate provides cell plate compression for sealing and minimum contact resistance. Active area is 51 cm²/cell.

During Phase I, operation of single cells up to 1000 mA/cm² of active cell area was demonstrated. Pressures ranged from atmospheric to 100 psig and temperatures from 50 to 100°C. Reactants included H₂/O₂, H₂/air and simulated reformed methanol (reformate)/air.

Single cell power outputs up to 26 W on H₂/air in 51 cm² active area cells were demonstrated. Currents were up to 50 A. Single cell power densities over 500 mW/cm² of active cell area were demonstrated.

Reduction of the Pt catalyst loading by one half on H₂/air at current densities of about 200 mA/cm² in the LCD hardware was successful. Performance at 4 mg Pt/cm² total after over 1000 hours of continuous operation on H₂/air was 95% of baseline performance at 8 mg Pt/cm² total.

Operation of single cells on pretreated reformate/air at low and high current densities was demonstrated. Simulated reformed methanol or reformate was taken as 0.3% CO, 25% CO₂

with the balance H_2 . In the LCD hardware, performance was 0.66 V @ 211 mA/cm² after 240 hours. Operating pressure was atmospheric while temperature was about 55°C. As a comparison, performance on H_2 /air is about 0.70 V @ 223 mA/cm².

In the HCD hardware, performance on pretreated reformat/air was 0.54 V @ 434 mA/cm². Operating pressure was about 20 psig while temperature was 70°C. As a comparison, performance on H_2 /air is about 0.65 V @ 440 mA/cm² under similar conditions of temperature and pressure.

During Phase I, an in house low cost membrane (BTC Membranes Inc.) was identified as being suitable for use in a Polymer Fuel Cell. This membrane is being tested during Phase II.

As mentioned, Phase I deliverables were three 50 to 100 W PFC stacks. BTC significantly exceeded this goal with the delivery of one 280 W H_2/O_2 , 190 W H_2 /air 12 cell stack and, two 140 W H_2/O_2 , 100 W H_2 /air 6 cell stacks. Tables I and II show performances of a 12 cell stack on H_2 /air and H_2/O_2 respectively.

Phase II - Technology Improvement

The objective of Phase II (April 86 to March 87) is to significantly advance PFC technology through the development of a high current density reformat/air stack. High current density performance/life testing on H_2 /air, reformat/air and, at low catalyst loading on H_2 /air will be performed in single cells. Testing of BTC Membranes Inc. low cost PFC membranes in addition to promising membranes from other companies will also be done.

Table III shows performance of the HCD hardware on medium pressure H_2/O_2 at 80°C after 1200 hours operation on H_2 /air at 500 mA/cm². Table IV shows performance on low pressure H_2 /air at 75°C after 1150 hours operation at 500 mA/cm². Table V shows performance on high pressure H_2 /air at 92°C.

Preliminary testing of BTC Membranes Inc. low cost membrane at high current density (400 mA/cm²) has shown performance slightly better than Nafion after about 150 hours of operation.

Table I

Performance of a 12 Cell Stack - Hydrogen/Air				
15 psig H_2 /20 psig Air - 65°C				
Volts	Current (A)	Power (W)	Volt/Cell	Current Density (mA/cm ²)
9.3	8.8	82	0.78	174
7.4	25.6	190	0.62	506

Table II

Performance of a 12 Cell Stack- Hydrogen/Oxygen				
15 psig H ₂ /20 psig O ₂ - 60°C				
Volts	Current (A)	Power (W)	Volt/Cell	Current Density (mA/cm ²)
9.9	9.3	92	0.83	184
7.8	26.7	208	0.65	528
82°C				
6.9	40.5	280	0.58	800

Table III

Performance on Medium Pressure H ₂ /O ₂ after 1200 Hours		
30 psig H ₂ /30 psig O ₂ - 80 °C		
Volts	Current Density (mA/cm ²)	Power Density (mW/cm ²)
0.89	108	96
0.78	323	252
0.70	538	377

Table IV

Performance on Low Pressure H ₂ /Air after 1150 Hours		
10 psig H ₂ /20 psig Air - 75°C		
Volts	Current Density (mA/cm ²)	Power Density (mW/cm ²)
0.79	108	85
0.68	323	220
0.60	500	300

Table V

Performance on High Pressure Hydrogen/Air		
5 psig H ₂ /100 psig Air - 92°C		
Volts	Current Density (mA/cm ²)	Power Density (mW/cm ²)
0.86	100	86
0.80	200	160
0.74	400	296
0.69	540	373
0.65	660	429
0.57	880	502
0.52	990	515

FUEL CELLS AS A LONG RANGE HIGHWAY VEHICLE PROPULSION ALTERNATIVE

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INTRODUCTION

The interest in fuel cell technology for highway vehicle applications is rooted in its potential for very high energy conversion efficiency, negligible exhaust emissions, and ability to utilize coal and/or biomass derived fuel sources. The development of fuel cell technology for automotive highway transportation is both long-term and high risk. The potential pay-off, however, in terms of petroleum and energy savings as well as environmental benefits, is tremendous.

STUDY OBJECTIVE

A comprehensive systems analysis of fuel cells for automotive highway transportation which analyzes and documents in one study the various applications, the various candidates, where technology actually stands, what technology capability would be required, as well as providing a consistent data base, has not yet been done for the long-term. Such a study would lead to an evaluation of the R&D required to develop advanced fuel cells for automotive highway vehicle use and include an assessment of their likelihood for success. Results could lead to the foundation for a directed R&D program.

STUDY METHODOLOGY

At least two recent assessments have attempted to methodically analyze fuel cells for automotive highway transportation. The Los Alamos National Laboratory (LANL) has analyzed three developmental fuel cell technologies for automotive highway vehicle applications using a consistent set of ground rules and a vehicle simulation computer program.(1) JPL, in a broader assessment of advanced electric and hybrid vehicles, used a similar technique to examine the near-term potential of fuel cell technology.(2)

These previous study efforts are significant in identifying the viable fuel cell candidates for transportation and the areas upon which to focus research but without specific quantification of the needed achievements.

PRIMARY STUDY TOOL--The Advanced Vehicle Assessment by JPL for DOE was notably different from other assessment studies in that it might be described as a "top down" study. Methodology of the JPL study is shown schematically in Figure 1.

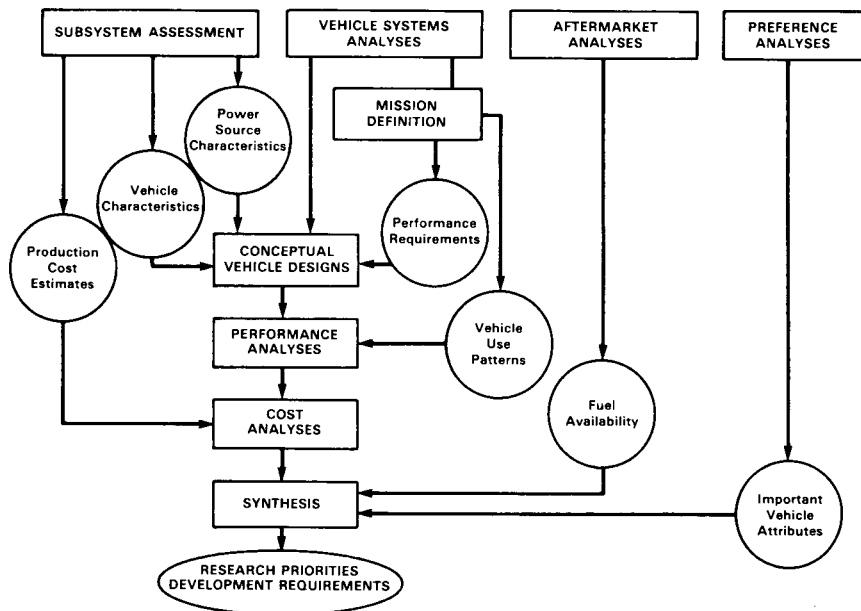


Figure 1. Advanced Vehicle Assessment Methodology

It began (Step 1) first with mission definition/performance requirements, use patterns coupled with subsystem requirements/vehicle characteristics, power source characteristics, and cost estimates to derive requirements for the key element which is the prime mover. These latter requirements were then used (Step 2) to collect material from notable experts and developers which were evaluated to project future characteristics of the energy storage devices for the early 1990's time frame. These future characteristics were then used (Step 3), through simulation modeling, to project the resultant vehicle characteristics of initial cost, life cycle cost, energy consumption, and break-even fuel price compared to a reference projected internal combustion engine (ICE) vehicle. The overall objective of the JPL study was to develop a methodology to compare many different technologies on a consistent basis and to employ the developed methodology to make the comparison.

STUDY METHODOLOGY--The study methodology (see Figure 2) would begin with a screening assessment. The screening assessment would follow the previously described JPL methodology and would utilize, to the extent possible, the existing data base. First, the JPL Step 1 technique would be applied to derive requirements for the prime mover.

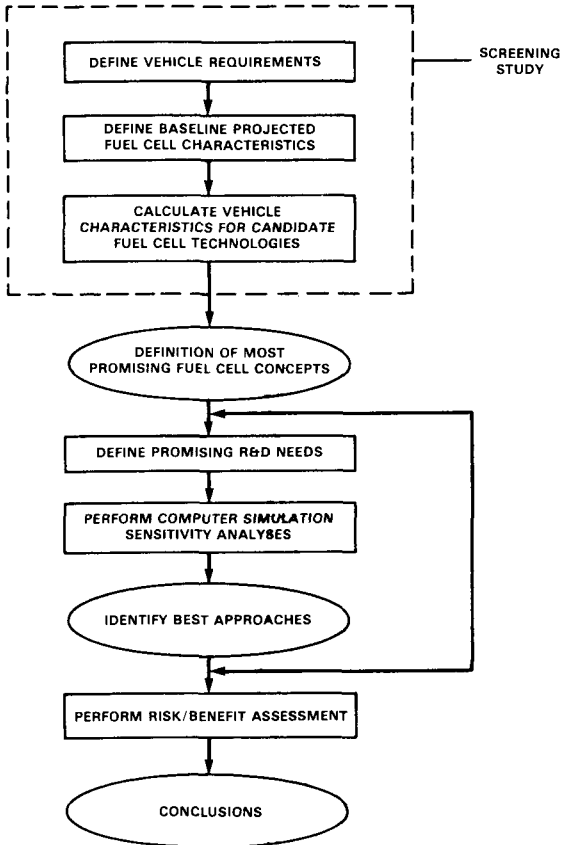


Figure 2. Planned Study Methodology

A study will have to be conducted to update the JPL data base in order to define vehicle mission and performance requirements and use patterns for the year 2000 and beyond. The same update operation must also be performed upon the JPL data base for subsystem requirements and vehicle characteristics. These two data bases would then yield the requirements to be imposed upon candidate fuel cell systems.

Then, the JPL Step 2 technique would be applied to yield initial information on the potential characteristics of fuel cell concepts and technologies in the post 2000 time frame based on current knowledge and research trends. Then, the JPL Step 3 computer simulation would be applied in order to project the resultant vehicle characteristics for the various fuel cell technologies compared to a reference projected ICE-driven vehicle.

The next step in the fuel cell study methodology would be to utilize the JPL computer simulation program as a tool to perform sensitivity analyses to evaluate the potential of further fuel cell technology advances and to assist in assessing the directions and goals of R&D. Before the simulations are performed, it is necessary to identify, for each fuel cell concept and technology, the most promising areas for technical advancement and then estimate their sensitivity on system performance and cost. Each candidate advancement can then be explored to assess its relative value versus other advancements to the fuel cell or supporting subsystems.

OBSERVATIONS

- o Fuel cell technology offers clear potential benefits for automotive highway vehicle applications. These benefits include highly efficient fuel utilization, the ability to utilize non-petroleum fuels, and dramatically reduced adverse environmental impacts.

- o As a result of dramatic advances in both the state of fuel cell technology and the understanding of the demands of fuel cell technology for highway vehicle applications, the potential of fuel cell technology now warrants more rigorous investigation for highway vehicle propulsion.

- o In light of the above statement, it is observed that no comprehensive systems analysis assessment of the long-term (post 2000 time period) potential of fuel cell technology for highway vehicle applications has been conducted.

- o If a fuel cell program is initiated for automotive highway vehicle applications, a comprehensive systems analysis as herein described should be conducted as the first step. This study would then fully analyze and document the potential of advanced fuel cells and identify fruitful directions to focus an R&D program.

REFERENCES

1. D.K. Lynn, "Analysis of Fuel Cell Systems For Transportation," Los Alamos National Laboratory.
2. K.S. Hardy et al., "Advanced Vehicle Systems Assessment," Jet Propulsion Laboratory Report No. 84-79, January 1985.

LIFE PREDICTION OF FUEL CELL REFORMER TUBE BY CREEP-FATIGUE ANALYSIS

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1. Introduction

The steam reformer in fuel-cell application is required to be compact in size and fast in response to the frequent startup/shutdown cycles. As a result, reformer tubes are subjected to extremely high temperature and severe thermal cycling like an example shown in Fig.1. Since such a condition will produce both creep- and fatigue-damage in tubes, creep-fatigue interaction should be taken into consideration not only in tube-material selection but also in structural design for fuel-cell reformer.

In this study, a suitable life assessment method for reformer tubes was developed by analysing creep-fatigue data on various materials. Also, appropriate tube materials were discussed applying this method to the model tube under a typical operating condition.

2. Experiment and Analysis

2.1 Creep and LCF test

Creep and LCF tests were carried out at 800°C and 1000°C on a series of materials taken from new- and used-centrifugally cast tubes (Table 1). Four different triangular strainwaves, fast-fast, fast-slow, slow-fast and slow-slow (defined as pp, pc, cp and cc, respectively) were used in LCF tests. A few tests were performed under trapezoidal waveforms with 15 min tension hold.

2.2 FEM analysis

The elastic-creep analysis by finite element method was conducted on the model tube shown in Fig.1. Two consecutive loading cycles were analysed for two candidate materials, low-C-HP-Nb and HP-BST-M (Table 1). The creep equation used in this analysis had the following form;

$$\dot{\epsilon}_c = a\sigma^b t^c + d\sigma^e t \quad (1)$$

The instantaneous creep strain was negligibly small.

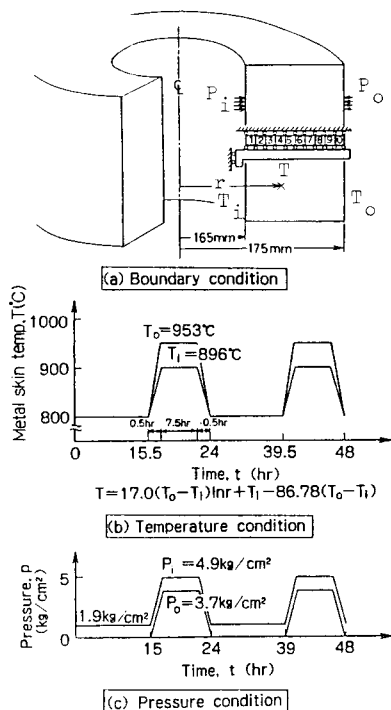


Fig.1 The model tube for FEM stress-strain analysis

Table 1 Chemical compositions of test tubes

Material	C	Si	Mn	P	S	Cr	Ni	Nb	Ti	Others
HK40	.43	0.88	0.52	.013	.013	24.4	21.3	-	-	-
HP	.48	1.19	0.78	.013	.014	25.5	34.3	-	-	-
HP-Nb	.45	0.99	1.33	.017	.016	24.8	35.1	1.38	-	-
Low-C-HP-Nb	.13	1.02	1.01	.013	.007	25.1	35.2	0.88	-	-
HP-BST-M	.49	0.90	0.81	.010	.009	24.9	35.0	0.72	.10	tr

3. Results and Discussion

3.1 Creep Rupture Property

Creep rupture curves at 1000°C of various materials are shown in Fig.2. HP-BST-M showed the highest strength, followed by HP-Nb, HP, low-C-HP-Nb, and HK40. The addition of appropriate amount of Nb and/or Ti to HP-alloy improved creep rupture strength, which is attributed to precipitation of fine Nb- and/or Ti-carbides.

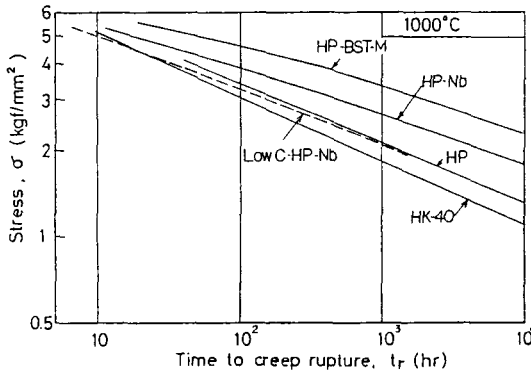


Fig.2 Creep rupture curves of various materials

3.2 Low-Cycle-Fatigue Property

The effect of strain waveforms on LCF life was shown in Fig.3. The pp-waveform gave the longest life, while cp- and hold-waveforms were the most damaging to materials. Metallographic examinations of failed specimens revealed that the fatigue-dominated (transgranular) failure occurred under pp- and pc-conditions. On the other hand, the creep-dominated (intergranular) failure took place under cp- and hold-type test conditions, which resulted in large reduction in fatigue life. Therefore, the evaluation by cp- or hold-type LCF test is required for the selection of tube materials.

The cp-type fatigue lives of various new- and used-materials were compared in Fig.4. It is shown that low-C-HP-Nb and HP-BST-M had more excellent lives than conventional HK40 and HP. Fatigue life can be improved generally by increasing ductility. Since Nb and/or Ti improved both creep ductility and strength, these elements were more effective to improve cp-property than lowering C-content.

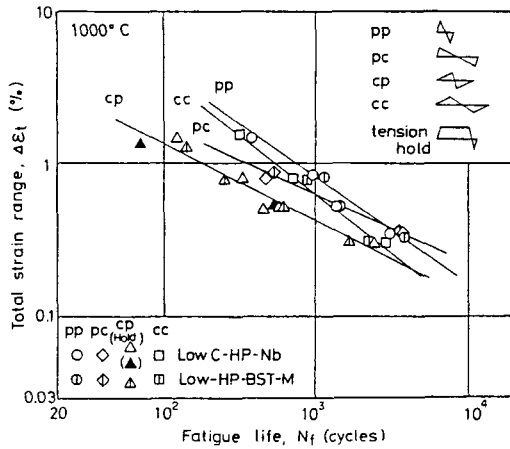


Fig.3 Effect of waveforms on LCF life

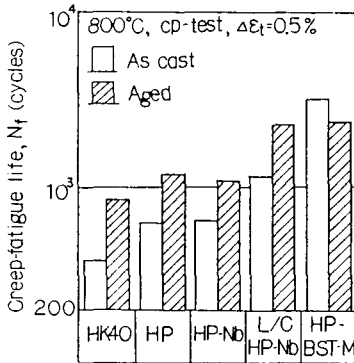


Fig.4 Comparison of cp-life for various materials

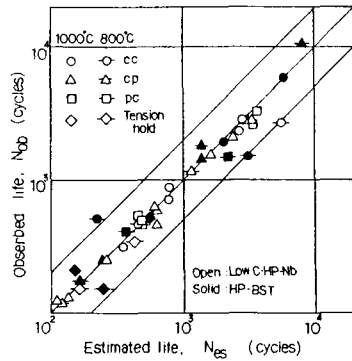


Fig.5 Life estimation by SRP method

3.3 The Creep-Fatigue Life Assessment Method

The estimation by the conventional linear-damage-rule (LDR), which is based on a linear summation of creep- and fatigue-damage, was too conservative for 800°C, but unconservative for 1000°C. The other method, strain-range-partitioning (SRP), requires to partition the inelastic strain range, $\Delta\epsilon_{in}$, into four basic strain ranges ($\Delta\epsilon_{pp}$, $\Delta\epsilon_{pc}$, $\Delta\epsilon_{cp}$, $\Delta\epsilon_{cc}$) and ratchet strain δ . These basic strain ranges are related independently to cyclic life, N_{ij} , as follows;

$$\Delta\epsilon_{ij} N_{ij}^{\alpha_{ij}} = B_{ij} \quad (2)$$

The life can be calculated by applying each N_{ij} for associated strain range, $\Delta\epsilon_{ij}$, to the following equation;

$$1/N = 1/N_{pp} + 1/N_{pc} + 1/N_{cp} + 1/N_{cc} + \delta/D_c \quad (3)$$

where D_c is creep ductility. The predicted life by SRP method was in good agreement with the observed life as shown in Fig.5.

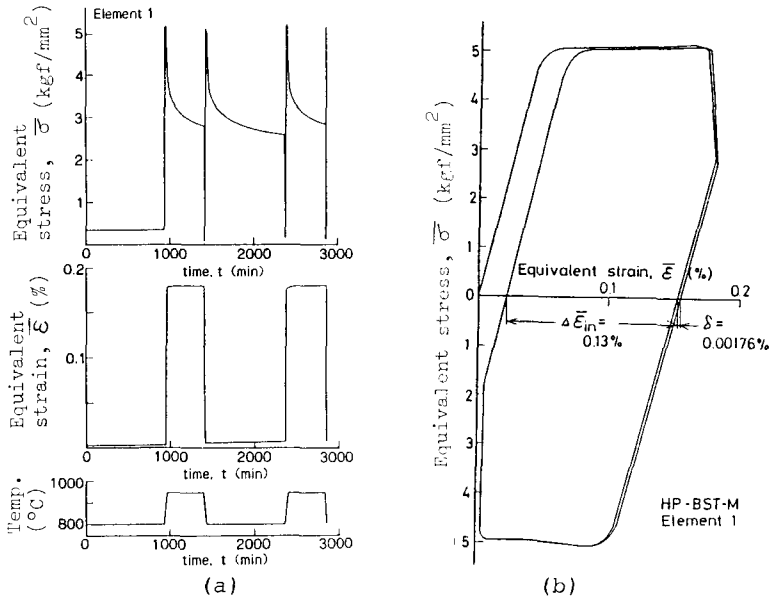


Fig.6 Stress- and strain-history of model tube

Table 2 Results of FEM analysis for model tube

	Material	Inelastic strain range $\Delta\epsilon_{in} (\%)$	Ratchet strain $\delta (\%)$	Estimated life N(cycles)
case 1	Low-C-HP-Nb	0.148	0.00352	1,700
case 2	HP-BST-M	0.130	0.00175	2,290

3.4 Creep-Fatigue Life Estimation of the Model Tube

The stress- and strain-history at maximum stress region (inner surface of tube) are shown in Fig.6(a). It implies nearly strain-controlled trapezoidal waveform is repeated in the model tube. The equivalent stress-strain loop at the region is shown in Fig.6(b). The value of inelastic strain range and ratchet strain, which are major factors determining LCF life, are summarized in Table 2.

The lower-bound life, which will be useful for a conservative design, can be obtained by regarding inelastic strain range as completely cp-type strain range. About 35% life extension can be expected by using HP-BST-M for this reformer model, as compared with low-C-HP-Nb.

4. Conclusions

- (1) The strain-range-partitioning method is an appropriate creep-fatigue life assessment for fuel-cell reformer tubes.
- (2) HP-BST-M has superior creep and fatigue resistances.
- (3) About 35% life extension can be expected by using HP-BST-M for a typical reformer model, as compared with low-C-HP-Nb.

TESTABILITY ANALYSIS OF A FUEL CELL
AIR PRESSURIZATION SYSTEM USING THE
SYSTEM TESTABILITY AND MAINTENANCE PROGRAM (STAMP)

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This paper describes a computer-aided model, used for conducting testability analyses and developing fault-isolation strategies, and its application to a major subsystem of a fuel cell power plant. The application was chosen to demonstrate the need for enhanced maintenance procedures and design for testability.

The computer-aided model is ARINC Research Corporation's System Testability and Maintenance Program (STAMP). Through engineering analysis of the functional flow of a system, the first-order relationships among components and test points are determined. A dependency-analysis algorithm within STAMP then identifies all higher-order dependencies and their implications with respect to fault isolation and maintenance. This process permits a complete testability assessment, including automatic identification of component ambiguity groups, redundant test points, feedback loops, and multiple-failure conflicts. The model also provides testability measures that are useful in comparing competing designs and in evaluating the effects of testability design changes such as test-point relocations.

STAMP also develops fault-isolation strategies. A new approach based on information theoretics provides troubleshooting procedures that minimize the expected number of tests required. The STAMP fault-isolation approach can consider such important factors as failure rate, test time, and test cost to yield strategies that have optimal characteristics with respect to the use of maintenance resources. In summary, STAMP is a powerful, flexible tool for improving design testability and maintenance characteristics.

Testability is now recognized as a major engineering discipline for controlling the performance and cost of system fault isolation and maintenance. Studies have confirmed that troubleshooting or fault isolation is a major consumer of maintenance resources and can seriously degrade operational availability. System testability design must address the quantity and location of test points as well as the troubleshooting strategy. STAMP can be applied to all system levels -- from piece parts to subsystems -- consistent with the maintenance replacement concept and electronic and nonelectronic systems. For electronic systems, STAMP can be used to develop or evaluate the test programs for built-in test equipment (BITE) and for automatic test equipment (ATE). A consistency check procedure is available within STAMP to provide analysis of false-alarm potential.

STAMP provides two types of fault-isolation strategies. One type is the equivalent of a troubleshooting manual, in which STAMP develops fault-isolation "trees" characterized by the known initial conditions of the failed system. The second type of fault-isolation strategy uses the algorithm "on line" and guides the technician through the fault-isolation task via computer video output.

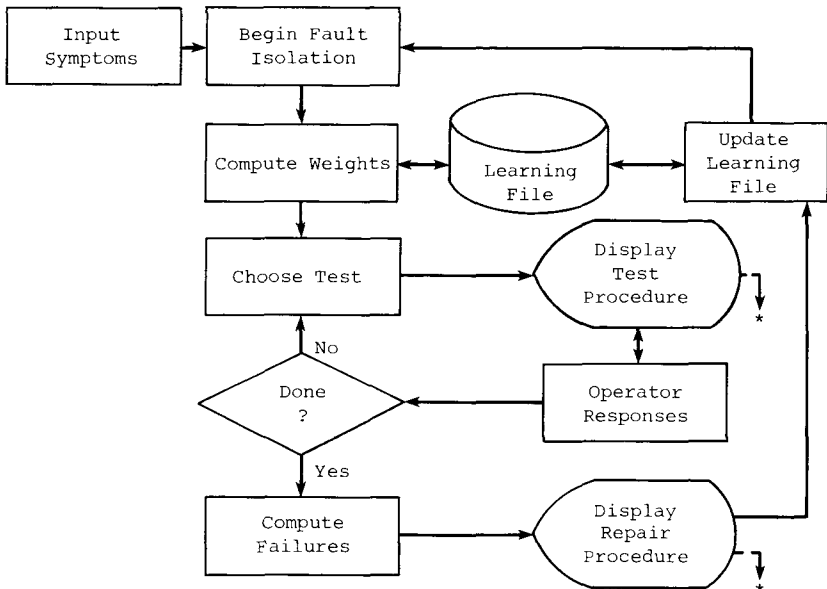
STAMP also allows for textual or pictorial display of the detailed test directions for repair or replacement. In design, prototype, and fielded-system applications, STAMP has yielded up to 75 percent improvement in testability and fault-isolation characteristics; its use has reduced the mean time to restore (MTTR) of fielded systems and helped in the writing of ATE driver programs.

STAMP has the following features, which can provide the acquisition manager or the system user with a powerful tool for ensuring or improving testability and fault isolation:

- Simplified inputs
- Generation of testability assessment reports
- Identification of ambiguities, redundant test points, and feedback loops
- Fault-isolation strategies
- Specification of initial conditions (e.g., failure rate, test time, or cost weighting)
- Multiple-failure analyses
- Automatic generation of fault trees

STAMP has a learning capability, wherein the history of failure causes is recorded and the information is used as a weighting factor for fault-tree generation. This process is illustrated in Figure 1. The procedure is applicable to all systems that have a logical relationship and may be used for hardware systems (electronic and nonelectronic) as well as software debugging, medical diagnosis, and management analysis.

To demonstrate STAMP's capabilities as a design tool and maintenance aid, ARINC Research conducted an analysis of the air pressurization system (APS) of a fuel cell power plant under development. The outputs of the analysis were STAMP-generated fault-isolation trees and testability measures that were used to assess STAMP's ability to isolate failures using a defined number of tests or test points.



*Video tape or disk may be added as an option.

Figure 1. STAMP REPAIR ASSISTANCE IMPLEMENTATION OF FAULT-ISOLATION METHODOLOGY

Working from existing system documentation (process and instrumentation diagrams [P&IDs] and failure modes and effects analyses [FMEAs]), ARINC Research created initial test dependency models for two modes of APS operation -- a start-up mode and a run mode. These initial models were then used by STAMP to generate a testability report for the APS. The STAMP testability report identified component ambiguity groups and component leverage. An ambiguity group is defined as a failure event whose cause may depend on more than one component; i.e., the failure event cannot be uniquely defined as having been caused exclusively by the failure of a specified component. Component leverage is a measure of the percent of subsystem components uniquely fault isolatable with given test points. From the information provided by the testability reports, a determination was made as to the adequacy of the defined tests and test points. Where results were inadequate, additional test points were added and specific tests defined to improve system testability. This new information was then fed back into STAMP, and new results were generated. This iterative process continued until an acceptable level of test capability was achieved.

Some components of the start-up mode were not required for the run mode. Initial results for the start-up mode showed that only 33 percent of more than 54 APS components were uniquely isolatable by using 15 existing test points. By using STAMP-generated testability reports, ARINC Research was able to define an additional 26 tests, which increased the percentage of uniquely isolatable components to 77.4. This finding implies that, with the addition of tests defined through STAMP usage, fault-isolation capability in the event of a failure at start-up is more than doubled. Similar results were achieved for the run mode of operation. On the basis of the experience of the start-up mode analysis, initial STAMP results showed that 60 percent of all components defined were uniquely isolatable. With the aid of STAMP, tests were defined such that unique fault isolation was improved to greater than 75 percent. In addition, for the APS analysis fault trees were optimized on frequency of failure such that the most unreliable components were isolated first, using the fewest number of tests possible. Thus, fault trees are a valuable aid in the creation of troubleshooting charts or procedures to be contained in the system maintenance manuals.

EFFECT OF IMPROVED HEAT TRANSFER CATALYST SUPPORT ON STEAM REFORMING OF METHANE

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The transfer of heat into and through the catalyst bed is a key element in the successful operation of an efficient steam reformer. Within the catalyst bed, heat is transferred primarily by conduction and convection. In conventional packed catalyst beds, where the catalyst is normally comprised of insulating, ceramic-type material, a compromise is achieved between the size of catalyst particles which will maintain high heat transfer without raising the bed pressure drop to an unacceptable level. Maintenance of the balance of heat transfer, pressure differential, and catalyst activity for a chemically dynamic system such as in the case of steam reforming is difficult to achieve in small, efficient reactors.

For the past few years at JPL, an alternative catalyst system has been under investigation for steam reforming in which a metal is used as the catalyst support as opposed to a conventional alumina particle packed bed. The purpose of examining this novel catalyst system was to determine the extent to which the heat transfer improvements that a metal support would offer to the steam reforming activity could be achieved, while at the same time reducing the bed pressure drop. The initial work was done with an alumina-washcoated, nickel-catalyzed, honeycomb design monolith of thin metal support. The activity that was recorded was better than that of a comparable packed bed of conventional nickel steam reforming catalyst. The pressure drop was on the order of two orders of magnitude less in the honeycomb monolith due to the high void fraction. While this catalyst had not been optimized for performance, it did illustrate that the use of a metal support could provide important improvements in the operation of a steam reformer. The questions which were raised were 1) how much was the heat transfer improved by use of the metal support, 2) what was the important heat transfer mechanism that assisted in this activity if heat transfer was improved, and 3) was the activity of the nickel increased by use of the washcoating approach rather than heat transfer improvements being responsible for the improved performance.

The first step in determining the relative impact of each of the parameters which could have contributed to the observed increase in activity was to determine the heat transfer characteristics of a metal monolith with a honeycomb design. This work was conducted and a heat transfer model was developed in an effort to explain the relationship of the parameters at work in the heat transfer mechanisms. A comparison was made to a packed bed in an experimental task which included varying the flowrates of nitrogen, as well as the outside wall temperatures. The results showed that the honeycomb design does provide for more uniform temperature profiles throughout the monolith and a higher bed exit temperature at the centerline could be achieved at low space velocity. However, it also showed that 1) the heat transfer was primarily by conduction and that a tortuous path was necessary to substantially improve the heat transfer from wall to centerline, and 2) the washcoated catalyst was probably more active than the conventional catalyst observed in the earlier tests. In order to clarify the parametric analysis, further tests were required.

Experimental steam reforming of methane was performed on a novel metal supported (monolith) nickel catalyst and compared to a conventional nickel catalyst bed. The experimental apparatus used was an Inconel tube 6.0 cm diameter and 107 cm long in which a bed of catalyst 8.6 cm long was positioned. The tube was located in a three-zoned furnace. Thermocouples (36) were emplaced throughout the catalyst bed to measure the radial and axial bed temperatures. Gas inlet and outlet temperatures as well as the tube skin temperatures were also monitored. Both nitrogen and steam/methane were flowed independently through the beds in order to gain information on heat transfer under active and inactive operation. Four different flowrates were used at one external tube wall temperature of approximately 845°C (1550°F). The flowrates varied over a range of gaseous inlet hourly space velocities (G_i HSV) of from 3350 to 8400 hr^{-1} . The nickel catalyst was 10 wt% for the monolith and 15 wt% for the 6.4 X 6.4 mm right cylinder particle packed bed. The configuration of the monolith provided for a tortuous path for the gas flow which allowed for three dimensional communication of the gases through the bed as compared to two dimensional for a honeycomb monolith design.

Results from these tests over a G_i HSV range of 3350 to 6700 hr^{-1} illustrate that the monolith catalyst bed, relative to the packed bed, maintains:

1. Higher inlet temperatures [greater than 150 C°],
2. Higher activity [approximately 5%],
3. Lower pressure drop [approximately 10^{-2}],
4. A divergent tendency in axial temperature profile.

The bed inlet radial temperature varied as much as 270 C° for the packed bed, while the highest temperature deviation for the monolith was 110 C°. At a G_i HSV of 8400 hr^{-1} , the packed bed catalyst was slightly more active than the monolith. The temperature profiles were quite different in that the centerline temperature for the packed bed was 100 C° lower than the monolith. The indication from these tests is that the activity of the nickel catalyst, which was present at nearly two orders of magnitude less on the monolith than on the packed bed particles, is maintained because of the increased heat transfer properties inherent in the monolith. The evidence of this is illustrated in the comparison of the temperature profiles that will be presented. In Figure 1 is the comparison of the methane conversion between the monolith and the packed beds over the four space velocities used in these tests.

Based on the results from the experimental results, it is clear that the metal supported catalyst (monolith) does provide a definite advantage to maintaining catalytic activity over a conventional packed bed, while simultaneously not increasing the pressure drop through the bed. Use of this type of catalyst in the inlet portion of the steam reforming reactor, for example, would add a significant improvement in the steam reformer efficiency.

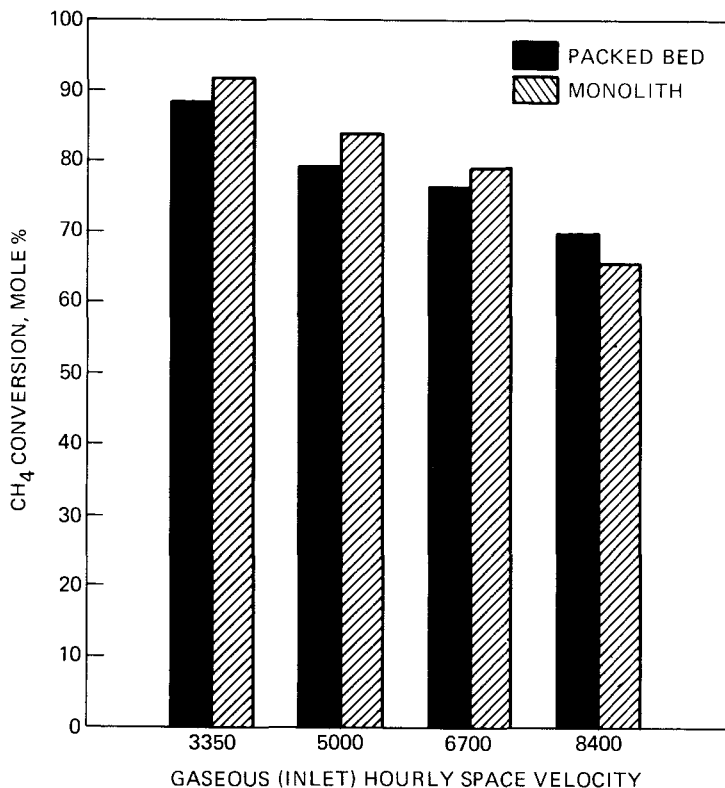


Figure 1. Relative Activities of the Monolithic vs Packed Catalyst Bed for the Steam Reforming of Methane.

References

1. Flytzani-Stephanopoulos, M. and Voecks, G. E., in "Conversion of Hydrocarbons for Fuel Cell Applications", DOE Final Report, DOE/ET-11326-1, JPL Publ. No. 82-37, October 1981.
2. Flytzani-Stephanopoulos, M., Charrng, T., and Voecks, G. E., in "Modeling of Heat Transfer in Non-Adiabatic Monolith Reactors and Experimental Comparisons of Metal Monoliths with Packed Beds", Chem. Eng. Sci., Vol. 41, No. 5, pp. 1203-1212, 1986.

Acknowledgement

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INTEGRATED ELECTRODE SUBSTRATE OF PHOSPHORIC ACID FUEL CELL (KES-I)

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Introduction

Various kinds of carbon electrode substrates for phosphoric acid fuel cell (PAFC) have been developed at Kureha Chemical Industry Co., Ltd. In addition to a carbon paper type and a mold type, which are currently sold to fuel cell manufacturing companies, an Integrated Electrode Substrate (KES-I) has been developed for the purpose of lowering the electrical and thermal resistance, improving the strength and reducing the cost. This paper presents the features of the KES-I.

Structure of KES-I

The structure of KES-I is shown in Fig.1.
It consists of a separator, a couple of ribbed electrode substrates and edge seal plates on both sides of each ribbed electrode substrate. Ribbed electrode substrate is made of a porous carbon material, while separator and seal plate are of dense carbon which is impermeable to reactant gases. They are bonded onto both faces of the separator, and then carbonized in an inert atmosphere at about 2,000°C. A separator and a couple of electrode substrates are united to form a new type of electrode substrate including a separator.

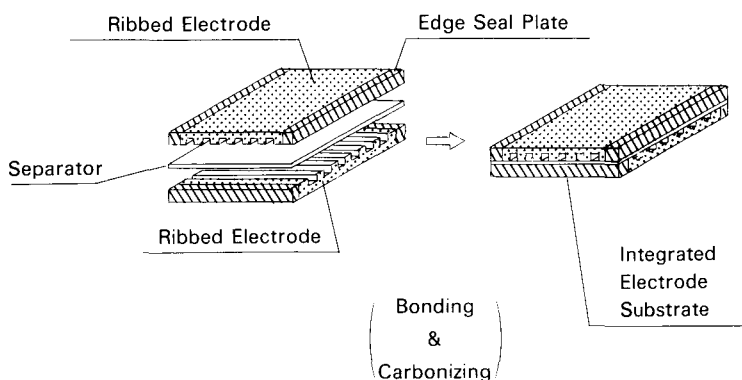


Fig. 1 Integrated Electrode Substrate (KES-I)

The features of KES-I

The purpose and merits of this integrated substrate are shown in Table-1.

Table-1 Effects of Integrated Electrode
Substrate (KES-I)

Purpose	Merit
Reduction of electrical resistance between electrode substrate and separator	High efficiency or high current density
Reduction of thermal resistance between electrode substrate and separator	High efficiency or high current density or decrease of number of cooler
Mechanically strong electrode	Easy handling & thin electrode
Reduction of raw material consumption & fabrication process	Reduced cost

The fuel cell equipped with KES-I has low electrical and thermal resistance between the separator and electrode substrate, resulting in high efficiency or high current density, or reduced number of inter-coolers in the stack. A comparison of properties between KES-I and ordinary case is shown in Table-2.

Table-2 Comparison of properties between
KES-I and ordinary case.

Item	Unit	KES-I	Ordinary case
Electrical resistance	m ohm·cm ²	18	75
Thermal resistance	m·hr°C / kcal	4	7.2
Thickness	mm	3.8	4.5
Flexural strength	kg-mm	10	0.9

The ordinary case was measured by putting a separator between a couple of electrode substrates without bonding. Electrical resistance for carbon materials in the fuel cell was about one forth of that found in the ordinary case. Electrical resistance of KES-I is nearly same as the calculated value of the electrical resistance of a separator and a couple of electrode substrates. It means that the contact resistance between a separator and a couple of electrode substrates is negligible in KES-I. Thermal resistance also decreases by half.

KES-I is very strong mechanically, because it has a separator which is about 10 times stronger than the electrode substrate, as a core. It makes handling easier and reduces handling loss in catalyst treatment and assembling. Due to the existence of this strong separator as a core, KES-I can be made thinner and the raw material consumption is reduced.

As the electrode substrate and the separator can be processed in the same manner (extruding, molding, etc.), the production facility of KES-I can be simplified. KES-I has edge seal parts in both side of each ribbed electrode substrate. As these parts are impermeable to reactant gases, KES-I does not require the edge seal treatment of electrode substrate. These simplifications have drastically reduced the assembly cost.

Our research and development activities on KES-I in KUREHA are shown in Fig.2.

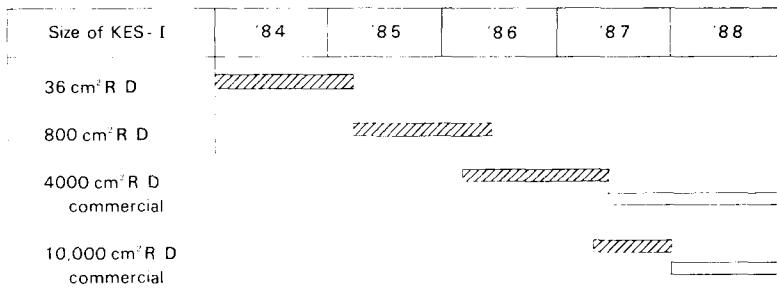


Fig. 2 R & D of KES I in KUREHA

All the targets in properties were achieved using KES-I of 36 cm²class in 1984, then the scale-up problems were studied using several pieces of KES-I of 800 cm²class in 1985. The problems such as warp and cracks accompanied with the scale-up of electrode were solved. Using the know-hows accumulated in these scale-up experiments, the KES-I of 4,000 cm²class has been successfully produced in a trial run. The KES-I of 10,000 cm²class will be produced without any serious scale-up problems. Currently several hundred pieces of KES-I of the 4,000 cm²class are being produced under sponsorship of the New Energy Development Organization (NEDO).

As all the problems appear to be solved up to this stage, KUREHA has a plan to bring KES-I of the 4,000 cm²class to market from the fall of next year. The KES-I of 10,000 cm²class will be the next item in the program and be brought to market in early 1988.

Acknowledgement

This work was supported by the New Energy Development Organization (NEDO) in 1984, and is also supported by NEDO in 1986 and 1987.

COMPUTER ANALYSIS OF COOLING EFFECTS IN PHOSPHORIC ACID FUEL CELL STACK

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For the design of phosphoric acid fuel cell (PAFC) systems, modeling is needed to obtain the local current generation as a function of temperature, pressure, reactant utilization, flow rate, feed concentrations, voltage, etc. A generic engineering analytic model for simulating the performance of PAFC powerplant is developed by combining energy, mass, and electrochemical analyses. This model calculates the temperature, current density (CD), and flow rate distributions for various coolant and design configurations specified by the user. It also is used to determine the effects of design and operating parameters on the performance.

Two examples of the simulations are presented here. Figure 1 shows the temperature distribution as calculated by the model for an air-cooled PAFC plate of similar size and characteristics as that of Westinghouse stack 561 (Ref.1). A branched cooling configuration (Figure 4b) is applied in the cooling plates which are separated by five cell plates. It is noted that the hot-spot is shifted to right as the fuel input temperature is much lower than mean operating temperature.

Another example is shown in Figure 2. The temperature distributions within a water-cooled PAFC stack are presented for a system having seven cell plates sandwiched between each pair of cooling plates, which is similar to IFC 10-ft² short stack. A 30-pass serpentine type cooling tube is molded in the cooling plate (Figure 4a). It can be observed that a parabolic temperature gradient in the stack direction.

Applications for Cooling Effects Study

Reducing the non-uniformity of CD, and thus non-uniformity of heat generation, one can increase the operating temperature which in turn increases efficiency. Efforts of improving the uniformity of performance have been made in two directions. One direction is to redesign the geometry of reactant streams across the cell plate in order to obtain constant reactant utilization. This will result in an uniform CD distribution.

cell configurations

Studies indicate that U-flow (examples of U-flow are shown in Figure 3 and Figure 4a) produces more uniform CD distribution than standard cross-flow cell. A study on an isothermal cell with four patterns and diverse flow area ratios of reactant flows is performed. Of the trial patterns, which include

1-1, 1-2, 2-1, and 2-2 passes, the 2-1 passes (2 for fuel flow and 1 for air flow) with area fraction $R1 = 0.4$ ($R1$ is defined in Figure 2), give the best CD distributions in both ambient and pressurized (4.75 ata) conditions. Figure 3 shows the determination of area ratio for the 2-1 pass case. Being compared with 2-2 pass pattern with equal oxidant U-flow area and 2:1 ($R2:R1$) area ratio in the fuel flow direction (Figure 4a), the optimal 2-1 pattern can decrease the range of CD (maximum CD - minimum CD) on one plate from 0.1 to 0.077 A/cm^2 for the same operation conditions (4.75 ata) listed in Figure 3. Even for a 2-2 pass pattern with equal oxidant U-flow area, the current design is not a good one (from an uniformity point of view). The patented Westinghouse "Z" plate (Ref. 1) combines counter-flow, co-flow, and cross-flow of reactants. This results in more uniform distributions than the cross-flow cell.

cooling schemes

The other direction is to devise better cooling schemes. There are two considerations for improvement; one is to remove more heat at the locations of highest CD , and the other is to improve the heat transfer between coolant and stack.

For the water cooled PAFC, an unequal pitch layout of serpentine type cooling tube will provide more coolant for the more heat generated area, and thus will result in an even temperature distribution. A design, with 16 passes on the right half (of equal oxidant U-flow area) and 14 passes on the left, with a longer pitch in the first three passes, will decrease the average temperature range from 28.6 °K (in an existing equal 30-pass design) to 26.1 °K. The optimal layout is dependent on the operating conditions, especially the CD which is changed in the load ramping period.

A similar result was obtained for the air-cooled stack. The varying-width scheme (Figure 4c), by which more coolant flows through the more heat generating area, will decrease the peak temperature by 30% at Westinghouse 7.5 MW powerplant rated conditions. In addition, this simple structured scheme does not suffer from structural defects and complications which the branched channel does.

The branched cooling channel was designed to prevent the formation of fully developed flow, to increase the flow rate (as the total crosssectional area is decreased), and to increase the heat transfer area. In one study, this layout can save the coolant input by 17% and reduce the peak temperature by 33% with the same average operating temperature as a straight configuration.

Two-phase heat transfer is an advantage of the water-cooled stack. One constraint on this is limiting steam quality of coolant to avoid film-boiling. Moreover, the pressure, temperature, and flow rate of coolant and the number of cell plates sandwiched between each pair of cooling plates should be optimized versus the cost.

Reference:

1. Hoover, D.Q., "Cell Module and Fuel Conditioner Development", Westinghouse Report, Feb. 1982.

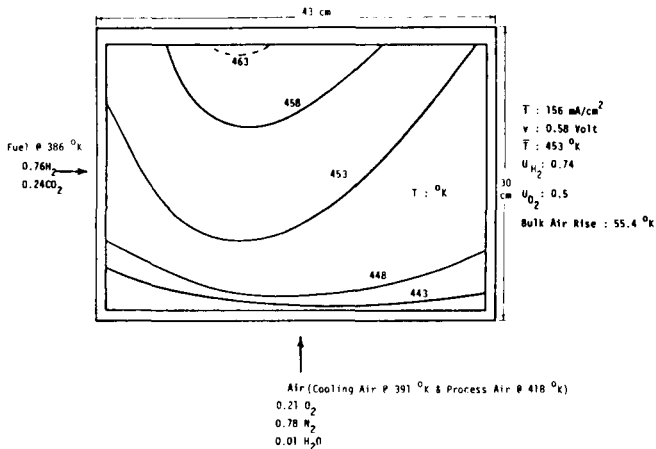


Figure 1 Calculated Temperature Profile in a 30 cm x 43 cm Air-Cooled PAFC with Cross-Flow.

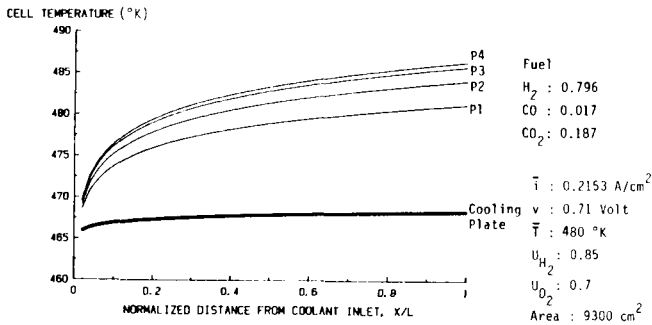


Figure 2 Temperature Distributions Along Coolant Flow Direction For a Water-Cooled PAFC Stack (P1, P2, P3, & P4 are Cell Plates Counted from the Cooling Plate to Center)

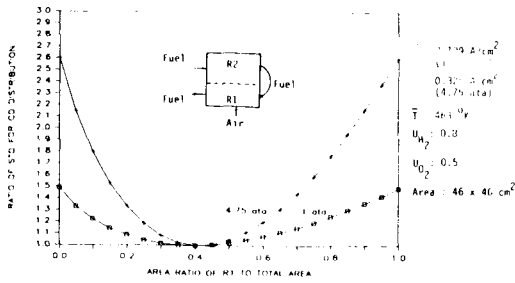
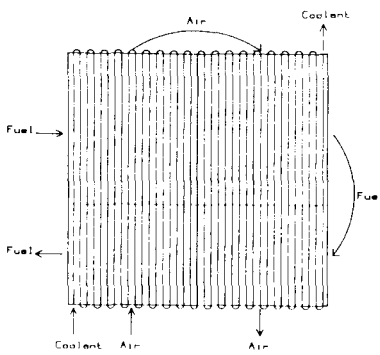
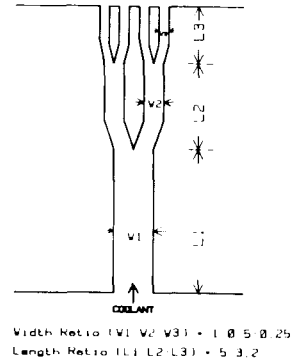


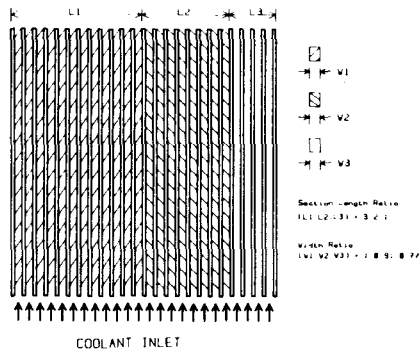
Figure 3 Current Density Uniformity Comparisons (2-1 Passes)



a 2-2 Pass Flow Pattern and Serpentine Cooling Tube



b One Branched Cooling Channel



c Varying Width Cooling Channel Configuration

Figure 4 Various Cell Configurations and Cooling Schemes

ADVANCED ELECTROCATALYSTS FOR PHOSPHORIC ACID FUEL CELLS

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An abstract of this presentation was not available at press time. Copies will be provided to attendees at the Seminar.

ECONOMIC STUDY ON FUEL CELL POWER GENERATION AT KENTENG VILLAGE IN INDONESIA FOR RURAL ELECTRIFICATION

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ABSTRACT

The increased emphasis on rural development in Indonesia will mean increased demand for small-scale sources of energy, since most rural areas in Indonesia will not be reached soon by the electric grid. For example, small-scale energy sources are needed to power public TV set, small pumping system for drinking water, refrigerator for health center, and other small electric appliances for households in remote areas. Fuel cells cost more initially than does the equipment now in widespread use for such applications - chiefly primary cells and diesel generator - similar to solar cells - but in many cases will be cheaper in the long run.

This paper discusses the cost comparison of energy generated by fuel cell power generation, solar cell, diesel generator, and the extension of electric grid. The site that is chosen for this study is Kenteng, an agricultural village. The results indicated that there are sufficient economic incentives for fuel cell power generation in this case if the projected goals of capital cost and heat rate can be met.

MODELLING OF POROUS GAS-DIFFUSION ELECTRODE STRUCTURES
FOR PHOSPHORIC ACID FUEL CELLS

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Progress in the development of optimized gas-diffusion electrode structures for phosphoric acid fuel cells requires a detailed understanding of the physical parameters operating within the porous electrodes. The challenge heretofore has always been to obtain a sufficiently detailed model that takes into account all of the kinetic, conduction (electronic and ionic), and diffusion parameters (gas-phase and liquid-phase), operating within the porous electrode structure. Previously the link between the theoretical models and real experimental data has not been sufficiently solid so that predictive capabilities for development of real electrode structures could be obtained. The present work has fulfilled that connection and exact descriptions of dynamic processes within porous gas-diffusion electrode structures have been obtained. The linkage between the experimental data and the theoretical model is very good.

Extensive computer modelling now is able to separate diffusivity parameters, reaction kinetic parameters, and conduction parameters within the gas-phase, the solid-phase, and within the liquid-phase. Comparisons of the model to experimental performance data are carried out using diagnostic gas mixtures of oxygen, air, 1% oxygen in helium, and 1% oxygen in nitrogen. The use of helium in a diagnostic gas mixture allows a separation of diffusivities for oxygen molecules in the electrolyte free regions of the electrode structure (the diffusivity of oxygen in helium is significantly greater than the diffusivity of oxygen in nitrogen).

By fitting the model of the electrode structure to the experimental performance data, numerical values have been obtained for all of the physical parameters operating within the electrode structure. An example of the success for fitting the theoretical model to the experimental data is shown in Figure 1. Here, the electrode contains 0.5 mg/cm^2 of Pt and is supported on an ungraphitized black (Vulcan XC-72). The data were obtained under galvanostatic conditions using BCL200 potentiostats with iR correction. It should be noted that the iR correction solves for the ionic resistance in the free electrolyte up to the face of the electrode, but does not solve for that resistance within the electrode structure. Operating characteristics are 190°C in 100% phosphoric acid with all gases humidified at 62°C with water saturation. This maintains the acid concentration. The data obtained in Figure 1 were for intermediate gas flow rates (80 cc/min. cm^2). At these flow rates, and at high utilization of the oxygen (either high current density or low oxygen concentration), the theoretical model correctly predicts that diffusion of oxygen molecules to the reaction sites produces voltage losses. Numerical values for the solution of the data set shown in Figure 1 will be presented. With an increase in the gas flow rate to 320 cc/min. cm^2 , this gas transport limitation no longer controls and the data set shown in Figure 2 is obtained. Here, mass transport of oxygen molecules to the reaction sites is no longer limiting and the major voltage loss becomes ionic conductions within the electrode structure. The numerical values for the computer solution are also provided.

Not only has the theoretical work, in conjunction with the experimental work, been able to define more exactly the operation of porous gas diffusion electrodes in real fuel cell environments, but it has enabled for the first time, a determination of the gradients within the electrode structure. These gradients are: the localized electrode potential within the electrode at the electrocatalyst sites; the oxygen concentration gradient within the electrode structure as a function of current density; and the localized reaction rate through the porous electrode structure.

Considerable success has been obtained for cathode structures. Numerical values have also been obtained for anodes operating on simulated reformed fuel mixtures. The modelling for the two electrodes (anodes and cathodes) are similar, although the electrode reactions are distinctly dissimilar.

Acknowledgement: This work was performed under the NASA Contract DEN3-350, R. King, Program Manager, NASA-Lewis Research Center, Cleveland, Ohio 44135.

CATHODE PERFORMANCE CURVE

POINTS: DATA; CURVES: MODEL 2

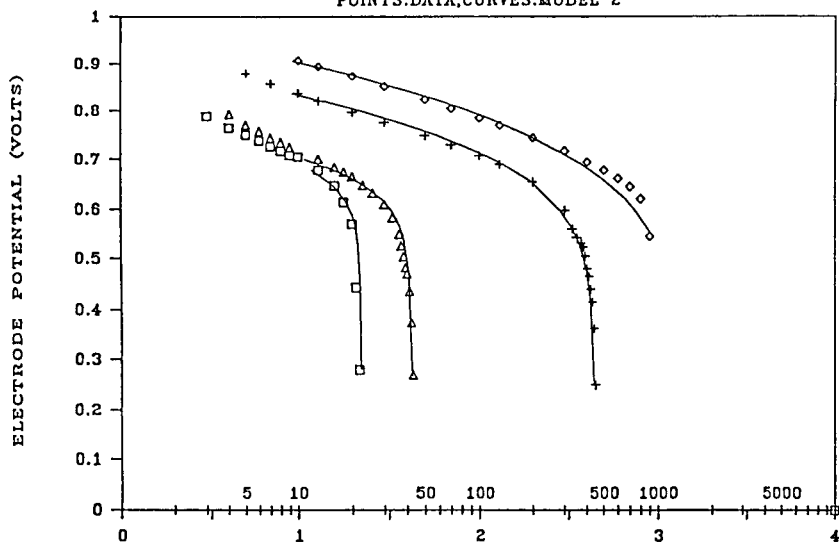


FIGURE 1. Experimental data on electrode AH180. Fitting parameters carried out according to the detailed model but locking the oxygen kinetic point on the third (10 mA/cm²) datum on the air curve,

□ O₂, N₂; y₁₀=0.01 + AIR ◇ PURE O₂ △ O₂, He; y₁₀=0.01

CATHODE PERFORMANCE CURVE

POINTS: DATA; CURVES: MODEL AH2-003

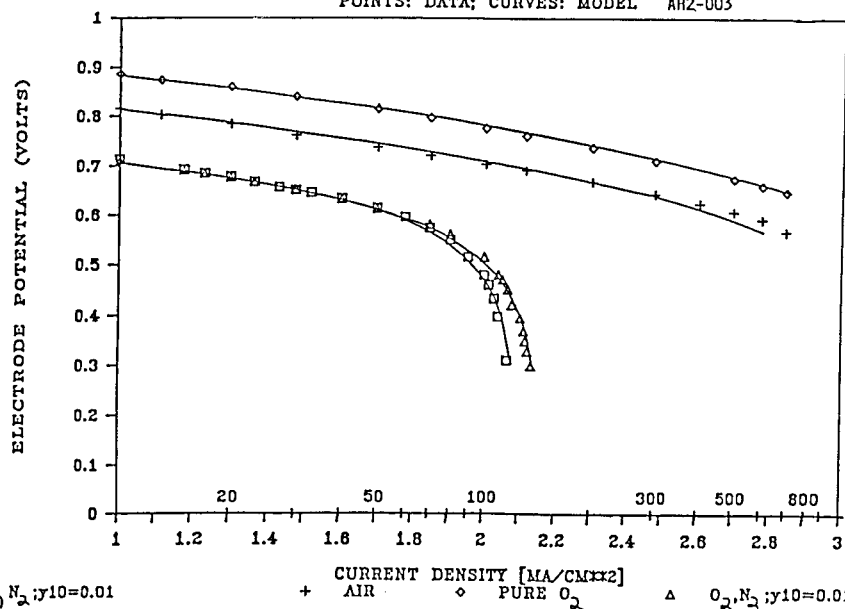


Figure 2. Experimental data on electrode AH2-003. Fitting parameters carried out to the detailed model. Comparison between experimental data and theoretical fitting (solid lines).

ASSESSMENT OF MOLTEN CARBONATE AND PHOSPHORIC ACID FUEL CELLS FOR UTILITY CENTRAL STATION APPLICATIONS

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Considerable government resources have been allocated to the development of fuel cells in recent years. Motivated by projected oil conservation, major programs were initiated in the late seventies to scale-up the Phosphoric Acid and Molten Carbonate fuel cells. Due to their high efficiency and their ability to operate on gasified coal, the fuel cells were seen as an excellent technology for future utility base-load plants.

Much has changed in the world economy since these programs were initiated. Energy prices have not risen as anticipated, and capacity projections by utilities have been revised downward. A reassessment of the economic viability of fuel cells for the intended applications is needed.

The difficulty of assessing fuel cells for power plant applications is in estimating the economics of such plants on a consistent basis with more mature technologies. Plant costs for a technology that is still in a development stage are often grossly underestimated simply because the need for certain types of equipment is not recognized. Then, when estimating the operating costs, developers tend to be optimistic in their performance assumptions.

Recognizing these sources of error we emphasized the engineering aspects of the cost analysis in the assessment reported here.

METHOD OF ANALYSIS

After selecting representative competing technologies we establish a process diagram for each system to be analyzed. The process is then simulated by computer to determine the system efficiencies, using identical performance assumptions for similar pieces of equipment. The steam turbine isentropic efficiency, for example, is assumed to be 85% in all systems that have equivalent steam conditions. Our code¹ calculates a complete energy and mass balance of the entire process, giving temperature, pressure, flow rate, and enthalpy at the inlet and exit of every piece of equipment in the process.

We then estimate the equipment costs for the plant using cost algorithms. Some of the algorithms are simple functions of size, consisting of a scaling exponent and a base cost number for a given size. However, for turbines, compressors, heat exchangers, and some other components we use algorithms that reflect operating conditions in addition to size. For a combustion turbine, for example, the flame temperature is part of the cost equation.

Operating and maintenance expenses are estimated using the rules recommended by the Electric Power Research Institute².

To obtain a cost of electricity estimate for each system, we amortize the plant cost over 30 years (except fuel cells which are replaced every 40,000 hours). Project and process contingencies are applied to the equipment costs in conformance with TAG². Fuel costs are calculated using a cost of coal of \$2.00/million Btu.

SYSTEM SELECTION

Existing utility central stations are either nuclear or use pulverized coal/oil combustion technology. A design representing state-of-the-art pulverized coal combustion plants was taken from the literature³ as our benchmark competing system.

A second competing system selected for our assessment is the gas turbine combined cycle operating on gasified coal. This technology is in the demonstration stage at Barstow, California, and represents a potential future power plant technology. Again, we took a system design from the literature.³

A system design for a 150 MW power plant based on phosphoric acid fuel cells was described by Brown⁴. Wellman Galusha gasifiers were used. Rather than correcting the system efficiency for the energy content of the coal fines which are produced by Wellman Galusha gasifiers, we decided to conceptualize a system for Texaco gasifiers. Our system design is discussed by V. Minkov elsewhere in this volume.

Molten carbonate fuel cells were evaluated by General Electric for utility central stations⁵. We used the the GE design initially for our assessment. As the analysis progressed, it became clear that the economics of a MCFC system could be considerably improved by decreasing the power output from the fuel cells relative to the power output from the bottoming section of the power plant. However, provisions had to be made to raise the inlet temperature and hence the efficiency of the combustion turbine. We eventually made several design changes which are discussed by V. Minkov elsewhere in this volume. The economics of the ANL designs were used for the assessment.

SYSTEMS ANALYSIS

To compare the four plants some groundrules had to be established. The size of all plants was set for a net electrical capacity of 575 MW. Illinois No. 6 coal with a higher heating value of 12 235 Btu/lb was specified as input. The performance of the major power producing or consuming components was taken as shown in Table 1. The fuel cell operating conditions assume about twice the power density than that usually considered (see V. Minkov's abstract for reasons).

The results of our thermodynamic simulation are summarized in Table 2. Although higher than for the competing systems, the efficiencies of the fuel cell systems are only in the upper thirties or low forties. The reason is that both fuel cell systems have substantial turbine capacities, because the economics of such systems are better than when most of the power is generated by the fuel cells (see Minkov's abstract for detail).

Cost of electricity estimates are listed in Table 3. Sulfur removal equipment for the two competing plants was sized to meet the New Source Performance Standard, and for the fuel cell systems to meet a specification of 1 ppm H₂S at the fuel cell inlet. For each of the systems, the various contributions to the COE are given. The two fuel cell plants are a bit more expensive than the competing technology, but have lower fuel costs.

SENSITIVITY ANALYSIS

The impact of plant size, fuel cost, and fuel cell stack life on the economic viability of the fuel cell systems was analyzed. The study showed

Table 1. Subsystem Component Performances

Steam Turbines	
Maximum inlet temperature & pressure	1000°F and 1800 psia
Condenser pressure	2.5 in Hg
High-pressure (>30 atm) turbine	
isentropic efficiency	0.85
Low-pressure (<3 atm) turbine	
isentropic efficiency	0.82
Intermediate-pressure (3-30 atm)	
turbine isentropic efficiency	0.86
Gas Turbine Isentropic Efficiency	0.87
Compressors	
Axial isentropic efficiency	0.82
Centrifugal isentropic efficiency	0.65
Pump Efficiency	0.75
DC to AC Inverter Efficiency	0.96
Plant Stack Exhaust Temperature	260°F
Phosphoric Acid Fuel Cells	0.66 V at 475 mA/cm ² and 45% fuel utilization
Molten Carbonate Fuel Cells	0.6 V at 400 mA/cm ² and 65% fuel utilization

Table 2. Power Summary

	Power (MW)			
	PC/FGD	GTCC	PAFC	MCFC
Fuel Cells	0	0	234	246
Expansion Turbine	0	25	33	53
Gas Turbine	0	768	335	636
Steam Turbine	612	216	175	101
Compressors	--	-327	-108	-362
Auxilliary Power				
including oxygen plant	-37	-107	-94	-99
Net Power	575	575	575	575
Net Efficiency (% HHV)	35.3	37.2	37.9	44.1

that a decrease of the design capacity from 575 MW(e) to 100 MW(e) would increase the competitiveness of the fuel cell systems by 4% over the competing combined cycle.

A change in coal price to \$1/10⁶ Btu would change the difference between molten carbonate fuel cell and combined cycle COEs by approximately 1%. For a coal cost of \$5-6/10⁶ Btu, the COE of the MCFC power plant will be 3-4% lower than that of the combined cycle.

Table 3. Cost Components of COE Estimates.

EQUIPMENT	Cost Components (mills/KWh)			
	PC/FGD	GTCC	PAFC	MCFC
EQUIPMENT				
Coal handling and preparation	0.81	0.98	0.88	0.78
Oxidant preparation	0.00	2.23	2.05	1.91
Gasification, cooling, and ash handling	0.00	3.55	3.47	3.00
Desulfurization	2.51	0.71	1.45	1.26
Iron oxide guard	0.00	0.00	0.14	0.13
Sulfur recovery and tail gas treating	0.00	0.24	0.24	0.21
Shift conversion	0.00	0.00	0.74	0.00
Fuel cells	0.00	0.00	1.67	2.04
Power conditioning	0.00	0.00	0.60	0.63
Steam turbine generator set	4.08	0.49	0.62	0.27
Gas turbine generator	0.00	1.84	0.74	1.06
Heat exchanger steam generation	3.80	1.10	1.09	0.93
Cooling tower	0.49	0.25	0.22	0.22
Electrical equipment and instruments	2.51	2.48	2.59	2.51
General facilities	2.10	2.00	2.34	2.09
AFUDC	1.53	1.49	1.77	1.60
Other capital charges	1.10	0.88	1.03	0.92
Fuel cell replacement	0.00	0.00	2.11	1.45
Subtotal	18.93	18.25	23.77	21.01
OPERATION & MAINTENANCE				
Fixed O&M	6.50	8.34	9.60	8.72
Variable O&M	1.62	2.09	2.40	2.18
Subtotal	8.12	10.43	12.00	10.90
FUEL	21.40	20.18	19.82	16.80
TOTAL COST OF ELECTRICITY	48.45	48.86	55.59	48.71

If fuel cell developers are not able to provide a cell with 40,000-hr life, the system economies will be affected significantly. For example, for a replacement every 20,000 hr instead of 40,000 hr, the COE of the MCFC system would increase by 5-6%, eliminating the competitive advantage of the MCFC relative to the combined cycle. Alternatively, if a stack life of 100,000 hrs were achieved, an additional 3% cost would be saved.

CONCLUSIONS

The COE estimates of all four technologies are rather close to each other, suggesting that the fuel cells are still viable contenders for future utility plants.

The balance would be shifted in favor of the fuel cells if sulfur emission regulations should become tighter. Further, the three gasification based plants are modular, each having 6 or 7 parallel trains, while the pulverized coal combustion plant was costed as one train. The availability of the modular systems may be higher because repairs and maintenance can be performed by shutting down just one of the trains.

Alternatively, if utility base-load plants should become smaller in the future, the gasification based plants would still have about the same COEs, whereas the pulverized coal combustion plants would become more expensive.

ACKNOWLEDGEMENT

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REFERENCES

1. M. K. Geyer and G. F. Berry, "The System Analyses Language Translator (SALT) User Guide," ANL/FE-85-3 (1985).
2. TAG, Technical Assessment Guide, EPRI-P-2410-512, May 1982.
3. "Design of Advanced Fossil Fuel Systems (DAFFS)," ANL/FE-83-9.
4. J. Brown, A. Murphy, P. Pietrogrande and J. Tien, "Site Specific Assessment of a 150-MW Coal Gasification Fuel Cell Power Plant," EPRI-EM-3162, November 1983.
5. K. M. Parker, "Development of Molten Carbonate Fuel Cell Power Plant," DOE/ET/17019-T3, September 1982.

A COMPARISON OF PHOSPHORIC ACID FUEL CELLS TO INTERNAL COMBUSTION ENGINE COGENERATION SYSTEMS AS SUPPLIERS OF UNINTERRUPTABLE POWER

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The US Navy operates a number of facilities around the world which require highly reliable or uninterruptable power. The conventional method for satisfying this need is to install a number of back-up engine-driven generators and power conditioning equipment. The number of generators is dictated by the level of redundancy needed to meet the reliability goal. The conventional solution to this problem dictates that a large capital investment remains unused most of its life. The Navy Civil Engineering Laboratory commissioned Arthur D. Little, Inc. to study the economic feasibility of using the stand-by equipment in a cogeneration mode.

In this study, ADL used a lifecycle cost-benefit analysis to compare a phosphoric acid fuel cell based system and two internal combustion engine based packaged cogeneration systems to the conventional uninterruptable power system (UPS) option. The key features of the three cogeneration systems are summarized in Table 1. Most of these data

TABLE 1
COGENERATION SYSTEM DATA

	Fuel Cell	Thermo Electron CM-60	Cogenic M-120
Unit Capacity KW	50	60	120
Capital Cost (Installed) \$/KW	1460	800	1000
Maintenance \$/KW-h	0.009	0.015	0.015
Hot Water Temperature °F	160	220	210
Steam Pressure PSIG	60	N/A	N/A
Fuel	Nat. Gas	Nat. Gas	Diesel
Full Load Efficiency (%)			
Electrical	33.4	26	29
Total	67.6	83	81
Useful Life (yr.)	25	10	10
Unit Availability (%)	97	97	97

were supplied by the manufacturers of the respective systems. Most fuel cell data were provided by United Technologies Corporation. The fuel cell cost is an ADL estimate for moderate production levels. The baseline system components are summarized in Table 2. These are ADL estimates based on a 1980 NASA study.

TABLE 2
BASELINE SYSTEM COMPONENTS

Baseline System	Component Capacity	Cost (1983 Dollars)
Centrifugal Chiller	360 Ton	121,000
Boiler, Gas Fired	14 MMBTU/hr	147,000
Domestic Hot Water Tank	10,000 gal	18,000
Air Handler Units (4 units)	40,000 CFM/unit	54,000/unit
Cooling Tower	360 Ton	36,000
Conventional UPS*	250 KVA	301,000

* (Includes: batteries, rectifier, inverter, generators and switch gear)

The basis of comparison was a simulated hospital building in Washington, D.C. Cogenerated thermal energy was used to meet service hot water and space conditioning loads while generated electricity satisfied both equipment and lighting loads. All economic analysis used constant 1983 dollars. Fuel prices were based on 1983 DOE estimates and inflation rates were based on US Bureau of Labor and Statistics data.

The simulation used the Arthur D. Little, Inc. Cogeneration Computer Model. The model starts with hourly loads for space heating, space cooling, service hot water and electricity (non HVAC). The building hourly HVAC equipment operation is modeled to determine hourly fuel and electricity consumption. The hourly figures are then totaled to determine the annual consumption and these results are passed to an economic model which uses realistic energy price structures and inflation rates to calculate a lifecycle total cost and savings. The economic results are then used to optimize the mix of HVAC equipment such that the combined cogeneration/HVAC system yields the greatest net lifecycle savings. The economic results are summarized in Table 3.

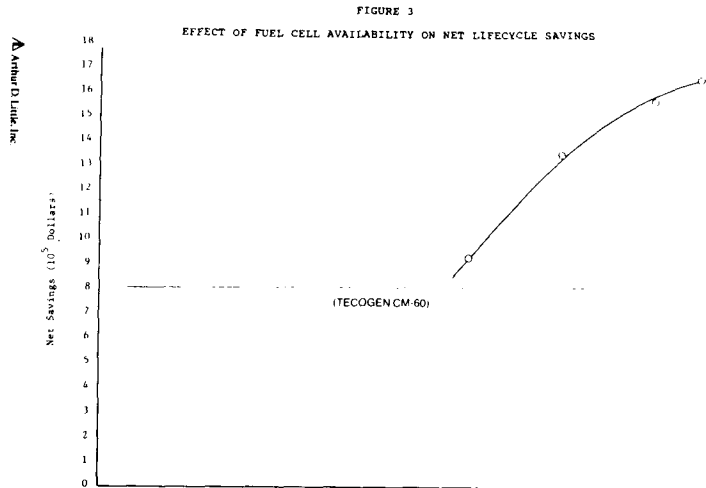
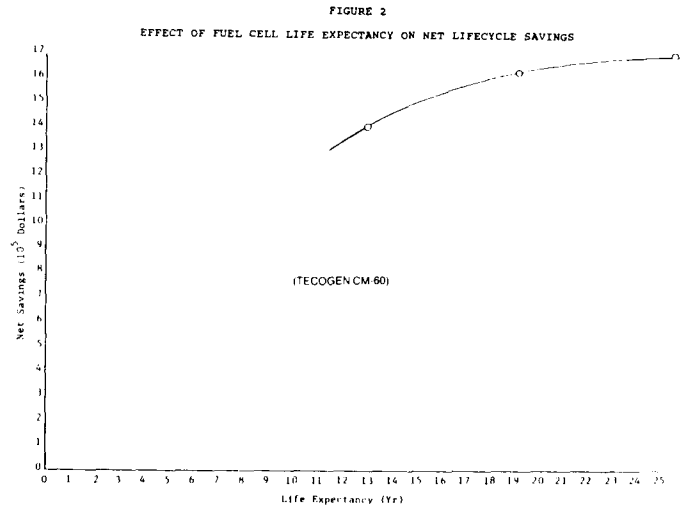
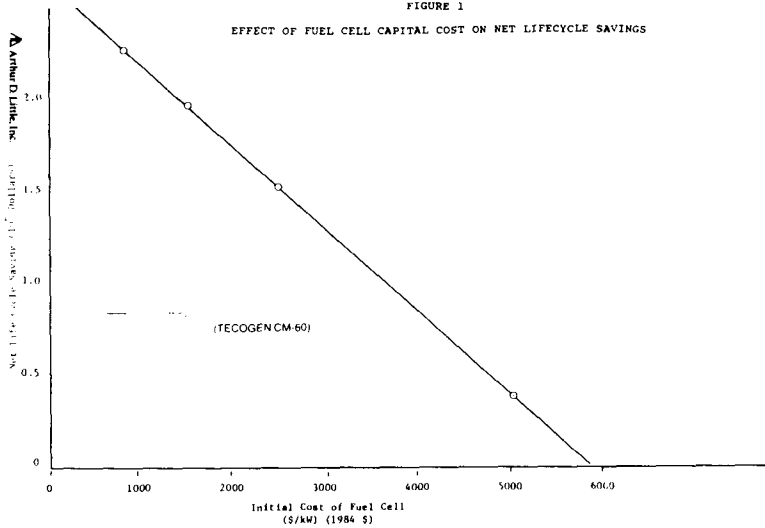
TABLE 3
ECONOMIC PERFORMANCE OF OPTIMIZED SYSTEMS

	Fuel Cell	CM-60	M-120
Total Lifecycle Cost (10 ⁶ Dollars)	6.32	7.47	8.67
Net Lifecycle Savings (10 ⁶ Dollars)	1.95	0.80	(4.11)
Savings/Investment Ratio	6.12	2.07	5.85
Annual Energy Savings/Cap- ital Cost Ratio MBTU/yr/\$	7.15	4.55	44.1

These results show that, of the three systems, the fuel cell has the lowest lifecycle cost and greatest net lifecycle savings. One of the IC engine based systems also shows positive lifecycle savings while the other does not. The poor economic performance of the Cogenic unit results from the large unit capacity and the number of units needed to meet the redundancy requirement for the system. This combination of factors resulted in a great deal of unused generator capacity, and, as a result, the system capital cost was not recovered.

The sensitivity of the results to three key assumptions was also studied. Figure 1 shows that the preference for the fuel cell over the CM-60 system disappears when the installed cost of fuel cells approaches the current value of \$4,000/KW. Figure 2 shows that the preference for fuel cells is relatively insensitive to cell life expectancy because future replacement costs are discounted and have little impact on the total present value cost. Figure 3 shows that the results are sensitive to fuel cell availability in that if availability were reduced to about 55% the advantage of fuel cells would be neutralized. Availability data from the GRI sponsored field test may reveal the importance of this result.

In conclusion, on-site cogeneration can be a cost-effective way to supply uninterruptable power when it is required. In addition, the fuel cell is the preferred power source for the application studied. The preference for fuel cells, however, is strongly dependent upon assumptions regarding capital cost and unit availability. If an alternate set of assumptions were used, the advantage of fuel cells could be eliminated.



SITE SPECIFIC FUEL CELL/COAL GASIFICATION PLANT DESIGNS

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Ebasco Services Incorporated was commissioned by the Department of the Army (DOA) to study whether fuel cell technology could be combined with a coal gasification cogeneration program at specific sites where coal conversion potential existed. The objective of the program was to determine if the fuel cell/coal gasification concept would lead to increase in energy efficiency, higher conversion standards, and economic benefits sufficient to attract third-party equity investment to off-set a significant portion of the funds required from the DOA.

This paper reports on the designs of the fuel cell/coal gasification plant for the four sites chosen. Each site-specific design took into account the indigenous coal supply alternatives, land use, present and future thermal-electric demand, local energy markets, climate, esthetic requirements and other variables. System designs were developed around an 11.6 MW fuel cell module being developed by United Technologies Corporation (UTC) and 7.5 MW fuel cell module being developed by Westinghouse.

The four plant sites were:

- Georgetown University Campus, Washington, D.C.
- Scranton Army Ammunition Plant, Scranton, Pa.
- Fort Hood, Texas
- Fort Greely, Alaska

BASE SYSTEM DESIGN

A functional block diagram of the base system is shown in Figure 1. Coal is gasified by two 50% capacity air blown atmospheric single stage Wellman-Galusha gasifiers. Wellman-Galusha gasifiers were chosen because of their commercial availability in sizes compatible with this project and their ability to handle a large range of coals. Feed coal requirements were based on producing sufficient fuel gas to meet the fuel cell manufacturer's design input.

The hot gases are scrubbed of particulates, ammonia and volatile tars and oils. The tars and oils are recovered for their heating value. The cooled gas is compressed and directed to a CO shift section where hydrogen concentration of the gas is increased to the range of 30% to 35%.

The gas contains sulfur compound impurities which must be reduced to less than 5 ppm to prevent long term degradation of the fuel cell electrodes. A liquid oxidation Stretford type of removal process was utilized. Elemental sulfur was recovered for offsite sale.

The cleaned gas is fed to a fuel cell section consisting of either one 11.6 MWe fuel cell module designed by UTC or one 7.5 MWe fuel cell module designed by Westinghouse. Due to

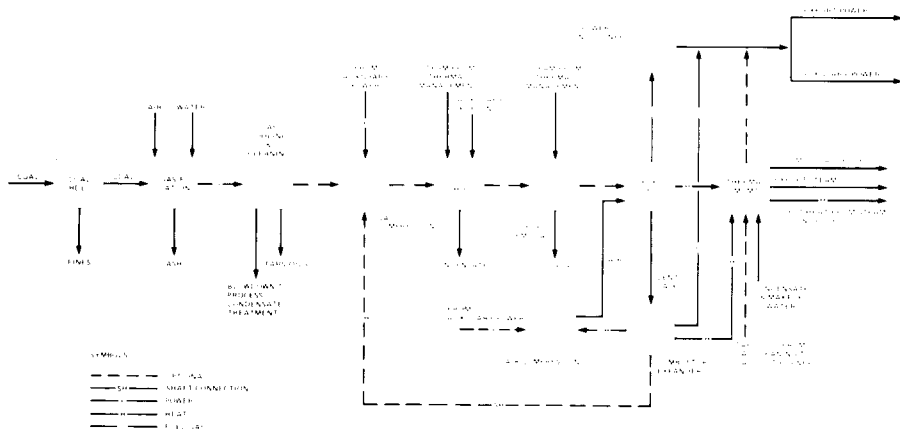


FIGURE 1 FLOW DIAGRAM

the different cooling schemes and operating temperatures, the thermal management system (TMS) for the two fuel cell vendors were different.

THERMAL MANAGEMENT SYSTEM

The Thermal Management System (TMS) receives and manages heat from the fuel cell electrochemical reaction, from the catalytic combustion of fuel cell vent gases and from any process heat source including by-product tars and oils.

Energy of the fuel cell vent gases is recovered by catalytic combustion of the mixture which drives a gas expander prior to being routed to a heat recovery steam generator (HRSG). Steam is obtained from both the fuel cell coolant loop and the HRSG. Some of this steam is diverted for use in the CO shift process and for feedwater heating. The remaining or "net available steam" is apportioned between the production of additional power by a steam turbine-generator and for export to the site customer.

Firing the tars and oils produced during gasification in a burner located upstream of the HRSG raises the expander exhaust gas temperature approximately doubling the heat recovery. However, depending on the available market for tars and oils, this by-product may be sold rather than burned.

The Westinghouse TMS has additional equipment because the fuel cell is air cooled. There are two separate steam systems: low pressure served by the cooling air HRSG and high pressure served by the combustion gas HRSG. Steam is also used to drive the cooling air circulator and cathode air compressor.

PLANT PERFORMANCE

A fuel cell cogeneration system design was successfully integrated into the local plant at each site, and required about 2 acres of land excluding coal storage. The performance of the six plant designs are summarized in Table 2. The thermal efficiency, steam and electric output vary; and may be understood by examining the TMS design and the properties of the coal utilized.

Thermal Efficiency - The biggest effect on thermal efficiency was the disposition of tars and oils, and the plant electric to thermal (E/T) ratio. Thermal efficiencies were lowest at those sites where tars and oils were sold instead of burned or not produced because of the coal type. Plant efficiency increases as steam is emphasized over electricity production, thereby avoiding the electric conversion losses. Steam production is increased to meet the customers needs or due to the firing of the tars and oils. However, if electric rates are high enough, opting for the lower efficiency plant having greater electrical output may well provide the higher return on investment.

Coal Properties - Coal properties affect system performance largely by determining the composition of the raw gas and the quantity of by-product tars and oils. Depending upon the amount of hydrogen and CO produced in the raw gas, more or less steam must be supplied to the CO shift process. Tar and oil production depend upon the coal volatile matter and are an important energy source for the system when fired as a supplementary energy source. The gasification of anthracite produced the lowest amount of hydrogen and consumed the largest amount of steam while producing no tars for supplementary firing.

Fuel Cell Gas Flow - Gas flow rates to the fuel cell anode and cathode depend on the coal properties and the fuel cell manufacturer's design. In the anthracite fueled Scranton system, anode gas flow is about 35% more than the Fort Hood lignite design. This results in higher internal power demand as well as higher piping and gas processing costs. Similarly, flow of compressed air to the cathode is a function of fuel cell oxygen utilization efficiency. A higher efficiency requires less air flow and for the same cathode pressure, less compressor work per kw.

TABLE 1 - PERFORMANCE SUMMARY

	<u>WASH. DC</u>	<u>SCRANTON, PA</u>		<u>FT. HOOD, TX.</u>		<u>FT. GREELY</u>
Fuel Cell*	UTC	UTC	W	UTC	UTC	W
Coal Type	Eastern Bituminous	Eastern Bituminous	Anthracite	Lignite	Sub bitumin-C	Sub bitumin-C
Coal Input to Gasifier, tpd	172.2	172.2	91.5	286.3	244.8	175.6
Gross Power, MW ac	14.4	15.9	8.8	14.6	14.0	9.9
Auxiliary Power, MW	3.6	3.6	4.1	3.5	3.8	4.8
Net Power, MW	10.8	12.3	4.7	11.1	10.2	5.1
Gross Steam Output, PPH	38,100	79,100	36,400	66,800	62,400	46,300
Steam for internal use PPH	21,500	29,800	33,500	25,500	32,300	32,600
Net Available Steam, PPH**	16,600	48,300	2,900	41,300	30,100	13,700
Tars and Oils, PPH	2,163***	2,163	0	1,434	1,224	878
Thermal Efficiency, o/o	23.8	27.7	19.0	36.9	38.9	28.9
E/T Ratio, KW/mmBtuh	5,400	1,270	1,600	540	433	370

* UTC: United Technologies, Inc. W: Westinghouse

** Available either for export or power generation

*** Tars and oils sold at Washington, D.C. site instead of burned

DEVELOPMENTS AND APPLICATIONS OF PHOSPHORIC ACID FUEL CELL POWER PLANT MODELS

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Under DOE support, NASA Lewis Research Center (LeRC)/Cleveland State University (CSU) have developed simulation models capable of predicting the Phosphoric Acid Fuel Cell (PAFC) power plant system performance under steady and transient states, and of designing the configuration of components and the synthesis of systems optimally. The nature of these models and their applications are presented.

Two kinds of computer models are developed. One is the system model and the other is the engineering model. The system or "single-stage" model calculates the material and energy balances and the physical and chemical properties of the streams at one operating condition, such as the mean temperature and pressure. The engineering or "multi-staged" model, which usually is solved by the finite-difference method, handles the balances and properties at different sections.

There are four areas of application that the developed models could operate in. For the system model these are :

- (1) To use on the system conceptual designs, where the layouts of power plant systems, with various fuel processors (i.e., coal gasifiers, methane steam reformer, and shift converters), are defined.
- (2) To perform, being combined with cost and optimization models, the trade-off and sensitivity analyses of system synthesis.

For the engineering model these are :

- (1) To simulate the designed system's performance in the transient state (i.e., load changing period).
- (2) To optimize the component configurations and operating conditions.

The application of system model in the design of coal gasifier/PAFC integrated systems will be shown at the Poster Session of this Seminar, then illustrations presented here will be on engineering analytic models.

For the engineering model, two major component models in the PAFC system are presented here: one is the PAFC stack, and the other is the methane-steam reformer.

PAFC Stack

A generic PAFC stack model to calculate the current density and temperature distributions at steady state in the stack was developed. A semi-empirical formula to estimate the polarization curve was used. A symmetrical set of cell plates

and cooling plates is analyzed; this set has one half of a cooling plate and a half number of cell plates sandwiched between every pair of cooling plates. This generic stack model can be used for simulating the performances of various kinds of coolant, configurations of cell plates, flow patterns, and cooling schemes. Two usages of this model have been applied: one to improve the cooling effects (the results will be presented in the Poster Session of this Seminar); the other to predict the input conditions of coolant for various current density (CD) operations in a water-cooled PAFC stack. Summary of the results for various CD operations is presented in Table 1. As expected, the higher current density operation will result in lower efficiency and higher power. The trade-off between stack cost and fuel cost should be performed to determine the optimal CD.

A dynamic model to handle air-cooled PAFC stack at load changing period was also developed. Simulated results using this model are shown in Figure 1. Transient temperature profiles on the symmetric (middle) cell plate are shown for ramping of the stack output from 100% to 47% of full load. The initial steady state (ISS) and final steady state (FSS) temperatures are given, plus an intermediate calculation at 10.152 seconds. Analyses of these typical cases can determine stable ramping rates and dead times for the power plant control purposes.

Reformer

A generic kinetic distributed reformer model was developed to simulate the performance of steam reformer at steady state and transient state. Various features of the reformer can be handled in this model, which include straight-through flow of feed gas, regenerative operation (with or without shift converter catalyst), and fixed wall temperature profile types. One generic regenerative reformer diagram and simulation results for a steady state performance are shown in Figure 2.

Transient Responses of PAFC System (Ref. 1)

By combining all the unit operation models, one can simulate the PAFC power plant system at steady and transient states. The system considered here is a Westinghouse 7.5 MW air-cooled PAFC powerplant using methane as the fuel. One simplified system diagram is shown in Figure 3. In this study the load is step-changed from full to 90%. Several assumptions were made: changes of PAFC operating pressure and temperature are assumed to follow the constant phosphoric acid concentration line (Ref. 2); in addition, two reservoirs for FC fuel and oxidant are added to offset the transport lag in the fuel processor subsystem. The variables that can be manipulated for control of the system are the input flow rates of fuel (methane) and oxidant (air), which are changed in proportion to the power change. Figure 4 shows the temperature changing rates at

In conclusion, with these developed models one can predict the PAFC power plant system performance under steady and transient states, as well as design the configuration of components and the synthesis of systems optimally.

1. Lu, C.Y., "Transient Responses of Phosphoric Acid Fuel Cell Power Plant System," Ph. D. Dissertation, CSU, Dec. 1983.
2. Pierce, B.L., "PAFC Power Plant Control Mode Trade Study," Westinghouse Report, DRM: 095, Dec. 1981.

Constraints: T_{max} < 460 °F T_{ave} = 405 °F Steam < 10%

Operating Conditions:

Operating Pressure: 120 psia Utilization of Hydrogen: 85%

Utilization of Oxidant: 70% Cell Area: 10ft²

Input Fuel Compositions: 0.546 H₂, 0.007 CO, 0.405 CO₂, 0.023 H₂O, and 0.018 N₂.

Figure 10 consists of two vertically stacked graphs showing the variation of temperature (T in $^{\circ}\text{K}$) versus time (t in sec). Both graphs show a linear increase in temperature over time.

Top Graph (FSS):

- Y-axis: $T : ^{\circ}\text{K}$
- X-axis: $t \text{ in sec}$
- Initial temperature: 458
- Final temperature: 473
- Current: $i = 0.325 \text{ A/cm}^2$
- Voltage: $V = 0.688 \text{ Volt}$
- Time: $\theta 10.2 \text{ sec.}$

Bottom Graph (RSS):

- Y-axis: $T : ^{\circ}\text{K}$
- X-axis: $t \text{ in sec}$
- Initial temperature: 443
- Final temperature: 443
- Current: $i = 0.1353 \text{ A/cm}^2$
- Voltage: $V = 0.775 \text{ Volt}$
- Time: $\theta 10.2 \text{ sec.}$

Load Change from 100% to 47.

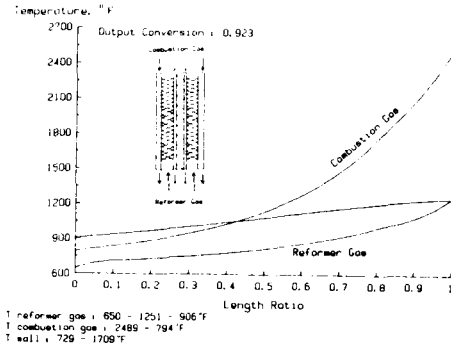


Figure 2 Simulated Temperature Profiles of a Regenerative Steam Reformer

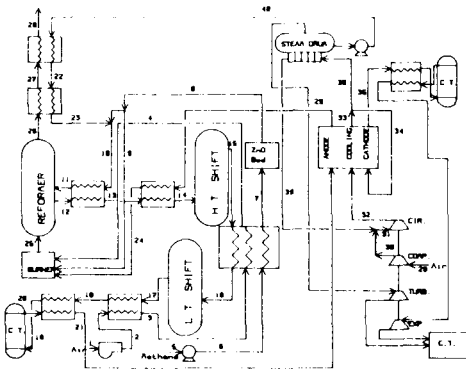


Figure 3 7.5 MW Air-Cooled PAFC Powerplant Diagram for Transient State Study

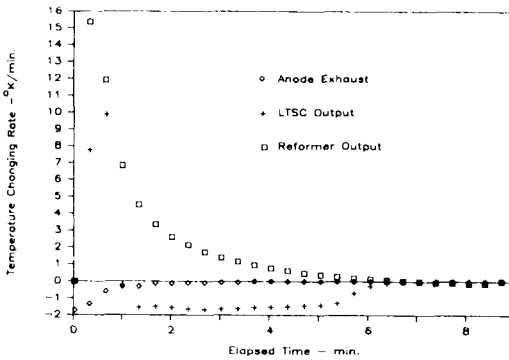


Figure 4 Temperature Changing Rate at Transient State (Load Changed from Full to 90%)

FUEL CELL AND FUEL CELL/BATTERY HYBRID
POWER SOURCES FOR VEHICLES

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Fuel cells potentially can provide the range advantages of an ICE in a power system but with clean and quiet operation. Because a fuel cell will deliver power as long as fuel and air are supplied, the range is limited only by the amount of fuel carried. Proton exchange membrane (PEM) fuel cells show the most promise for use in passenger vehicles. The features of a PEM system will be discussed. Decomposed methanol is proposed as the fuel. However, the system may be limited in its ability to respond to severe load transients because of the thermal inertia of the fuel processing system. Furthermore, in order to be able to satisfy the large peak power requirements in automotive duty cycles, the fuel cell system may require cooling, fuel delivery, and reaction air supply subsystems sized to meet peak power conditions, thereby worsening weight and volume considerations. For these reasons and because of improvements in battery performance over the past several years, a fuel cell/battery hybrid power source feasibility study was carried out based on phosphoric acid and PEM fuel cells in conjunction with advanced lead-acid and nickel-zinc batteries. Fuel cells and batteries complement each other for the electric propulsion automotive application, providing long range, peak acceleration power, and recharge capabilities. As a hybrid configuration, the fuel cell/battery system may offer the advantage of reduced complexity, weight and volume compared to ICE/battery hybrids because the fuel cell and battery both have electrical outputs, eliminating the need for complex mechanical-electrical couplings. Results of this hybrid assessment will be discussed.

FINANCIAL AND STRATEGIC BENEFITS OF FUEL CELLS

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Introduction

The conventional means employed by utilities to evaluate which generation technology to use focuses on production cost comparisons and the present value of future revenue requirements (PVRR) necessary to cover the cost of production, return of capital investment and the approved rate of return to the utility. Utilities use sensitivity analysis to determine how much the study results will change due to some incremental change in input data. This type of analysis focuses attention on the input variables and the probability that one set of them will more likely occur than another set. Pick which assumptions will most likely occur and the corresponding mix of generation units that produce the lowest PVRR is most likely seen as the best choice.

But utilities have found that this approach can lead to plant construction programs that are lowest cost in the long term (20 to 30 years) if the assumed conditions prevail, but that are, in the near term, terribly inflexible and financially disastrous in times of uncertainty if some conditions change radically such as load growth, cost of plant, or construction lead times. It's not a question of planning to meet what you think might happen; it's a matter of planning to be flexible enough to respond to a number of situations that you don't think will happen, but that are too important to ignore.

The high efficiency fuel cell with its modular character, small size and short lead time was seen as a technology that would give utilities the financial flexibility they need in times of uncertainty where the wrong decision could ruin the company and/or cause excessive burdens on the ratepayer.

EPRI and the Fuel Cell Users Group (FCUG) therefore formed a task force of utility planners (system, financial and corporate) to assist EPRI in identifying and quantifying the financial and strategic benefits of applying fuel cells.

Approach

The utility planners developed a 5000 MW hypothetical utility with realistic existing generation, load, plant costs, etc. Optimal 20 year generation expansion plans

were developed with fuel cells and without fuel cells, both under conditions of certainty, that is, conventional analysis. These served as base cases for future reference. Then the effects of uncertainty in capital cost, lead time and load growth were determined and compared against the base case. Specific indicators of financial significance were used by the task force for comparison to the reference cases. Such indicators are total construction expenses, required external financing, total capitalization, interest coverage ratio (by how much do pretax earnings exceed fixed charges like interest) and AFUDC to common stock earnings (how much is allowance for funds used during construction--no cash earnings--as a percent of total earnings).

The base case was:

1. Most likely scenario.

The cases of uncertainty were:

2. Coal plants cost one third more than expected.
3. Coal plants take two years longer to build than expected.
4. Load grows more quickly than expected.
5. Load grows more slowly than expected.
6. Fuel cells cost fifty percent more than expected.

In each case the unexpected condition is typically noted by the planner several or more years into the 20 year expansion period. The planner reacts to the unexpected and reoptimizes the plan. The study results provide objective, measurable values of indicators used by utilities to measure how things are going both if fuel cells were available and if they were not available.

Results

The results of each scenario were:

1. Most Likely Scenario. This scenario sets forth base case assumptions and compares a conventional capacity mix--coal units and combustion turbines (CTs)--with an alternative plan that also includes fuel cells. By the year 2008, fuel cells come to constitute 10 percent of capacity. The substitution of fuel cells over a 20-year planning horizon reduces the present value of revenue requirements by \$57 million. The average total price of electricity in the Fuel Cells Case is higher than in the Conventional Case in the early years, but lower by a greater amount in later

years. Largely because of the postponement of coal units, the Fuel Cells Case, compared with the Conventional Case, lowers overall construction costs by \$137 million and total capitalization by \$347 million. Over the length of the planning period, external financing declines, and two common indicators of financial condition improve--interest coverage ratio and the ratio of AFDC to earnings available for common stockholders.

2. High Coal Capital Cost Scenario. In the midst of coal unit construction, the utility realizes that capital requirements have been underestimated. The substitution of fuel cells allows the postponement or cancellation of coal units. The Fuel Cells Case reduces the present value of revenue requirements by \$131 million. The substitution of fuel cells also lowers total capitalization by 20 percent, or \$2.7 billion. Indicators of financial health follow the same pattern as external financing requirements. Interest coverage and quality of earnings improve in all years but four.
3. Long Coal Lead Time Scenario. While building new coal capacity, the utility finds that construction takes more time than anticipated. In the Conventional Case, longer coal lead time means higher financing costs, and combustion turbines are used to make up the shortfall in capacity. Using fuel cells reduces the present value of revenue requirements by \$73 million. Over the planning period, total capitalization in the Fuel Cells Case declines \$1.95 billion from the Conventional Case. Again, the utility's quality of earnings and interest coverage ratio both improve, compared to the Conventional Case, from the substitution of fuel cells.
4. High Load Growth Scenario. In the Conventional Case, the utility, having underestimated demand, quickly adds combustion turbine capacity and initiates coal unit construction. In the Fuel Cells Case, fuel cells provide a much more economical alternative than CTs at medium capacity factors to meet the capacity shortfall. Fuel cells reduce revenue requirements by \$154 million from the Conventional Case and reduce prices in every year they operate. The fuel cells' high capital costs relative to CTs prevent financial benefits from appearing until late in the planning period; but fuel cost savings more than compensate for the difference. Furthermore, the fuel cells' short lead time also compensates for initial investment and helps to maintain healthy financial indicators, as in the previous scenarios.

5. Low Load Growth Scenario. In the Conventional Case,

the utility responds to lower than expected demand by cancelling CTs but reserve margins still climb to 37 percent. In the Fuel Cell Case, early fuel cells are cancelled. The present value of revenue requirements in the Fuel Cells Case is \$51 million lower than in the Conventional Case. External financing is lower in the Fuel Cells Case in the early years, but higher later on, while total capitalization is consistently lower. The benefits of fuel cells for other financial indicators are strongest during the period of greatest uncertainty.

6. High Fuel Cell Capital Cost Scenario. In this scenario, the risks of a new technology are encountered as fuel cell capital costs rise beyond expectations, causing the present value of revenue requirements in the Fuel Cells Case to exceed the Conventional Case for the first time. The average price to consumers is also consistently slightly higher. Nevertheless, external financing and total capitalization still are both reduced, and the other financial indicators are superior to the Conventional Case in most years.

General Observations

The most salient of the quantified results from the six scenarios are summarized in Figures 1, 2, and 3. The reported values reflect the following characteristics of fuel cells relative to CTs and coal units:

- o In general, fuel cells pose less of a financial burden than coal units because fuel cells have shorter lead times, are built in smaller sizes, and are less capital intensive.
- o Fuel cells can help utilities hedge against uncertainties such as load growth because of their short lead times. In case of lower-than-expected load growth, fuel cells can be canceled more easily than coal plants and as easily at CTs. In case of higher-than-expected load growth, fuel cells can be added more quickly than coal plants and are much more economical to operate than CTs at intermediate capacity factors.
- o Fuel cells also reduce technological risk exposure. Once again, fuel cells' modularity and short lead time mean that they do not require as much commitment as a coal plant; this advantage lowers the impact of unforeseen adverse changes in cost, performance, leadtime, or regulatory requirements.

It is important to recognize the relative size of the fuel cell program and its benefits to this test case utility. To put the results in Figures 1 and 2 into context, the

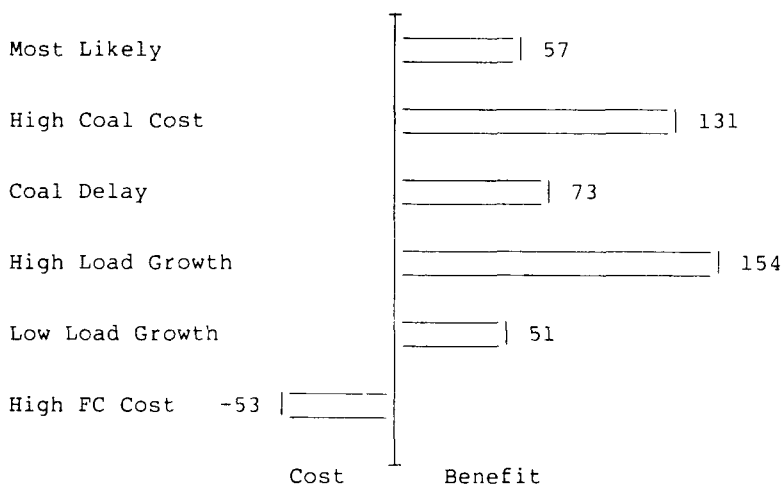


Figure 1. Reduction in Revenue Requirements
(millions of 1984 discounted dollars)

present value of revenue requirements is reduced \$57 million (in the Most likely scenario) from \$18.6 billion. Total capitalization is reduced \$347 million from \$10.5 billion in the year 2008. While these reductions may seem small when compared to the entire company, they are not insignificant when compared to the scale of the fuel cell program--the present value of the fuel cell capital expenditures is approximately \$250 million.

Perhaps the most important finding of this research is that the benefits of fuel cells generally increase under uncertainty. Figure 1 shows that the economic benefits (as indicated by the reduction of revenue requirements) are greatest for unexpected load growth, when the short lead times of fuel cells have a high value. Revenue requirements increase only for the unexpected increases in fuel cell capital costs.

The financial benefits of fuel cells are even more robust as shown in Figures 2 and 3. In every scenario, including High Fuel Cell Capital Cost, fuel cells lead to lower financing requirements. For three of the six scenarios, the capitalization reductions are dramatic--\$1.1 billion to \$2.7 billion. Similarly, the quality of earnings (summarized here by the average improvement in the ratio of AFDC to earnings during the three worst years) improves for all scenarios, again including the case of high fuel cell capital cost.

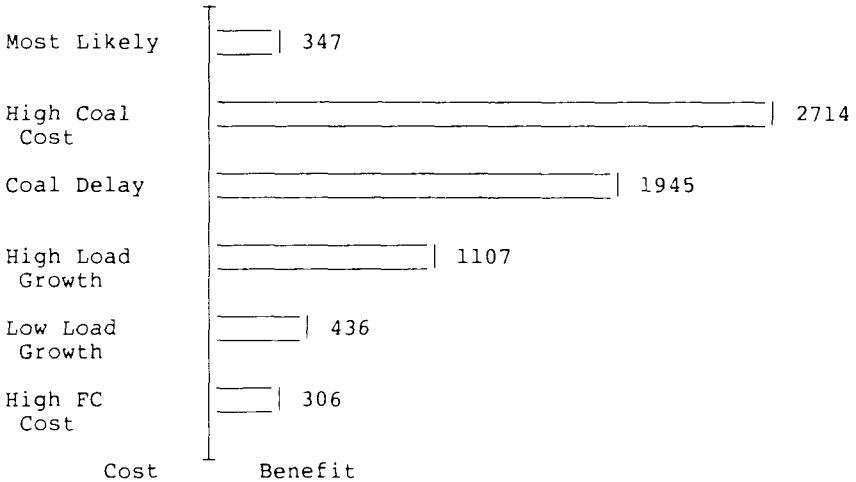


Figure 2. Reduction in Total Capitalization (millions of dollars)

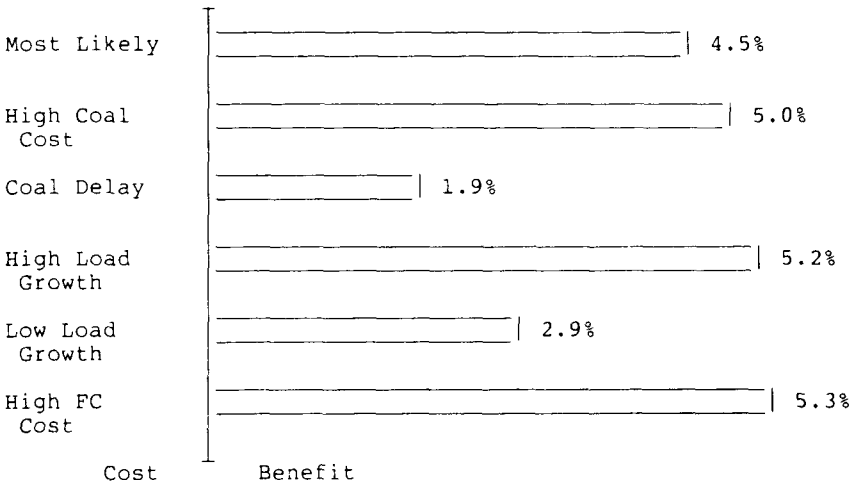


Figure 3. Improvement of Worst AFDC/Earnings Ratios (average of three worst values)

Conclusions

The benefits of fuel cells, which recommend them to the consideration of electric utility managers planning for an uncertain future, are both financial and strategic.

- o The introduction of fuel cells is likely to reduce the need for external financing and to improve traditional measures of financial condition.
- o The introduction of fuel cells can help a utility manage better in the face of unexpected changes in planning forecasts. The greater the uncertainty, the greater the expected benefits of fuel cells. In addition, the downside risks are small.

References

1. EPRI Final Report EM-4511, April 1986.
2. IAE International Symposium on Fuel Cell and Advanced Battery, January 21-22, 1985, Tokyo, Japan.
3. Credit Overview by Standard and Poor, August 1983.

COALBED METHANE AS A FUEL FOR FUEL CELL POWER PLANTS

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On January 31, 1986, Southern Company Services (SCS), along with Kaneb Services and The University of Alabama School of Mines and Energy Development (SOMED), completed a test project that included the first operation ever of a fuel cell with coalbed methane fuel. The test verified that onsite fuel cells are highly efficient and capable of using the large (approximately 800 trillion cubic feet) U.S. resource of coalbed methane (Figure 1). The results were achieved during a 16-month test of a 40-kW phosphoric acid fuel cell at The University of Alabama Student Recreation Center in Tuscaloosa, Alabama.

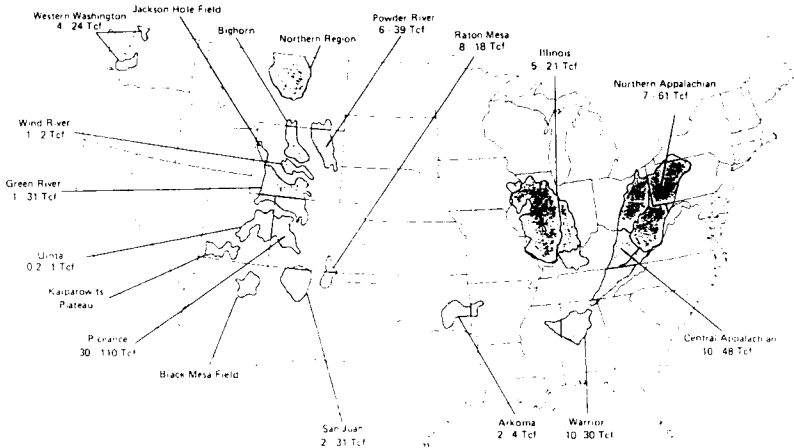


Figure 1 Coalbed Methane Resources In The United States

The SCS fuel cell was part of the 40-kW Onsite Fuel Cell Field Test Program sponsored by the U.S. Department of Energy, the Gas Research Institute, and International Fuel Cells (the fuel cell manufacturer). In this program, 46 fuel cells were tested by 37 participants at 42 sites in the U.S. and Japan. Unconventional fuels such as coalbed methane received special emphasis in testing by two of the program participants.

SCS, Kaneb and SOMED funded the installation, operation, and maintenance of the fuel cell at the recreation center. Several unique features made the recreation center a particularly attractive test site, including its design and construction as an energy efficient building incorporating aquifer thermal energy storage and passive solar principles. However, of most importance was the presence nearby of two coalbed methane production wells which support ongoing University of Alabama research programs to recover natural gas from coal seams located some 2000 feet beneath the campus. These wells provided the opportunity for operation of the fuel cell on coalbed methane.

Nine months of site energy consumption data were collected to confirm the recreation center's compatibility with the 40-kW fuel cell. The unit was delivered on August 30, 1984 and installation proceeded with connection to the electric grid and interface of the fuel cell heat recovery equipment to the building hot water system (Figure 2). The first successful startup was achieved on October 4, 1984 and the fuel cell was operated for a total of 8011 hours. A 68-percent operating availability was achieved until operational activities were terminated on January 31, 1986. The fuel cell was returned to International Fuel Cells on February 17, 1986.

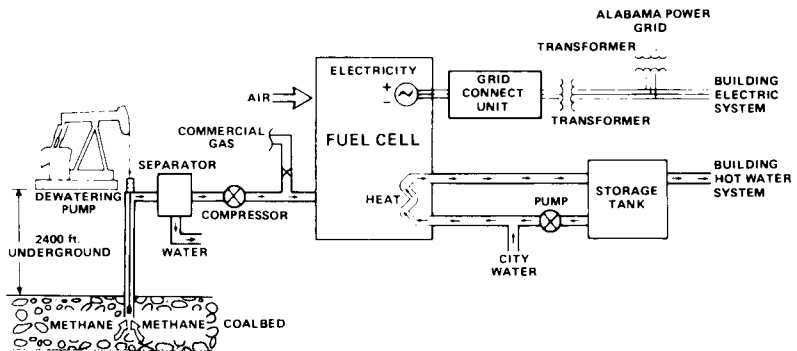


Figure 2 Schematic of SCS Fuel Cell Installation

Performing as predicted, the fuel cell achieved an average electrical efficiency of 37 percent and an average overall fuel utilization of 50 percent including recovered heat (Figure 3). Overall efficiencies regularly exceeded 70 percent during high building usage periods. The fuel cell provided more than 230,000 kWh of electricity and 286 million Btu of heat (equal to 450,000 gallons of 145°F hot water) to the recreation center, supplying one-fourth of the building's total requirement over the entire test period. It is estimated that \$4800 in energy cost savings resulted from using the fuel cell electrical and thermal output.

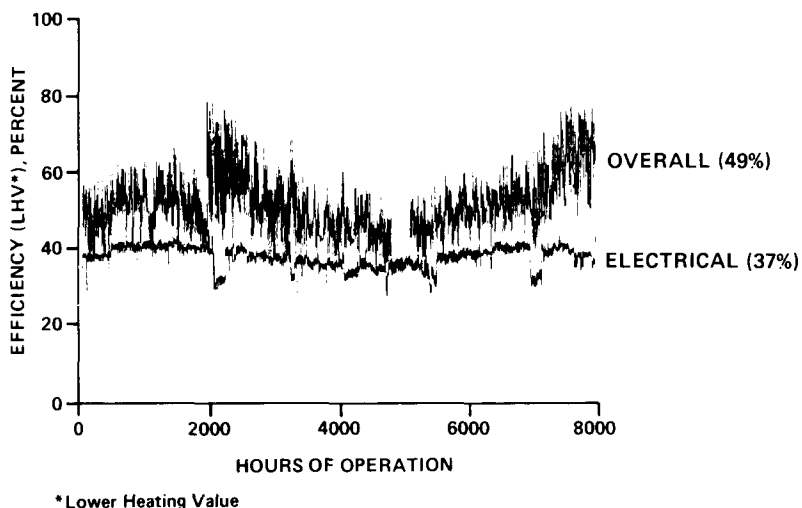


Figure 3 SCS Fuel Cell Efficiency Versus Time
(6376 Data Hours Plotted)

Initial operation using coalbed methane fuel was successfully achieved on May 29, 1985. Over the next 4 months, 900 hours of operation were accumulated on this fuel including three runs of more than 200 hours each. No significant performance differences were found for fuel cell operation on coalbed methane versus commercial natural gas (Figure 4). Difficult hydrologic conditions and mechanical problems associated with the methane wells, methane supply station, and the fuel cell prevented additional operating time on coalbed methane. The unusual hydrologic problems experienced were site specific and should not be an obstacle to commercial coalbed methane recovery programs. Fuel cell test time with coalbed methane was sufficient to clearly demonstrate its acceptability as a fuel source.

All the major goals and objectives of the test were achieved. The test developed information on an important national energy resource (coalbed methane), provided hands-on experience with fuel cell technology, analyzed the business potential of onsite fuel cells, and provided actual experience with small cogeneration and distributed power production. Several important conclusions were derived that affect onsite fuel cell commercialization potential.

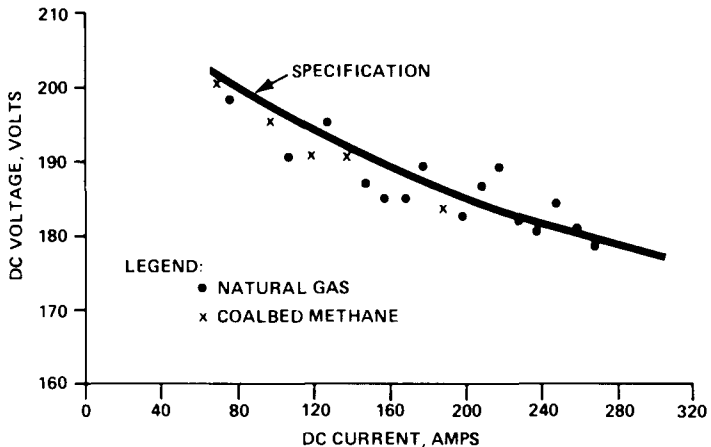


Figure 4 Power Section Performance For SCS Fuel Cell

Onsite Fuel Cell Technology. The test proved that coalbed methane is a suitable alternative fuel for fuel cell systems designed for natural gas operation. The fuel cell power plant performed as predicted with the new technology components (i.e., cell stack, reformer, and power conditioner) functioning satisfactorily on both coalbed methane and commercial gas. Most problems encountered during the test were caused by conventional auxiliary systems associated with thermal management and water treatment. Simplification and improved materials selection and quality control in these systems will be required.

Utility Operations and Personnel Compatibility. No significant utility compatibility problems were identified. Southern electric system personnel currently have the necessary skills to design site interfaces and perform fuel cell maintenance, although some further diagnostic training would be needed. Also, care must be taken to address electric grid interconnect safety and operational issues. Fuel cell grounding requirements, as an example, should be determined on a site specific basis to prevent unacceptable voltage hazards from occurring during possible electrical faults.

Onsite Fuel Cell Energy Service. Onsite fuel cells are capable of producing energy of the same quality as conventional service. High reliability remains to be demonstrated, although the test showed that significant improvements are likely in commercial units. Coalbed methane resources exist in many areas of the U.S. and could provide a means for expanding the potential onsite fuel cell market.

OPERATION OF FUEL CELLS
ON LANDFILL GAS
FUEL - UTILITY, CONTRACTOR, AND
MANUFACTURER PERSPECTIVE

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INTRODUCTION

This paper describes how three individual companies worked together to prove the viability of using landfill gas in a phosphoric acid fuel cell power plant (FCPP). The companies are: Southern California Edison Company (Edison), an electric utility; Kinetics Technology International Corporation (KTI), a worldwide engineering contractor; and International Fuel Cells Corporation (IFC), a leading fuel cell manufacturer.

Edison has been involved in various fuel cell development activities since 1972 and as a result of those activities, believe FCPP have unique capabilities to use gaseous waste fuels available in our service territory. The nationwide program sponsored by the Department of Energy (DOE) and the Gas Research Institute to field test forty-six 40 kW phosphoric acid FCPP provided an ideal vehicle for Edison to demonstrate this unique capability. In late 1982, Edison submitted a proposal to DOE to field test a 40 kW fuel cell on either processed landfill or digester gas. Edison's proposal was accepted and in December 1984, received a 40 kW FCPP.

The FCPP was installed at the Industry Hills Exhibit-Conference Center and operated on a landfill gas feedstock which was upgraded to natural gas specifications. The gas was upgraded by using activated carbon for trace contaminants removal and a membrane system for CO₂ removal. The Industry Hills FCPP operated over 5,500 hours proving the technical viability of using processed landfill gas. Although the technical feasibility of FCPP operation on upgraded landfill gas was confirmed, internal studies indicated that the economic viability of fuel cells could be enhanced by using landfill gas without the costly equipment necessary to upgrade the fuel to natural gas specifications.

In order to explore the feasibility of direct biogas utilization in FCPP's, KTI was contracted by Edison to analyze the

performance and identify any potential problems of operating the 40 kW PC18 FCPP on untreated landfill gas, i.e., without CO₂ removal. KTI developed for Edison an analytical model which considered both process and instrument related capacity limitations. KTI concluded in that assessment that with appropriate control modifications, the PC18 was capable of achieving 50-75% of the rated capacity.

After KTI completed the assessment on the 40 kW unit, Edison approached IFC soliciting their participation in an off specification test program to use landfill gas without CO₂ removal at Industry Hills. IFC agreed to participate in the test and suggested specific control modifications which would be necessary prior to using a lower Btu gas. In April 1986, the 40 kW FCPP at Industry Hills successfully operated nearly 100 hours on landfill gas without CO₂ removal. The CO₂ content of the gas had little impact on unit efficiency. The unit was found to operate in a stable fashion at 65% of rated capacity and achieved 72% capacity for short periods thus confirming the model predictions. The off specification gas testing and field test was concluded on April 17, when the FCPP tripped due to an electrical grid separation causing high reformer temperatures. The high reformer temperature resulted from the fuel control valve being on manual mode and the unit was unable to respond to the sudden drop in load. Further analysis now indicates that the 11 MW PC23 FCPP is capable of achieving full rated capacity while operating on untreated landfill gas.

In the following subsections, each of the program participants present their own unique perspective on the subject of biogas utilization in FCPP.

UTILITY PERSPECTIVE

Edison as an electric utility must explore new ways to provide low cost electricity for our customers in the future. Studies performed by us and others have identified over 1,000 MWe of alternative fuel resources in the form of landfill gas or municipal refuse located within Edison's service territory which could be used for the production of electrical energy.

One factor which diminishes Edison's ability to utilize this vast resource pool using conventional power generation methods is the concern for air quality in the L.A. basin. However, a fuel cell is unique in that electricity is produced by an electrochemical reaction instead of by combustion. Thus, the use of fuel cells would allow Edison to produce electricity with minimal air quality impact while simultaneously taking advantage of inexpensive local alternate fuels. The operation of the 40 kW FCPP at Industry Hills on landfill gas is significant not only in that it provided direct utility operating and maintenance experience but offered a means to

use an available intraterritory resources in an environmentally acceptable manner.

ENGINEERING CONTRACTOR PERSPECTIVE

KTI's participation in FCPP development was a natural role for an engineering contractor experienced in the transformation of hydrocarbon feedstocks to hydrogen. Engineering contractors are commonly confronted with the task of integrating specialized subcomponent technologies within a system framework - be it a modern petrochemical complex or a fuel cell power plant. KTI believes that as the fuel cell market matures, the electric utility industry will require contractors to package fuel-flexible systems which are specifically configured to meet their objectives.

In an endeavor to develop more fuel-flexible systems and to expand the range of acceptable FCPP feedstocks, KTI recently completed a study for the Electric Power Research Institute⁽¹⁾ to determine the feasibility of direct utilization of untreated landfill gas in a commercial size FCPP. The modular 11 MW plant described in EPRI publication EM-3161⁽²⁾ served as the baseline design for this analysis.

The results of the study indicated that no technical barriers would prevent the direct utilization of untreated landfill gas in the 11 MW unit. A maximum derating penalty of 16% was calculated for the baseline design. Minor modification of certain critical heat exchangers reduced the derating penalty to only 10%. Excluding the energy for landfill gas compression, the heat rate for the unit operating on landfill gas was only marginally higher than for operation on natural gas. Based on the study results, it was concluded that there is no economic incentive to remove carbon dioxide from landfill gas prior to use in a FCPP. Successful field tests at the Industry Hills facility lend credibility to the analytical models used to derive these results and furthermore confirm the technical feasibility of direct landfill gas use in a FCPP.

MANUFACTURER PERSPECTIVE

For the last 20 years, United Technologies (and now its subsidiary IFC, International Fuel Cells) has put considerable effort into development of phosphoric acid fuel cell power plants for utility applications. This effort is now paying off. Within a few years, IFC expects to see utilities operating larger-scale demonstration plants which will be the forerunners of mass-produced units for the world market.

As a manufacturer of commercial FCPP, IFC has an interest in supplying systems capable of operating on the broadest possible range of fuel feedstocks. The 40 kW PC18 was originally designed to run on pipeline natural gas, and the

11 MW PC23 is presently being designed to run on natural gas and/or liquid distillate. Obviously a fuel cell plant will run best on the fuels for which it was designed. Therefore, the results of the operation of the 40 kW FCPP operated on untreated landfill gas are particularly encouraging.

IFC has carried the KTI analysis of the effects of landfill gas on the 11 MW power plant one step further by taking into account the system changes to the design which have been made since the publication of the EPRI reference document, EM-3161.

The effect of these changes have been favorable. While a small heat rate degradation is still predicted due to the inefficiency of heating and cooling the carbon dioxide in the landfill gas, it now appears the PC23 can achieve its full 11 MW rated power on untreated landfill gas because the heat exchanger and reformer limitations identified by KTI have been alleviated in the new design. Therefore, minor changes to control and valve specifications are expected to be adequate to preclude any derating of the PC23 capability.

IFC also examined KTI's concerns about carbon formation, reformer performance, and burner operation with the higher carbon dioxide concentration and higher volume flow associated with landfill gas. IFC concluded none of these issues presented a real problem.

Based on this work, IFC concluded fuel cell power plants could be sited near large landfills and operated on landfill gas without removing the carbon dioxide. If the landfill gas supply is insufficient to support the fuel cell plant by itself, natural gas could be mixed with the landfill gas to provide the necessary amount of methane.

CONCLUSION

Each of the participants in this program have offered their own diverse perspective on the feasibility of power generation from landfill gas in FCPP's. Common among each of these perspectives is the conclusion that FCPP's may offer a strategic and environmentally acceptable means for power generation from local alternate fuel resources which might otherwise be wasted.

REFERENCES

1. P. Pietrogrande, D. Warren, S. Mullick, "Performance Evaluation for a 11 MW Fuel Cell Power Plant which Utilizes a Generic Landfill Gas Feedstock," Kinetics Technology International Corporation for EPRI (unpublished but available from EPRI), January 15, 1986.
2. UTC Corporation, "Description of a Generic 11 MW Fuel Cell Power Plant," EM3161, September 1983.

MTCI'S ADVANCED FUEL PROCESSOR DEVELOPMENT

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COLUMBIA, MD 21045

Management and Technical Consultants, Inc. (MTCI) is developing an Advanced Fuel Processor that has successfully processed No. 2 fuel oil under a DOE Contract. MTCI's Fuel Processor employs a two-stage system in which the first stage is a fluidized bed catalytic reactor. MTCI built and operated the first stage on No. 2 fuel oil.

In a DOD funded study, more than 99.9% of the feedstock (DF #2) was reformed to product gas in the first stage, with virtually no soot formation or other carbon laydown on the catalyst.

The demonstrated system was a bench scale unit operating at 40 to 60 psig and 1650 to 1800°F with feed rates of oil in the 3 to 7 lbm/hr range and steam-to-carbon ratios of 3 to 10. A novel feature of the bench scale unit is a proprietary 12 KW immersible electrical heater which can operate upto 1900°F continuously. Description of results obtained in the above study are presented in the paper.

AIR FORCE REMOTE SITE FUEL CELL DEVELOPMENT PROGRAM

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The objective of this congressionally mandated program is to demonstrate logistic fueled fuel cell power plants at an Air Force remote site in Alaska in the early 1990s. Performance goals are 40% electrical efficiency based on the fuel's lower heating value, 20 year life and 30% life cycle cost savings over existing diesel engine generators.

In August of 1984, a Memorandum of Understanding was established between the Air Force Wright Aeronautical Laboratories (AFWAL) and the Belvoir Research, Development and Engineering Center (Belvoir). AFWAL is responsible for program management and Belvoir has responsibility for technical accomplishment.

Primary aspects of the program are:

- ° Field test a 40kW power plant at Elmendorf Air Force Base, Alaska.
- ° Demonstrate processes capable of converting diesel fuel to fuel cell quality hydrogen.
- ° Establish requirements for remote site fuel cell power plants and determine performance and life cycle cost baseline of the competition.
- ° Conduct the Remote Site Fuel Cell Development.
- ° Demonstrate power plant(s) at an Air Force site in Alaska in the early 1990s.

40kW Power Plant Field Test at Elmendorf Air Force Base.

The 40kW field test program sponsored by the Gas Industry and DOE has been described in an earlier session. The Elmendorf power plant is the last of four installed at DOD sites. Since start-up on July 23, 1985 the power plant has accumulated 7600 hours of operation (as of 8/28/86) for an availability of 79%. This has been one of the best power plants in the fleet. Virtually all operation and maintenance has been performed by Government personnel at Elmendorf Air Force Base. They are credited with keeping downtime to a minimum.

The field test, originally planned for one year, has been extended until 1988 to enable assessment of component durability. The Fort Belvoir, Virginia power plant operated by the Facilities Engineering Support Agency is included in the extended test.

Fuel Conditioning Process Demonstration.

Processes capable of converting diesel fuel to fuel cell quality hydrogen were sought. Contracts were awarded to three firms in August of 1985. Table 1 summarizes the outcome. Preliminary and final technical reports have been distributed.

Remote Site Evaluation - Life Cycle Cost.

The Alaskan Air Command manages manned, remote radar sites throughout Alaska. Many of the sites have been completely replaced during 1984 and 1985 with modern facilities. The power plant consists of four 250kW or 175kW diesel engine generator sets depending on the site. Waste heat from the engine and exhaust is transferred to a glycol loop and is used for facility and hot water heating. These modernizations have resulted in greatly reduced fuel consumption and manpower.

Several sites are accessible only by air, others have seasonal windows to barge materials and supplies. Sites are operated by Radio Corporation of America personnel. A photo of a modern remote site is shown at Figure 1.

Science Applications International Corporation, under contract since January 1985, has determined general power plant requirements and has instrumented two sites to obtain thermal, electrical and fuel usage. In addition, a life cycle cost model has been developed and will be applied to existing power plants. This work was described at the Poster Session and a report covering the 1985 effort has been published.

In summary, the activities described above are in support of the power plant development program and eventual demonstration. Award of the development contract is anticipated in early 1987.

TABLE 1

DIESEL FUEL CONDITIONING DEMONSTRATIONS

ENERGY RESEARCH CORP	INTERNATIONAL FUEL CELLS	R.M. PARSONS CO.
○ FUEL IS FIRST DESULFURIZED ○ CLEAN FUEL IS STEAM REFORMED ○ CATALYSTS BY HALDOR TOPSOE	○ CYCLIC REACTOR - ONE MAKES H₂ WHILE OTHER IS REGENERATED ○ SULFUR IS REMOVED AFTER REFORMING ○ PROPRIETARY RHODIUM CATALYST	○ STEAM REFORMING FOLLOWED BY AUTOTHERMAL REFORMING ○ SULFUR IS REMOVED AFTER REFORMING ○ PROPRIETARY TOYO ENG. CO CATALYST & PROCESS
○ 400 HOUR DEMO COMPLETED ○ PERFORMANCE AS PREDICTED ○ VIABLE POWER PLANT CONTENDER	○ PROCESS FAILED DURING FIRST 20 HOURS OPER. ○ NOT A POWER PLANT CONTENDER	○ PROCESS INOPERABLE DUE TO MECHANICAL PROBLEMS ○ DEMONSTRATION INCONCLUSIVE - PROCESS MAY BE A VIABLE CONTENDER

FIGURE 1



MODERN REMOTE SITE

TASCHER ET AL
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MARKET ASSESSMENT OF BY-PRODUCT GASEOUS FUELS FOR PHOSPHORIC ACID FUEL CELLS

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INTRODUCTION

Southern California Edison (Edison) is a leader in evaluating fuel cells that operate on by-product gaseous fuels. The completion of a 40 kW fuel cell field test at the Industry Hills Exhibit-Conference Center has proven through operation on landfill gas that the fuel cell technology can utilize waste derived fuels. The use of by-product gaseous fuels for power generation offers a utility and its customers many benefits including the displacement of scarce fuel oil and natural gas resources, and a decrease in the adverse social impact of by-product waste disposal. This paper presents the results of a study by Science Applications International Corporation (SAIC), looking at the technical and economic market potential for 11 MW fuel cell power plants within Edison's territory.

FUEL CONVERSION TECHNOLOGIES

The conversion of by-product wastes into gaseous fuels can be achieved through three basic processes: anaerobic digestion, thermal gasification and direct utilization. The processes involve different technologies which are best suited to a particular type of waste input. Table 1 presents several market segments along with the conversion processes which are most technologically compatible.

TABLE 1

BY-PRODUCT CONVERSION PROCESS BY MARKET SEGMENT

Market Segment	Anaerobic		Direct
	Digestion	Gasification	Utilization
Agricultural Crops	X	X	-
Agricultural - Livestock	X	X	-
Food and Kindred	X	X	-
Lumber and Furniture	-	X	-
Paper/Allied Products	-	X	-
Sewage Systems			
Biogas	-	-	X
Stable Sludge	-	X	-
Refuse Systems			
Transfer Stations	X	X	-
Landfills	-	-	X

The anaerobic digestion process has been widely used in the treatment of organic sewage solids and results in a gaseous product that is approximately 60 percent methane and 40 percent carbon dioxide. The digester gas is a medium Btu gas with a heating value in the 500 to 650 Btu/scf range. Gasification of biomass is accomplished by supplying limited amounts of air (or oxygen) to a high temperature reaction chamber to produce carbon monoxide and hydrogen. Carbon dioxide and hydrocarbons are also produced. Product gas composition and yield depend on the oxygen content of the combustion air, gasifier design, combustion rate, feedstock quality, pressure and temperature, etc. Direct utilization involves the capturing of methane gas produced by the decomposition of organic material. At a landfill site, several wells are drilled and placed at specific distances from each other and the gas is withdrawn under vacuum.

Five generic fuel systems were specified in the study which could meet the input fuel requirements of the 11 MW fuel cell. These include two gasification systems (MSW, wood waste), two anaerobic digestion systems (MSW, livestock manure/food products) and a landfill gas recovery system. These systems were specified according to the waste by-products of the market segments and sized for approximately 50 MMBtu/hr.

TECHNICAL MARKET QUANTIFICATION

For each market segment studied, the total number of 11 MW fuel cells which could be supported by the available by-product fuels was calculated. The number of power plants were aggregated by site for each market segment except agricultural-livestock which was aggregated by county. It was assumed that the fuel cell would be located at each site having an adequate fuel resource. For agricultural-livestock, the manure by-product wastes would have to be transported to a location central to the manure resource. Table 2 presents the technically feasible market potential estimate for Edison's service territory.

TABLE 2

SUMMARY OF TECHNICALLY FEASIBLE MARKET POTENTIAL

<u>Market Segment</u>	<u>No. of 11 MW Fuel Cells</u>	<u>Total MW</u>
Agricultural Livestock	21	231
Food Processor	7	77
Paper & Allied Products	6	66
MSW Transfer Stations	51	561
Landfills	33	363
Total	118	1,298

The 11 MW fuel cell was assumed to have a fuel input rate of 93.5 MMBtu/hr at full load (heat rate of 8500 Btu/kWh). For this study, Edison decided to apply the fuel cell as an intermediate/peak generating unit using a capacity factor of 40 percent (37.4 MMBtu/hr). The market quantification task identified those sites having a potential of 37.4 MMBtu/hr or more of gaseous fuel. Sites having a fuel potential below the 37.4 MMBtu limit were excluded from consideration.

A total technical potential of 118 power plants was calculated for the five best market segments representing 1,298 MW of fuel cell capacity. This is a technically feasible market potential based on a 40 percent capacity factor. Operating the fuel cell at full load would reduce the number of technically feasible sites or require supplemental natural gas use because of an increased requirement for fuel.

ECONOMIC ANALYSIS

Table 3 presents the estimated system and operating costs for each of the five fuel conversion systems specified previously. These are illustrative only and do not represent detailed cost studies.

TABLE 3

ESTIMATED SYSTEM AND O&M COSTS FOR BY-PRODUCT FUEL PROCESSING

<u>Technology</u>	<u>Market Segment</u>	<u>Estimated System Costs</u>	<u>O&M Costs/Yr</u>
Anaerobic Digestion (MSW)	Transfer Stations	\$19,500,000	\$ -135,000
Anaerobic Digestion (Livestock Manure)	Agricultural Livestock	\$16,100,000	\$ 975,000
Gasification (MSW)	Transfer Stations	\$ 6,000,000	\$ -190,000
Gasification (Crop & Wood Wastes)	Lumber & Furniture Paper & Allied Products	\$ 4,500,000	\$1,600,000
Direct Utilization	Landfills	\$ 2,100,000	\$ 200,000

The estimated system costs include the necessary front end processing equipment, the digesters or gasifiers, and the gas cleanup and gas storage equipment. The estimates are based on discussions with personnel from the Gas Research Institute (GRI), Omnifuels Gasification Systems, Energy Products of

Idaho, and Waste Management, Inc. Costs for the anaerobic digester systems are based on pilot projects rather than existing facilities. Actual costs will depend on specific site and manufacturer requirements and are provided for information only. Annual O&M costs include the waste feedstock (including tipping fee credits), labor, materials, power and waste disposal. The two systems which process MSW have negative O&M costs because tipping fees are assumed to be a revenue source.

The levelized operating costs for the by-product fuels were calculated using an assumption of utility ownership of the fuel processing equipment. An installed cost of \$2,700/kW and a carrying charge of 21.0 percent was assumed which includes a 20 year plant life and a 14 percent cost of capital. As can be seen in Figure 1, only gasification of MSW and direct utilization at landfills have a lower fuel cost than natural gas. This is due principally to the tipping fee credits that are taken for MSW gasification and the lower capital cost of landfill gas recovery systems. Levelized operating costs are all higher than a gas turbine operating on natural gas.

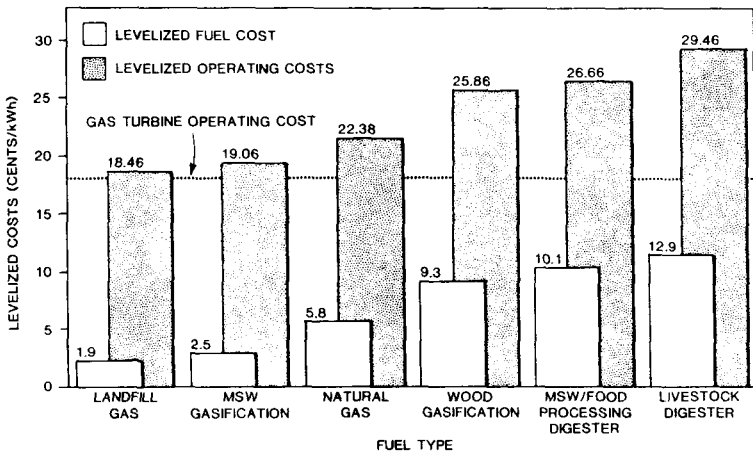


FIGURE 1

LEVELIZED FUEL AND TOTAL OPERATING COSTS FOR 11 MW FUEL CELL

CONCLUSIONS

A significant by-product market exists in Edison's service territory, however, the economic viability of fuel cells is heavily dependent upon lowering the fuel cell's installed cost. Once economic viability is established, the combination of high electrical efficiency and by-product gas capability should make fuel cells an attractive generation alternative for electric utilities.

PROSPECTS OF FUEL CELL APPLICATION FOR INDUSTRIAL USE IN JAPAN

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Introduction

Fuel cells offer advantages over the conventional process of power generation in that they:

- raise the efficiency of generation; plants in the small 100 kW-1 MW class could develop the efficiency equivalent of large scale power generation;
- produce waste heat of a relatively high temperature which could be combined with electricity for use in achieving a higher level of overall efficiency.

They are expected to serve actually for on-site use, as well as purposes of utility generation.

The conventional on-site generation has so far been promoted in the industrial field of Japan. Up for discussion here are prospects of fuel cell application for industrial use, one of the promising market for them.

1. Present Status of Autogeneration (on-site generation) and Applicability of Fuel Cells in Japan

Autogenerated energy of 75 million MWh in 1984 accounted for some 12% of Japan's total power requirements which stood at 580 million MWh that year. As a share of installed capacity, autogeneration installations covered some 9% (4,900 MW) of a total licensed output of 160,000 MW. For industrial use were 92% (13,600 MW) of these autogeneration installations, with only 4% each for commercial and traffic use.

Characteristic of autogeneration in the industrial field of Japan are:

- that petroleum products, paper and pulp, and chemicals -- industries with a demand of high heat/electricity ratio -- account for some 40% of autogeneration -- a level higher than for any other type of industry;
- that of the best three are chemicals, paper and pulp, and iron and steel. They cover some 84% of total autogeneration for industrial use.

A classification of these autogeneration installations by type of generation gives thermal power generation 94%, 83% is served by steam power plants and nearly 70% are of the co-generation type. (Fig. 1)

Autogeneration, though steadily on the increase up till the middle of 1970's, has not increased clearly in the past ten years. It appears that maturity has settled in for the use of the conventional type of autogeneration.

Therefore, those fields of industry which are advanced in the use of the conventional type may not have so much a new market for the introduction of fuel cells. So a suitable market is in the replacement of existing facilities.

Table 1 shows the actual use of autogeneration and the applicability of fuel cells for the industrial use. It is necessary to improve of

generation efficiency, diversification of working fuel, substantial reductions of installation costs, and effective production of higher temperature heat, in order to substitute fuel cells for the conventional type of industry autogeneration in the future.

2. Fresh Market for Fuel Cells

We extend our investigations of the market possibilities in industries from the economical point of view. Figure 2 shows the costs of purchased electricity in Japan, of steam turbine generation and of fuel cells generation against installation scale. (Credits for combined heat and power are included.)

This figure shows:

- (1) that the Japanese system of purchased electricity rates is designed to reduce them by steps of excess for 500 kW and 2 MW;
- (2) that steam power plants can generate electricity at a declining cost if they are of a scale larger than 10 MW, but the 100 kW - 1 MW class of them involving a higher installation costs loses competitive position toward purchased electricity, and
- (3) that fuel cells cost cause little change due to the scale of plants, those in the small 100 kW - 1 MW class will have advantages.

Therefore, an installed capacity is becoming of not more than 2 MW as the way of introduction of fuel cells.

Table 2 shows the temperature levels of heat required by type of industry. Waste heat from fuel cells registers some 200°C under the phosphoric acid type that is advanced in development. It holds out promise for industries in need of heat of up to those temperatures.

As a result, a food processing and textiles may be picked out for introduction of fuel cells from those industries. Both are less to introduce autogeneration, and consists of small and medium-size factories existing in much greater numbers than big factories. So much of the heat they need is in the range of relatively low temperatures.

A trial calculation of latent demand was made with regard to a food processing and textile industries. Given 100 kW as the minimum installed capacity of a fuel cell plant, factories on a greater scale of power requirements could bring about an estimated demand of 5,000 MW. Among these factories, those of a scale larger than 500 kW were about 2,000, requiring a total of 3,200 MW, and those small and midium size factories in the 100 kW - 500 kW class numbered 6,500, requiring a total of 1,600 MW.

In what proportion to these figures fuel cells will come into use is effected by the method of service for fuel cells maching with demand, the optimal ratio of installed capacity to heat demand and so on.

3. Conclusion

The likelihood is that fuel cell applications for industrial use give reasonable promise of introduction:

- (1) at the time when the existing autogeneration installations are replaced, and

- (2) in the type of industry which has relatively small scale factories failing to show their economic merits with conventional systems.

Entry into these markets will not be gained unless steps are taken to resolve such technical problems as:

- (1) achieving the desired installation cost and performance goals,
- (2) assuring reliability and operability (maintenance-free and other features) on a level not inferior to the existing generating installations,
- (3) developing technology for the recovery of high temperature waste heat of high utility value, and
- (4) promoting diversification of working fuel.

TABLE 1 THE ACTUAL USE OF AUTOGENERATION FOR THE INDUSTRIAL USE

Type	Field	Major generator	Fuel	Factor		Comments for
Power generation	Machinery	GT GE	Heavy & light oil	Both for on-peak and emergency use		High efficiency, cost, and start/standstill characteristics
	Nonferrous metals	Condensate	Coal	Merits of mass power use & large scale generation	Select low-cost fuel	Coal use and gasification combined MCFC
	Ceramics	Hydropower				
	Iron & steel	Condensate	By-product gas BFG CDG LDG HC H ₂		Effective use of by-product (waste) gas	Refining of by-product gas; high output with low partial pressure H ₂
Co-generation	Petroleum products	Bleed Backpressure system	Black liquid	Let cogeneration raise total energy efficiency		Difficult to make fuel out of by-product liquid? C heavy oil/ LNG as substitute
	Paper & pulp			Common use of boiler & other equipment		Generation efficient high enough to cover fuel cost gap
	Chemical		Heavy oil	Generation in line with heat demand	C heavy oil & other low-cost fuel easy to handle	Raise temperature waste heat

TABLE 2 THE TEMPERATURE LEVELS OF HEAT REQUIRED BY TYPE OF INDUSTRY

(unit:%)

Temperature levels Type of industry	below 100°C	~150°C	~183°C	from 183°C
Food processing	2.5	62.3	16.6	18.6
Textiles	0.4	50.3	49.3	0
Wooden goods	1.1	9.3	6.6	83.0
Paper and Pulp	0	85.9	4.1	0
Chemicals	4.8	26.5	50.0	18.8
Rubber goods	0	26.3	53.4	20.4
Pottery industry	0	85.6	14.4	0

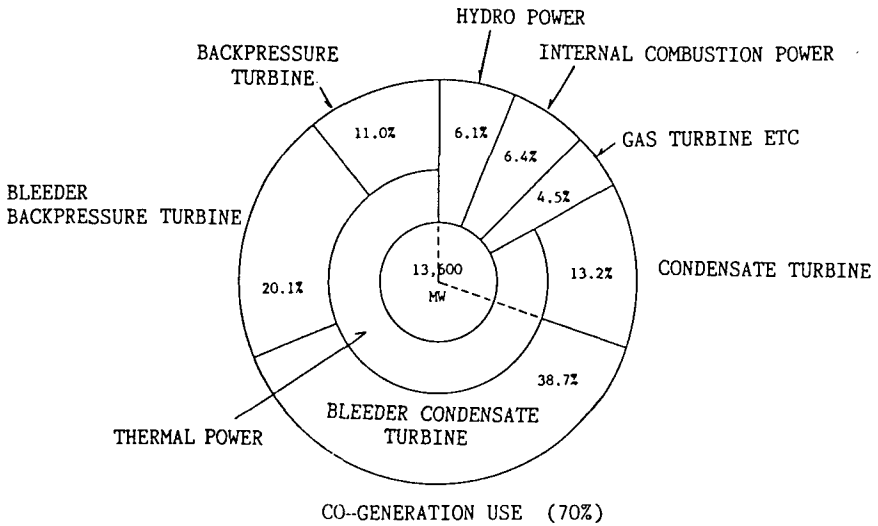


FIG.1 AUTOGENERATION INSTALLATIONS OF INDUSTRIAL USE (unit:%)

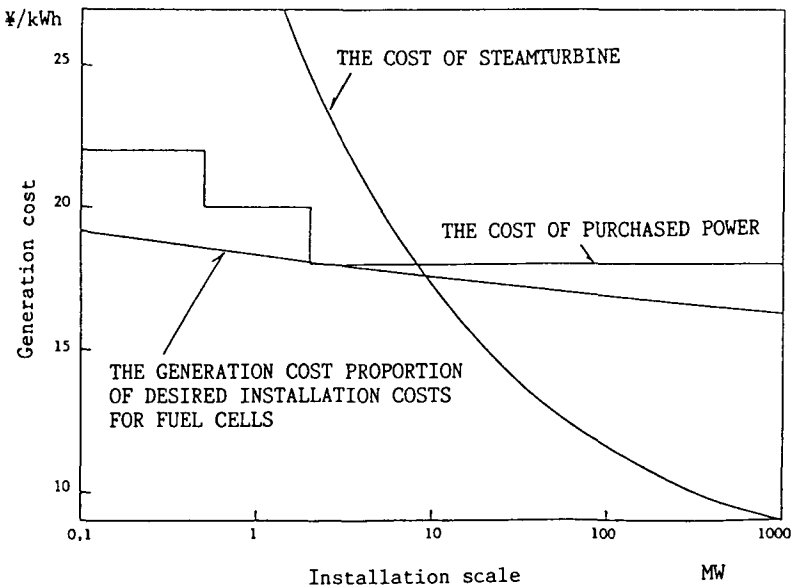


FIG.2 RELATIONS BETWEEN GENERATION SCALE AND GENERATION COST

APPLICATIONS OF FUEL CELLS TO THE PETROLEUM REFINING INDUSTRY

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Under the sponsorship of the U.S. Department of Energy's (DOE) Advanced Energy Conversion Program Office, Los Alamos National Laboratory has been analyzing and assessing potential applications of fuel cells in the period 1990 to 2000. A report on chlor-alkali industry applications has been published (1) and a report on petroleum refinery applications will be published in the near future. This paper deals with the refinery study. The Industrial Fuel Cell Association (IFCA) assisted in the conduct of the Los Alamos studies, and Joseph M. Anderson, former IFCA Executive Director, coordinated the IFCA input. The different process requirements of the industry were characterized and energy requirements determined. The competitive cogeneration systems were also characterized. To assist in the technical characterizations, a questionnaire was sent to planning personnel in all of the major refinery plants in the U.S. Using a Los Alamos computer code (2), levelized energy (steam + electricity) costs were calculated for the different competitive systems to determine their economic competitiveness. Other economic factors were also evaluated that might have a bearing on the choice of a cogeneration system.

The largest fraction of a refinery's thermal requirement is in the direct heat form. A quantity of process heat equal to roughly one-third of the direct heat is embodied in steam and used for a variety of purposes. Steam pressures range from approximately 15 to 650 psig and even up to 1500 psig. The latter high pressure is not necessary for the processes but is sometimes used to generate power with back-pressure turbines, with the back pressures being about 600 to 700 psig. Relative to the energy used for direct heat and steam, the energy used for electric power generation is low.

Highly detailed discussions of the major refinery processes are given in references 3 and 4. Steam requirements vary from plant to plant for a given process. Reasons for this can include process efficiency improvements, old vs. new plants, internal processing differences to produce the same product, possible plant capacity differences, process emphasis on a different product but using the basic process nomenclature, and combinations of the previous reasons. A similar situation is observed for the fuel and electricity requirements for the various refining processes. Under these circumstances, an energy description for a "typical" refinery becomes a difficult task. Nevertheless, a model was constructed and energy requirements determined for a 150,000 Bbl/D refinery, a size expected to compete in future fuels markets. This plant requires 50 MW of electric power at 100% capacity, giving a value of 8 kWh/Bbl of crude. Total connected load is probably a third higher, or around 65 MW. The power requirement and the high pressure steam requirement will vary inversely from one refinery to another, depending on how many turbine drives they use on their centrifugal compressors and large pumps. The steam consumptions in existing older refineries are generally higher than shown. The total energy consumption of the model refinery is 559 MBtu/Bbl. By way of comparison, the average energy consumption of U.S. refineries in 1983 was 580 MBtu/Bbl.

From the responses to the questionnaire, it was found that the total electrical demand per refinery ranged from less than 10 MWe to between 100 to 200 MWe with 29% at 11 to 25 MWe and 36% at 51 to 100 MWe. An average electrical demand of 10.8 kWh/bbl of capacity was indicated. There appears to be a strong interest in selling excess power. The industry's present electrical capacity is about 4000 MWe. Considering that fuel cell systems are modular, the respondents estimated that the initial facility would probably be no larger than 5 MW. Subsequent units would probably be in the 6-20 MW range, with only 22% as small as 5 MW. The respondents estimated that fuel cells could make significant inroads as an energy source by the year 2000, depending on the level of savings such systems could offer.

In addition to three fuel cell technologies considered for petroleum refinery applications, the gas turbine combined cycle (GTCC), and coke fluidized bed boiler (CFBB) options were included in the overall analysis. The three fuel cell technologies were phosphoric acid (PAFC), molten carbonate (MCFC), and solid oxide (SOFC). The GTCC technology is the most likely competitive cogeneration system in the coming decade. For all but the CFBB cogeneration technologies, we "normalized" to a 50,000 lb/hr steam output. A 300,000 lb/hr steam output was selected for the CFBB based on current prototypes. Table I shows our assumptions for the operating and performance characteristics of the candidate cogeneration systems. Assumptions for a steam boiler are also shown because they were used to estimate the value of steam in a petroleum refinery.

TABLE I
OPERATING AND PERFORMANCE CHARACTERISTICS ASSUMED FOR POWER AND STEAM
GENERATING SYSTEMS IN PETROLEUM REFINERIES

System Parameters	PAFC		MCFC	SOFC	GTCC		Purchased Power Plus Boiler	Coke Fluidized Bed Boiler
	Case 1	Case 2			Case 1	Case 2		
Fuel Type	N.G.	N.G.	N.G.*	N.G.*	N.G.	N.G.	N.G.	Refinery Coke
Fuel Heat Input (10 ⁶ Btu/hr)	149x10 ⁶	167x10 ⁶	252x10 ⁶	276x10 ⁶	161x10 ⁶	145x10 ⁶	409x10 ⁶	506x10 ⁶
Electricity (MWe)	18.3	22.0	38.4	43.7	21.3	14.9	0	7.5
Steam (lb/hr)	50x10 ³	50x10 ³	50x10 ³	50x10 ³	50x10 ³	50x10 ³	300x10 ³	300x10 ³
(psig)	15-125	15-125	125-400	400-600	15-50	125-400	~600	~650
Efficiencies:								
Electrical (%)	42	45	52	54	45	35	-	~5
Heat Extraction (%)	38	30	23	21	35	40	85	~80
Overall (%)	80	75	75	75	80	75	85	~85

N.G. - Natural Gas

*Other fossil fuels can also be used.

We had to assume typical operating and cost parameters but except for possibly the GTCC, the performance and cost assumptions are based principally on paper studies and educated estimates. Therefore, the base-case conditions for each system do not necessarily represent equivalent levels of accuracy. A more realistic economic comparison is presented in Figure 1 where net electric generating costs (\$/kW) are plotted against capital costs (\$/kW). The horizontal lines at 4.5 and 5.1 \$/kW, the net generating costs for the GTCC base-line systems provide ready benchmarks against which to judge cost competitiveness of other systems. One can read break-even capital costs directly from the figure itself. For example, the PAFC technology (case 2) at \$510/kW and \$450/kW provides the

same levelized annual electricity costs as the conventional gas turbine combined cycle technology, case 2 and case 1, respectively. However, the MCFC is similarly comparable at \$760 and \$720 per kilowatt respectively. We have not plotted the second PAFC case, case 1, option for the difference in results is fairly small. The CFBB technology results in significantly higher generation costs than the fuel cell technologies at capital costs below \$1500/kW. However, if the coke refinery fuel is priced lower (\$1.50/10⁶ Btu assumption used in baseline computation) then the plot for CFBB will fall commensurately. The CFBB is basically a steam generator with electricity only a secondary product.

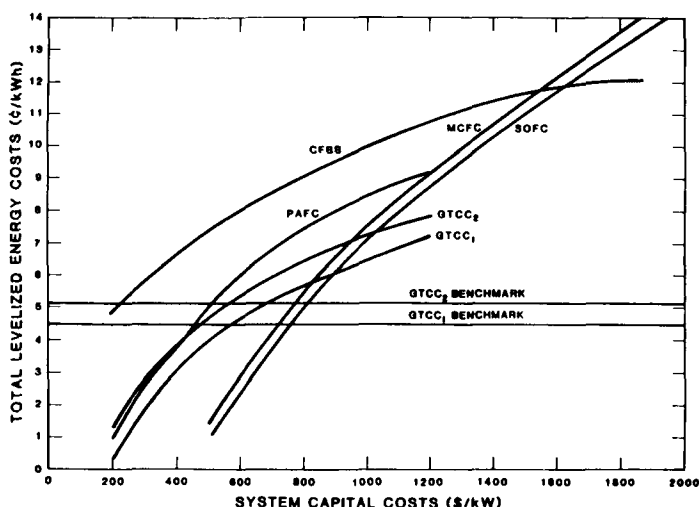


Fig. 1. TLEC for refinery base case systems.

Petroleum refineries in the U.S. have decreased in both number and capacity during the past 5-8 years. Today, there are fewer than 190 operating refineries and additional closings are likely. Product imports to the U.S. are on the rise; and world-wide refining capacity continues to increase as more producers enter the downstream market. The price of oil has fallen recently; the market mix of products continues to shift away from "heavies" to "lights;" the quality of crude processed by refineries, on average, is lower today than in the past; and profits and profit margins are relatively low--all of which indicates that even further pressure on U.S. refining capacity could easily result in more reductions. New investment in plant and equipment, although necessary to upgrade some older refineries and to increase throughput of marketable products (lights), will be delayed further.

The overall prognosis for petroleum refining in the U.S. is not good. However, expansion of refinery capacity in certain product categories will occur as demand continues to shift and even as total capacity decreases. This incremental capacity expansion may offer fuel cells an opportunity because fuel cells can easily be installed in incremented units. The results of our industry survey suggest that the market potential of fuel

cells may be greatest as a supplemental energy source to existing power and steam generating systems.

There are several other factors that could effect the market potential of fuel cells. First, the cost difference between fuel cell net generating cost and present or conventional systems costs would have to be above the 15 to 20% range for large scale purchases. The PAFC technology could achieve that goal in the next decade if systems prices are lowered as much as some have forecast or believe--a factor of 2 or more separates those capital cost figures today. However, the PAFC technology will only have a limited application because of its relatively low steam pressure and temperature operating levels (although there are significant low pressure and temperature requirements in a refinery). Second, because of the higher pressure and temperature requirements of a refinery there was strong indication that the MCFC and SOFC technologies would be better long-term candidates for adoption. Both of these technologies have received increased attention in the R&D community of late. Third, these two technologies could potentially make use of a variety of fuel sources available in the refinery such as off-gases and coke. The PAFC technology requires natural gas or hydrogen, a fuel that has grown in value that far exceeds that of natural gas itself.

States with large capacity and relatively high industrial electrical rates would appear to be potentially attractive markets for fuel cells. The state of California, Louisiana, and Texas comprise nearly 60% of U.S. refining capacity and in two of the three have relatively high electric rates. Electric rates are forecast to dramatically increase in the third, and all face higher prices in the future due to new plant expansion coming on line, nuclear rate shocks, and higher natural gas prices--especially true for Texas and Louisiana where much of existing electric capacity is gas-fired. Texas and California are considered two of the more supportive states--both institutionally and rate structure wise--for cogeneration. By examining again Fig. 1, and considering that electricity prices could easily be 2 to 3 ¢/kWh higher than the "base-line GTCC reference lines, then fuel cells look more promising even at higher capital costs. However, the GTCC technology appears to be a difficult competitor and will likely remain so for a number of years.

References

1. J. H. Altseimer, F. Roach, J. A. Anderson, and C. A. Mangeng, "The Potential Application of Fuel Cells in the Chlor-Alkali Industry," Department of Energy report DOE/MC/A146-1986 (Los Alamos National Laboratory report LA-10516-MS) August 1985.
2. R. W. Hardie, "Bicycle II: A Computer Code for Calculating Levelized Life-Cycle Costs," Los Alamos National Laboratory report LA-8909 (November 1981).
3. J. H. Gary and G. E. Handwerk, Petroleum Refining Technology and Economics, 2nd Ed., Revised and Expanded, M. Dekker, Inc., New York and Basel (1984).
4. L. L. Gaines and A. M. Wolsky, "Energy and Material Flows in Petroleum Refining," Argonne National Laboratory report ANL/CNSV-10 (February 1981).

FUEL CELL INTEGRATION WITH RENEWABLE POWER TECHNOLOGIES:
SOME TECHNICAL POSSIBILITIES AND POTENTIAL IMPACTS

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Changing wind speeds and solar insolation levels can cause the power output of wind and solar-electric technologies to vary dramatically from minute-to-minute and from day-to-day. This problem of output variability is a major constraint on the number of applications and the energy contribution which can be derived from wind and solar-electric technologies.

Fuel cells have recently demonstrated a capability to accommodate rapidly changing power demands, and may offer new hope for solving the output variability problem. This suggests that their combination with renewable power technologies could yield a system which produces firm power and derives much of its energy from renewable resources. Such complementarity could enhance the attractiveness of windfarms and other solar operations to electric utilities. It could also spawn a new generation of firm power technologies for rural and isolated areas. However, there are three technical problems which must be addressed in order to prove that fuel cells can be successfully integrated with wind and solar electric technologies.

First, although the Gas Research Institute field tests have shown that small fuel cells can follow commercial building loads, the adequacy of these designs to match the more erratic output patterns of wind machines and windfarms is yet to be demonstrated. For applications in isolated environments, there is the additional problem of meeting a variable demand. Although the fuel cell stack is able to respond almost instantaneously to any load condition, the fuel reformer has a much slower response rate. The current design of reformers may not be able to produce hydrogen-enriched gas quickly enough to respond to fast-changing wind outputs and load demands.

Second, the technological requirements for integrating fuel cells with wind and other renewable energy technologies remain to be explored. In order to coordinate the fuel cell's output with the wind output, an integrated system will require some connecting equipment which would likely include a power handling device and a microprocessor control apparatus. Also, research is needed to determine the most appropriate configuration of the system for particular

climatic and geographic conditions. The primary goal of this effort is to optimize the balance among components while minimizing capital and operating costs. This would primarily involve a determination of the types (wind, solar, batteries, etc.) and sizes (20-kw, 40-kw, 100-kw) of components through computer simulation and field tests. Additionally, by varying the size of the renewable energy technologies and the fuel storage mechanism, this research could yield data on how to manage the fuel inventory at minimum cost. Finally, research is needed on equipment for the integrated system that would enable the local electric utility to dispatch it when its output is needed.

Third, it has not yet been shown whether fuel cells can compete economically with diesel engines as an output-leveling device for renewable power technologies. DOE's Wind Energy Program is currently supporting research on integrated wind-diesel systems, giving this technology a head start on integrated wind-fuel cell systems. Foreign developments in integrated wind-diesel systems also have a head start on integrated wind-fuel cell systems. Wind-diesel systems may have an additional edge because both utilities and isolated users are more familiar with diesel power equipment than they are with fuel cells. But perhaps the most important advantage working for diesels is their much lower capital cost, even when compared with projected costs for the 200-kw phosphoric acid fuel cells being negotiated between gas utilities and International Fuel Cells, Inc.

FINANCIAL IMPLICATIONS OF ON-SITE FUEL CELLS
FOR A GAS UTILITY

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An abstract of this presentation was not available at press time. Copies will be provided to attendees at the Seminar.

POTENTIAL OF FUEL CELL APPLICATIONS FOR
DECENTRALIZED POWER GENERATION IN INDIA

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Energy consumption is an index of a country's economic development. It has been estimated that if the economic growth rates in India are to be in the range of 5-6%, the electrical energy supply would have to increase four-fold in the next 20 years. The total installed electricity generation capacity in the country was merely 2,300 mW in 1950. Since then an impressive growth by a factor of 30 has been achieved. The total installed capacity as on March 31, 1985 was 42,771 MW. Table 1 gives a breakup of the installed capacity as per the mode of generation. As is seen from the table, India relies heavily on hydro (32%) and coal fired (63%) thermal power stations.

TABLE 1
INSTALLED UTILITY POWER GENERATING CAPACITY IN INDIA

Mode of Generation	Capacity (MW)
Coal	27080
Hydro	13856
Nuclear	1095
Gas	561
Diesel	179
Total	42771

The demand for power, however, has outstripped its availability. The periods of comfortable power supply position generally noticed soon after the commissioning of new generating capacity are successively becoming shortened and the new capacity is being utilised almost as soon as the commissioning is over. The rate of growth in electricity consumption which averaged 12.7% per annum (compounded) during the decade 1950-60 came down drastically to 6.54% in the period 1970-80. The sharp decline in the growth rate of electricity consumption during the recent years can be largely attributed to widespread power shortages accentuated by the shortfall in achievement of targets set for installing new generating capacity, frequent monsoon failure and transport bottlenecks in coal movement. Apart from this, the growth of transmission and distribution system has not matched the expansion of power generation capacity, thereby affecting both the quality and the reliability of power supply. The present power transmission and distribution losses average 20% as against less than 10% in the developed countries mainly due to the lower density of power demand,

longer distances and the low transmission voltages. The growth in electricity consumption during the past decade, therefore, actually reflects the growth of availability of power rather than demand for it. The continued restrictions on the use of electricity has undoubtedly affected the industrial and agricultural development of the country.

An important feature of the power scenario in India is the extremely low per capita consumption of electricity particularly in the rural areas. The per capita electrical energy consumption in the country was about 250 kWh in 1985. It is clear that the electricity consumption would have to be enhanced and therefore, its availability, if economic activity, productivity and incomes are to be increased. A large part of India is not yet covered by an electric network. However, even where electrification has reached, electricity supply is not only unreliable and erratic, but has also proved uneconomical for isolated and dispersed settlements. This is on account of the high incremental cost of distribution on the one hand, and low load factors, resulting from very low purchasing power on the other. The use of diesel for small-scale power generation and kerosene for lighting have increased over the past few years. However, their transportation costs for decentralized supply are very high and the supplies are unreliable and erratic. These fuels could be used more gainfully in energy efficient modern plant and equipment, if suitable alternatives for decentralized power generation are found.

The non-commercial forms of energy (fuelwood, agricultural residues and animal wastes) still provide for more than 80% of the total energy requirements in rural and over 50% in urban households. Though the non-commercial energy sources are obtained at practically 'zero' financial cost, they are usually associated with very high social costs on account of the environmental degradation caused by them. Not only do they create an imbalance in the ecosystems, they are utilized at very poor efficiencies. Of all the newer vistas in power planning, fuel cells offer one of the best and the most efficient energy technologies that overcomes the inherent ills of the central grid system, and many a problem associated with generation of electricity from fossil fuels. In rural and semi urban areas, biogas can not only serve for cooking, but can also be utilised for electricity generation. In the context of a vast network of biogas plants in India, dovetailing fuel cell technology with the simple biogas system could result in a self-sustained decentralized energy system catering effectively to the diverse consumption needs of a particular area, howsoever low the load factor may be.

The prevailing energy scenario demands new strategies for energy and power generation technology to provide a modicum of substantial energy supplies to the millions in the

countryside. Fuel cell power plants operating on locally available fuels, therefore, can become the most crucial factor in power planning in the country. The potential availability of fuels for phosphoric acid fuel cells was examined in detail. Three fuels, namely, natural gas, ethanol and biogas have been found suitable with specific reference to Indian conditions. Biogas is mainly produced from anaerobic digestion of animal wastes in India. Whereas ethanol is produced by fermentation of molasses. Other biomass feedstocks for production of biogas and ethanol has now been a subject of wide discussion. Table 2 shows total potential and estimated availability of various fuels for PAFC applications.

TABLE 2
TOTAL POTENTIAL AND ESTIMATED AVAILABILITY
OF VARIOUS FUELS FOR PAFC

Fuel	Total potential availability per annum	Estimated availability for PAFC	Total potential for PAFC installat- ion (MW)
Natural Gas	15000 Mm ³	750 Mm ³	500
Ethanol	16.47 Mt	8.235	500
Biogas	20,000 Mm ³	8000 Mm ³	3000

The cost of electricity generation using fuel cells was compared with other options for decentralized electricity generation such as photovoltaic and wind turbines. Though the fuel cell option is found to be attractive as compared to other decentralized options, the cost of fuel cell stack has to be reduced to about \$ 1000/kW to provide electricity at competitive price than central grid supply. However, given the rapid growth in demand for power in the country and the increasing capital intensity and peak to base load power ratio, it is unlikely that the growing gap between demand and supply would be reduced. The present situation offers ample opportunities for the application of small sized (10-200 kW) fuel cells. A field demonstration project should be undertaken to carry out a site specific techno-economic feasibility of fuel cell biogas/ethanol system in India.

NATIONAL FUEL CELL PROGRAM AND ITS APPLICATION IN INDONESIA -- A PROPOSED PROGRAM

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ABSTRACT

This paper describes the long-term proposed program of a National Fuel Cell technical capability and application in Indonesia. The proposal for this program will be prepared by an Indonesia Fuel Cell Group which is consisted of researchers, scientists, entrepreneurs, government official, potential users, and interested foreign counter-parts.

The first goal of this program is to acquire, analyze, and document of fuel resources data in Indonesia. In this task, there will also be a study on the fuel cell market penetration in Indonesia. The other sub-programs will be emphasized on the development of technical capability.

INTRODUCTION

The problem on providing energy in Indonesia is still one that can not be solved yet, although Indonesia has many potential energy resources, such as fossil fuels (oil, natural gas, coal), hydro power, solar energy, biomass, etc.

This problem is not only caused by the limitation of national income, but also on the technological know how, geographical conditions, inefficient conventional power supply, etc. Therefore, a technology adoption on the new energy conversion devices, especially one which has bright prospects, should be implemented for the benefits of this country.

In realization one of the prospected new energy-conversion technologies, a National Fuel Cell Program for Indonesia will be proposed by a Fuel Cell Group. This group will consist of a small group of experts with an understanding and knowledge of fuel cell phenomena and devices, fuel cell systems and sub-systems, fuel resources in Indonesia, fuel cell markets and manufacturers in Indonesia, and the present status of fuel cell technology on a world-wide basis. In order to build-up this capability, the Fuel Cell Group must establish several sub-programs which each of them will

include staff development, facility and equipments requirements, required budget, expected schedule, etc.

This program is at its initial stage and government's approval must still be obtained as well as interest among the scientists in Indonesia. Interest to help Indonesia in this respect has been shown.

PROGRAM OBJECTIVES

The general objective of this program is to establish the necessary capabilities which will provide the required focus and forum for technical and staff development in the field of fuel cell technology and application in Indonesia. These capabilities are divided into six key areas with their specific objectives include :

1. **Acquiring, analyzing and documenting fuel resources data-** The objective of this sub program is to develop the capability to acquire, analyze and document data of the fuel resources which can be expected meet the fuel cell system specifications for application in Indonesia.
2. **Implementation of fuel cell demo plant-** The general objective of this sub program is to demonstrate the suitability of fuel cell utilizations as a means of achieving electrification and satisfying other needs, such as thermal energy, treated water, etc.
3. **Acquiring a facility for testing fuel cell system's components-** The objective of this task is to provide information to manufacturers and users of fuel cell systems and components which will ensure that fuel cell hardware used in Indonesia meets established standards for performance and reliability. In order to be successful, this sub program must ultimately include the development of communications channels with the interested manufacturers, potential users, and scientists.
4. **Establishing a center of excellence in fuel cell technologies** The objective of this task is to establish a facility to conduct research projects focused on key problems related to fuel cell technologies. Initially, the primary focus of this sub-program will be on PAFC (Phosphoric Acid Fuel Cell). Other technologies will be identified and will evolve as changing needs and economic factors modify the market scenario.
5. **Supporting the design and analysis of fuel cell applications** The objective of this sub program is to develop and sustain a base of expertise in the principles, tools, and methodologies of fuel cell system design which will permit the fuel cell laboratory to act as a resource for Indonesia manufacturers and users of such systems.

6. **Analyzing the data from test and demo installations-** This sub program has the major objective of providing data on the performance of operating fuel cell systems. The subsidiary objectives include : analyzing the data to identify trends, problems areas and specific factors contributing to failures; documenting and disseminating the information, etc. This capability will be of help for designers, manufacturers, suppliers and users in improving the performance of subsequently fielded systems and components.

PROGRAM OVERVIEW

The focus of this program during the first year will be on the acquiring, analyzing and documenting of fuel resources data in Indonesia. Other activities which will also be conducted are introducing the fuel cell power plant advantages, establishing communication channel with potensial users, preparing a study on the fuel cell market penetration which will include the technical, economical and environmental aspects.

In the further years, the activities will be mainly emphasized on the technical capability development, as summarized on table 1. For the whole activities, the estimated budget is amount to US\$ 1.86 M (year 1985), included for equipment, training, building, and miscellaneous.

FUTURE OUTLOOK

As the National Fuel Cell Program is being developed, it is also needed to assess on the prospect of fuel cell applications in Indonesia. Therefore, the efforts to introduce the advantages on fuel cell power system implementation in Indonesia should be performed by establishing the communication channel with its possibly potensial users either of governmental or private sectors.

In doing so, the technical and economical assessment on this subject should be undertaken. Also, another aspect has to be taken into consideration, i.e. environmental aspect, since there will be a regulation on the environment protection which will be expired on July 1987. So that, it is very interested in establishing this assessment since the application of fuel cell plant can be expected meet those three aspects, especially if the targets on its capital costs, life time and heat rate can be reached in the near future.

The projection on the fuel cell application in Indonesia is summarized on table 2 below :

Table 2. Projection on Fuel Cell Application

Application	Fuel	Unit Capacity	Remarks
1. Power Station	Coal, LNG	> 600 MW	At energy resource
2. Industrial	LNG, LPG	2-26 MW	Co-gen.
3. Rural Elect.	Biomass	70-200 kW	Stand-Alone
4. Urban Elect.	LNG, LPG	2-100 MW	Inter-Conn.
5. Transport	Methanol, CNG	12-20 MW	Stand-Alone

The prospect of fuel cell application in Indonesia is also interested if it is seen from view of point of its population and projected energy consumption in accordance with the National Development Program (PELITA) in Indonesia. The population in the end of next decade is predicted will be of more than 200 million people. And at the same time, the projected energy consumption/capita/year is about 500 kWh or totally is at rate of 100 TWH. Meanwhile, the present population and energy consumption are 167 million people and about 80 kWh/capita/year respectively.

Table 1. Fuel Cell Technical Capability

	Year 1	2	3	4	5	6	7	8
Project	Demo Plant	- Demo Plant Data Collection/Analysis - Testing of Demo-Plant - Fuel Resources Data Monitoring & Analysis - Test of System: Data Mon. & Analysis.	- Continue of Demo Data Collection - Develop initial Standards & Specifications for FC Component - Testing of Demo Plant	- Continue of Demo Plant - Testing of System for Testing & Evaluation Facility. - Components testing. - Test of system: FC Simulator - Develop. Standards & Specification - Develop. Initial Standards and specs. for other FC components.	- Continue of Demo Plant - Develop Stds & specs for other FCs Components - Develop. System Design Guidelines	- Services Activities for industry - Continue of Demo Plant - Continue of test & Eval. Program. - Develop. Initial Fuel Cell Research Lab. Program - Data Analysis	- Continue of Tests Eval. Program - Service Activities for Industry - Study Stability of FC Devices - Data Analysis.	- Continue of All Projects from Previous year - Research Activities - Preparing of integration of all Project into Lab Activities in the next year.
Equipment	PAFC Demo Plant	- Data Acquisition	- PAFC Test - Other FC Demo plant	- Other FC test beds - FC simulator - Data Acquisition - Computers - Device Testing PAFC Equipment	- Device Testing other FC Equipment	- Data Analysis	- Materials Analysis Equipment. - Device Fabrication Equipment	- Expansion of Lab. Equipment
Building	- Demo-site	- Data Analysis Center at Demo Site	- Stack and component equipment testing facility - Demo-site	- Component equipment - test facility - Data Analysis center at Demo - FC Simulator - Data Analysis Center for PAFC Device	- Data Analysis for other FC device	- Preparation of FC Research Lab	- FC Technologies Research Lab Partially completed	- Advanced FC Technologies Research Lab.

THE PC23 FUEL CELL - A STRATEGIC ALTERNATIVE

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For many electric utilities, today's business climate is harsh and uncertain. Regulatory agencies now tend to penalize utilities that build plants which are not "used and useful," but load growth varies with an unpredictable economy. Increasingly stringent environmental regulations can lead to extensive delays. Variations in the availability and price of fuel or purchased power may subject a utility to prudence reviews. Meanwhile, high interest rates make long-term construction an expensive and risky proposition.

In the face of these difficulties, utilities have limited options. One very attractive option is to add short-lead-time capacity in small increments as needed and in a form which is acceptable to both environmentalists and regulators.

Fuel cell power plants can be built in small, efficient blocks. Because of their attractive environmental characteristics, licensing and siting are straightforward. Fuel cell plants can be factory-produced in volume, assembled into truck-transportable equipment packages, dropped onto pads at pre-engineered sites, and interconnected with minimum on-site construction -- all of which translates into a lead time of about 2 years for production units. The combination of small-capacity increments with short lead times enables utilities to match capacity increments with system needs.

The rapid load response characteristics of fuel cells have recently attracted attention because they offer leveraged power production cost savings. A small percentage of dispersed fuel cell capacity in an electric utility system can improve the economics of the whole system. Fuel cell plants can help significantly with the rapid response portion of the operating reserve requirements, liberating baseload plants from this duty. In this way, fuel cells can maximize use of baseload plants for bulk power production. In addition, the baseload plants -- fossil or hydroelectric -- can now run at their optimum heat rates or "best gates." Maintenance needs of the baseload equipment are reduced. In an example 5000-megawatt system, the addition of 5 percent fuel cell capacity saves between 4 percent and 7 percent of the utility's total annual power production cost.

International Fuel Cells is designing and developing a new fuel cell power plant, designated the PC23, for sale to utilities. The PC23 is a complete, self-contained generating plant which converts natural gas or liquid hydrocarbon fuel into three-phase power at the utility's distribution voltage. It produces 11 megawatts net ac at a heat rate of 8300 Btu/kilowatt-hour. The PC23 has the fast response and good

part-power efficiency needed by an intermediate generator. Initial plants will be built to operate on available fuels -- natural gas or liquid hydrocarbons. As other fuels -- coal gases, landfill gas, digester gases -- become available, these plants can be adapted to use them. Heat from the plant can be recovered; in this way up to 80 percent of the fuel energy can be utilized. At 11 megawatts, the PC23 provides users with a practical generation increment at an acceptable level of investment.

Based on the experience gained in 25 years of fuel cell power plant development, the PC23 is a reasonable extension of demonstrated technology. The lessons learned in a series of plants from the first Apollo spacecraft fuel cell to the 1.0-megawatt pilot plant in 1977 to the recent 4.5 megawatt demonstrations are being used to advantage.

These programs have proven the viability of many features that have been incorporated into the PC23 design. Factory modular assembly, high efficiency in small power increments, low exhaust emission levels, automatic control and monitoring, siting and installation in urban areas, and operation by utility personnel -- all have been successfully demonstrated.

On-going programs are aimed at translating this experience into quality hardware that can be manufactured economically. Fuel cell components for use in power plants are currently undergoing testing. Critical subsystems and components in the dc module, water treatment system, power conditioner, and control system will be subjected to individual verification tests.

To provide a complete power plant design consistent with U.S. utility standards at a minimum cost, IFC entered last year into a cooperative agreement with Bechtel, one of the world's most experienced power plant engineers-constructors. Bechtel complements IFC's fuel cell capabilities by preparing the PC23 standard plant arrangement, designing and furnishing the support systems, and providing on-site installation services. The PC23 support systems to be furnished by Bechtel include plant fire protection, auxiliary electric power supply and distribution, and plant service systems. Bechtel will use the same design approach as IFC by developing factory-assembled, truck-transportable modules for these systems. In addition, Bechtel is also reviewing the overall design and arrangement to ensure consistency with utility operations and maintenance practices as well as safety and quality.

For those cases where local conditions dictate changes to the standard design, Bechtel will offer PC23 purchasers any necessary site-specific engineering and design services.

IFC and Bechtel together provide the total range of design, development, manufacturing, installation, and commissioning resources.

The fuel cell is a power generator which offers a vital alternative for dealing with many utility problems. IFC proposes that utilities, individually or as regional consortia, evaluate first-hand the fuel cell's potential by purchasing initial PC23 power plants. For this purpose, IFC will manufacture and deliver plants on a fixed-price basis, with delivery starting in 1989. Our hope and expectation is that the program will provide to utilities the evidence of fuel cell viability, which will enable IFC to make the transition to a bona fide supplier of reliable and economical fuel cell generating equipment. We expect this program will have a number of features which will prove useful both to utilities and to the manufacturer:

- o The initial power plants will have the characteristics of the production units to follow.
- o The number of initial power plants will be sufficient to provide an opportunity for a broad segment of utilities to evaluate fuel cells first-hand in order to develop the market for future production orders.
- o Enough hardware will be produced to establish quality standards and document the costs of production.
- o Field experience will be sufficient to verify the performance and reliability of the power plant and its components for both utilities and manufacturer.
- o The program will be manageable financially by both IFC and the utilities.

If this commercialization step is supported by the electric utility industry, the successful outcome will position both the manufacturing and utility segments for broad use of fuel cells in the 1990's.

THE WESTINGHOUSE 1.5 MW FUEL CELL PILOT POWER PLANT -
THE NEXT STEP TO COMMERCIALIZATION

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The Westinghouse commercialization program for air-cooled phosphoric acid fuel cells is directed toward a standardized, factory produced 7.5 MW Power Plant. These plants should be available for commercial sales in the early 1990's, however, acceptance by the Utility Industry will require firm operating and economic data. Westinghouse believes that this data should be developed jointly with interested Utilities to ensure suitability for their decision making process. Additionally, to ensure acceptance of their commercial offering, the plant should be developed with as broad a spectrum of Utility technical input as possible.

To achieve these objectives, Westinghouse intends to build a 1.5 MW Pilot Power Plant as the next step in their commercialization program and is soliciting Utility financial and technical participation.

The design of the plant is not a scaled down version of the 7.5 MW plant, but rather a composite of full size systems and components. This is possible due to the approach Westinghouse has taken to ensure a highly reliable 7.5 MW plant by breaking most major systems into modules. As shown in Figures 1 and 2, the resulting flow schematics for the two plants are virtually identical, allowing the utilization of the same control room and a full sized rotating equipment system. The fuel processor system was largely instrumental in determining the size of the plant. The 7.5 MW plant design calls for six reformer modules; therefore, utilization of one of these reformer modules will produce sufficient hydrogen to fuel 1.25 MW of fuel cells. Since the Westinghouse standard fuel cell module is rated at 375 kW, four will require operation of the single reformer module at full capacity; and with some supplemental hydrogen, allow production of 1.5 MW of electrical power. The 1.5 MW plant will also benefit from the reformer test program presently underway at the manufacturer. This test program will be completed in 1987, allowing the tested reformer hardware to be used as part of the 1.5 MW plant. Four 375 kW fuel cell modules also fit the configuration requirements for the modularized power consolidation and inverter systems, thereby allowing full size components for these systems to be utilized.

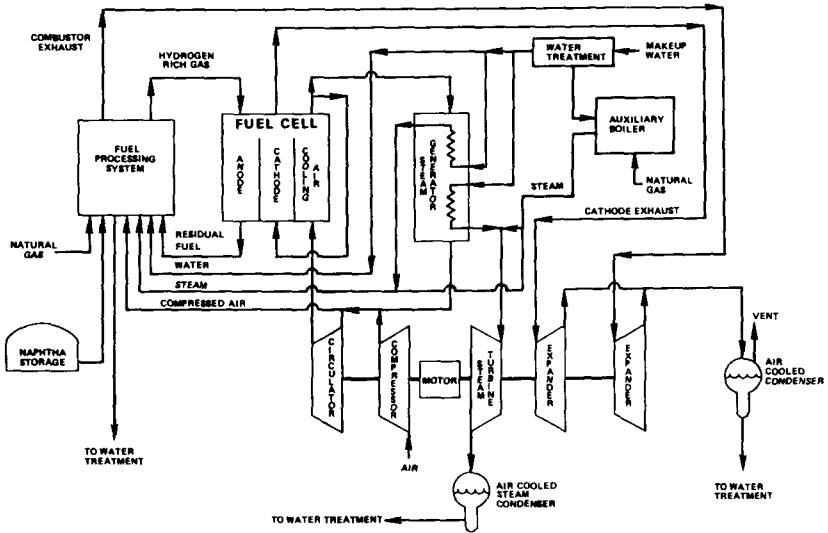


FIGURE 1

7.5 MW POWER PLANT SIMPLIFIED FLOW SCHEMATIC

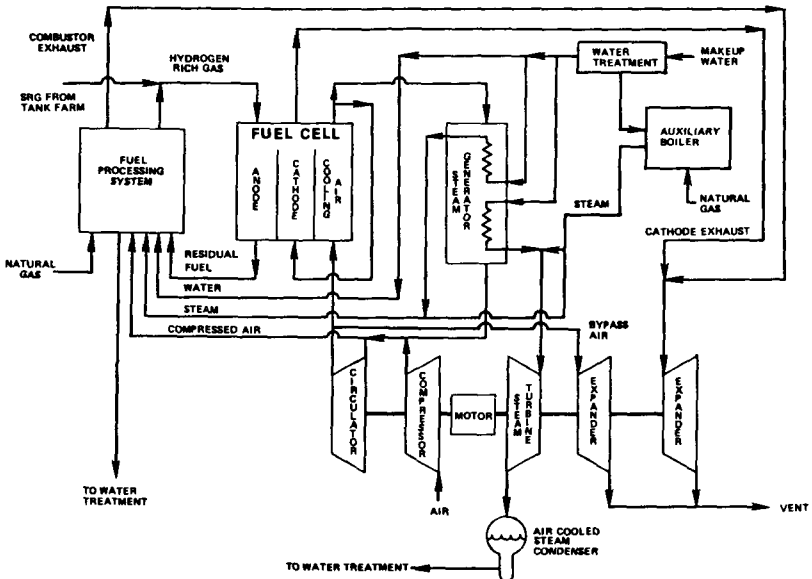


FIGURE 2

1.5 MW PILOT POWER PLANT SIMPLIFIED FLOW SCHEMATIC

Donald Newby

-3-

The major systems of the 1.5 MW Pilot Power Plant will, therefore, be designed and procured to 7.5 MW plant specifications; and components will be operated at full rated conditions. This will result in system performance and total plant integration tests closely matching the 7.5 MW plant, facilitating early resolution of start-up problems, confirmation of trade studies, and the conducting of meaningful tests to develop economic predictions.

The foregoing approach minimizes the financial commitment of any one participant, while providing the opportunity to influence the design of the 7.5 MW plant and obtain hands-on operating experience. This has particular value for potential future users of fuel cell plants since individualization of plants will be difficult when virtually the entire plant must be factory mass produced to meet cost goals. In view of this, Westinghouse considers it essential to have as wide a cross section of utility participation as possible in the 1.5 MW program. This innovative approach will provide Utilities a tool to answer operational and economic questions and ensure acceptance of the eventual 7.5 MW commercial offering.

COMMERCIALIZATION OF ENGELHARD
PHOSPHORIC ACID FUEL CELL TECHNOLOGY

BY

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Engelhard is currently developing two (2) fuel cell systems concepts: vehicular and on-site. A discussion of the prototype testing and commercialization plans for each of these technologies will be discussed.

Vehicular systems range from 5 to 30 kW and can be fueled by methanol or No. 2 diesel. Propane is also being examined as a potential fuel. This technology is expected to be commercially available by 1988.

Engelhard is also developing an on-site system in the module size range of 25 to 50 kW. These modules can be used individually or combined to multi-megawatt size and can be fueled by any hydrogen-rich stream. Prototype testing of these units is planned beginning in 1987.

Federal agencies and departments are equal opportunity employers and are committed to insuring that the benefits of programs receiving federal financial assistance are available to all eligible persons regardless of race, color, national origin, handicap or age.

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