Global SOFC activities and evaluation programmes

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Abstract

Perhaps there are a few hundred organizations worldwide at present such as universities, research institutes or companies where the research and development of SOFC is carried out, including basic research on materials for SOFCs. This paper, will not refer to the status of basic R&D materials similarities or on a single cell, but will observe developmental activities in Europe, USA and Japan, focusing on the development which has already the stage of fabrication and operation of a SOFC cell stack. Information will also include detailed operation and evaluation of the 25 kW class systems of Westinghouse.

Introduction

Organizations carrying out the fabrication and operation testing of SOFC (solid oxide fuel cell) cell stacks in Europe include Siemens AG, Dornier GmbH, Sulzer Brothers Limited and the Norcell Team organized with Elkem, Norsk Hydro and others. These organizations are all developing the planar plate-type cell stack. Its scale so far is around 100 W and it is planned to make and operate 1 to 5 kW cell stacks within one or two years.

In the USA, Westinghouse Electric Corporation, Ceramatec Inc., Ztek Corporation, and Allied Signal Aerospace Co. are conducting the development of SOFC cell stacks. Among them, Westinghouse has been carrying out the verification test of a 25 kW tubular SOFC system since 1992. The design of a 100 kW system is being carried out, and preparation is in progress for its manufacture. Ceramatec is planning to scale up the current 70 W planar-plate class of cell stack to 1 kW soon, and then, on to a 3 to 5 kW class. Ceramatec, is transferring the planar plate-type cell technology to the Norcell Team and Sulzer, is taking part in their programme.

In Japan, Fuji Electric, Sanyo Electric, Mitsubishi heavy Industries Ltd., Tonen Corporation and several other companies are conducting the development of SOFC cell stack. Their SOFC designs are mostly of the planar cell type and the present scale of cell stack is in the range of 400 to 1300 W. The verification test of a several kW cell stack is expected to be made in the near future.

In the current development status of worldwide SOFC, the area of the cell plate is 20 to 200 cm^2 with 0.1 to 0.2 W/cm^2 power density. The test duration of the cell stack is somewhere between 1000 and 3000 h.

The Westinghouse system is currently involved in a test of a maximum capacity cell stack. Since 1992, two units of an a.c. 25 kW class system have been operated by Osaka Gas, Tokyo Gas and Kansai Electric Power in Japan. The system is composed of two generator modules, having 1152 cell tubes in total with the active length of 50 cm. An internal reforming system is used employing a small prereformer. The

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operation time so far achieved with an initial system (d.c. generator) was 2595 h for one module and 1576 plus 3016 h for another one. The second system (a.c. cogeneration) has experienced 817 h with two modules. Both systems demonstrated the performance initially expected.

The development of SOFC technology has made progress during the past several years. As the SOFC has a number of advantages derived from its high operation temperature and non liquid electrolyte, many R&D programmes aimed at commercializing the SOFC will be accelerated aggressively by utilizing public funds of governments, etc., and/or private funds of industries.

Worldwide SOFC activities

In this section, emphasis is laid on the current status of four programmes of cell stack development in Europe, USA and Japan, respectively. The outline of their activities is shown in Tables 1 to 3.

Europe

In Europe, the development of a SOFC is being promoted by the funds of Commission of the European Communities (CEC), governmental organizations and private corporations.

In Germany, the joint development has been carried of a planar multiple cell array-type SOFC by Siemens with Energy Research Foundation (ECN) (Netherlands), Imperial College (UK) and GEC–ALSTHOM (UK). The verification of a 103 W cell stack was completed and the fabrication and operating test are planned to take place on 1 kW cell stack in 1993 and a 20 kW stack in 1995 [1].

Dornier in Germany has developed jointly with Cookson (UK) an externally manifolded planar SOFC cell stack. It uses a ceramic separator and 25 W power generation was conducted over approximately 3000 h using a 5-cell stack. The cells in this stack were 5 cm×5 cm and another test is planned for 10 cm×10 cm cells.

Sulzer in Switzerland is developing a heat exchanger integrated stack (HEXIS) SOFC. This HEXIS SOFC is specially composed using a circular metallic interconnector and a circular planar-type cell [2]. In Sulzer's development programme, the planar-type cell stack component is provided by Ceramatec. At present, Sulzer has made a two-cell stack using 70 mm diameter components with an active area of 31.4 cm^2 and has tested them. The goal for 1993 is operation of a thermally self-sustaining 1 kW system with 120 mm diameter cell stack.

In Norway, the Norcell Team was organized with Elkem, Norsk Hydro and others. The externally manifolder planar SOFC is being developed in the programme with Ceramatec, who is a group member of Elkem. They are planning to make a 3 to 5 kW prototype system by 1994 to be installed at the customer's premises for operation.

In addition, cell stack development in Europe is being carried out by ECN in The Netherlands and Statol in Norway, of which the latter has a target to operate a 5 to 10 kW planar SOFC plant in 1995. According to the CEC's SOFC development plan, it is scheduled to make and operate one unit of 20 kW in 1995 and another one of 200 kW in 1997.

United States of America

In the USA, the development of SOFC has been made with public funds mainly by DOE (Department of Energy), EPRI (Electric Power Research Institute), and GRI (Gas Research Institute).

TABLE 1

SOFC cell stack development – Europe

Company	Cell stack structure	Financial support	Present status	Future plan
Dornier GmbH (Germany)	Planar (ceramic separator)	BMFT[a] CEC[b] Badenwerk AG Daimler Benz AG	50 mm×50 mm 5-cell stack was operated with 25 W for more than 3000 h (350 $mA/cm^2 \cdot 0.6$ V/cell)	100 mm×10 mm cell stack test is planned
Norcell Team – Elkem included – (Norway)	Planar (Ceramatec's externally manifolded stack)	National Research Council	Stack technology optimization, system development	3–5 kW cogeneration system operation by 1994
Siemens AG (Germany)	Planar multiple cell array (metallic bipolar plate, internal manifolding)	BMFT[a] CEC[b]	10 layer stack (40 cells: 50 mm×50 mm 4 cells in one layer) was tested with 103 W (250 $mA/cm^2 \cdot 0.7$ V/cell)	1 kW stack test in 1993, 20 kW stack test in 1995, 300 kW demonstration plant in 1998
Sulzer Brothers Limited (Switzerland)	Planar (circular) cell, HEXIS[c] design stack (metallic interconnector, Ceramatec's ceramic parts)	Swiss Federal Office of Energy Swiss National Energy Research Fund	70 mm diameter 2-cell stack test	1 kW system test in 1993

[a]BMFT: General Federal Ministry of Research and Technology.
[b]CEC: Commission of the European Communities.
[c]HEXIS: Heat exchanger integrated stack.

TABLE 2

SOFC cell stack development – USA

Company	Cell stack structure	Financial support	Present status	Future plan
Allied Signal Aerospace Co.	Monolithic	DOE[a]	2-cell stack was tested over 500 h	
Ceramatec Inc.	Planar	GRI[b] EPRI[c]	Demonstrated 70 W in a 200-cell stack in 1989 at ABB, 45 W in a 10 cm^2 active area 40-cell stack (200 $mA/cm^2 \cdot 0.5$ V/cell) 4 in × 4 in cell stack fabrication	1 kW module test and, 3–5 kW prototype system test in 1993, 50 kW system test in 1996
Westinghouse Electric Corporation	Tubular	DOE	AC 25 kW systems operation in 1992	20 kW system for SoCal-Edison
		(Gas, Electric Utilities in Japan) and in the US)	Increasing generating capacity per cell	100 kW cogeneration system for SoCal-Gas (DOE Fund)
Ztek Corporation	Planar (circular) (internal manifold, metal interconnector)	EPRI	Achieved 25 W in a 10-cell stack test	

[a]DOE: Department of Energy.
[b]GRI: Gas Research Institute.
[c]EPRI: Electric Power Research Institute.

TABLE 3

SOFC cell stack development – Japan

Company	Cell stack structure	Financial support	Present status	Future plan
Fuji Electric Co.	Substrate type planar (circular) (center manifolded)	NEDO[b]	200 cm^2 10-cell stack was operated with 410 W for 2000 h (300 $mA/cm^2 \cdot 0.6$ V/cell)	Several kW module test in 1995, several tens kW module test in 1997
Mitsubishi Heavy Industries, Ltd.				
Kobe	MOLB[a] type	Chubu Electric (in part)	(150 mm × 150 mm 40-cell stack) ×3 tested with 1.4 kW for 1000 h in 1992.	Several kW module test before 1995 (200 mm × 200 mm cell)
Nagasaki	Tubular type (15 cells in 400 mm tube)	Electric Power Development (in part)	48-tube module operated with 1.3 kW for 1000 h in 1991	
	Planar	Tokyo Electric	100 cm^2 10-cell stack test with 100 W	
Sanyo Electric Co., Ltd.	Planar (inner manifold metallic bipolar plate)	NEDO[b]	125 cm^2 20-cell stack was operated with 415 W for 1000 h (300 $mA/cm^2 \cdot 0.56$ V/cell)	Several kW stack test in 1995, several tens kW test in 1997
Tonen Corporation	Planar (ceramic or alloy separator)	Petroleum Energy Center (in part)	225 cm^2 30-cell stack was operated with 1.3 kW in 1991	

[a]MOLB: Mono-block layer built.
[b]NEDO: New Energy and Industrial Technology Development Organization, Japan.

In the tubular-type SOFC development by Westinghouse Electric Corporation, the scale of the cell stack has been progressively enlarged to facilitate commercialization. The Corporation, while conducting a verification test of a 25 kW SOFC system since 1992, has also been carrying out the design of 100 kW cogeneration system. It is scheduled to come into manufacture and operating test within a few years. At present their system is the internal reforming type with the cell employing a cathode on the surface of a porous support tube. Another development is under way on the air electrode support cell (AES cell) in which the cathode material itself is used as a support tube. Also, the active length of a cell tube at present is 50 cm but, in the next step, this will be lengthened to 100 cm.

Ceramatec Incorporation has continued with the development of a planar-type SOFC for more than six years. They have succeeded in producing 70 and 45 W power generation, respectively, in 200-cell and 40-cell stacks (active cell area is 10 cm^2). Moreover, it is scheduled to test 1 kW module in 1993 and a 3 to 5 kW prototype system later. The present development target is for a cell about 4×4 inches, with the performance of 300 $mA/cm^2 \cdot 0.7$ V/cell. Ceramatec is engaged in a joint development programme in Europe in such tasks as providing cell stacks or cell components for SOFC development.

Ztek Corporation is developing a circular planar-type SOFC using a metallic interconnector and a 10-cell stack test was conducted with 25 W output [3]. The recent state of development has not been reported.

Allied Signal Aerospace Company has been continuously developing a monolithic SOFC (MSOFC), and their major effort is in research on materials and fabricating methods. The scale is kept small as far as the power generation test of cell stack is concerned. The company, however, have been successful in the operation of a flat plate SOFC with thin film (1 to 10 μm) electrolytes developed based on the technique of MSOFC, at reduced temperature of 600 to 800 °C.

DOE is planning to begin a new planar SOFC area programme which will include variations of planar SOFC configurations for both intermediate and high temperature SOFCs [4].

Japan

In Japan, a lot of fabrication and operating tests of cell stacks are in progress both as part of NEDO's* project and also by private funds.

Fuji Electric is developing a centre manifold circular planar-type SOFC with support from NEDO. Its interconnector was originally made of ceramic material but now seems to be changed to a metallic interconnector. A cell stack with 10 cells of 200 cm^2 area was tested and about 2000 h generation was achieved with 410 W output. The performance of this cell stack is approximately 300 $mA/cm^2 \cdot 0.6$ V/cell. It is planned to proceed with the development of a cell offering 300 $mA/cm^2 \cdot 0.7$ V/cell with a diameter of 30 to 40 cm. According to NEDO's development programme, development and fabrication will be conducted on several kW modules by 1995 and of operating tests of scores of kW module by 1997.

Sanyo Electric Company is currently developing an inner manifold planar-type SOFC using a metallic bipolar plate, with NEDO's support. A test was made on a cell stack having 120 cm^2 area and 20 cells and approximately 1000 h generation was achieved with the output of 415 W. The performance of this cell stack is about 300 $mA/cm^2 \cdot 0.56$ V/cell. They plan to shift to the multiple cell array-type in the future

*NEDO: New Energy and Industrial Technology Development Organization, Japan.

and enlarge its scale up to scores of kW, in accordance with NEDO's development programme.

Mitsubishi Heavy Industry, in part by joint development projects with electric power corporation, is carrying on three developments of SOFC in Kobe and in Nagasaki simultaneously, namely: (i) a monoblock layer built (MOLB) SOFC; (ii) a tubular-type (15 cells in one tube) SOFC, and (iii) a cosintered planar SOFC. A cell stack test of the 1 kW class generation of MOLB-type SOFC (i) was performed using three-cell stacks of 150 mm × 150 mm 40 cells, and 1328 W power generation at 0.65 V cell voltage was obtained at about 70% fuel utilization. The accumulated hours of generation exceeded a thousand. Also, about a 1000-h test was conducted with 48 cell tubes with 1.3 kW (ii) and 100 $cm^2 \cdot$10-cell stack with 115 W, respectively (iii).

Tonen Corporation is developing a planar SOFC, funded by the Petroleum Energy Center in Japan. It achieved 1.3 kW output with a 225 $cm^2 \cdot$30-cell stack in 1991.

As for other tests on other SOFC cell stacks in Japan, 100 $cm^2 \cdot$25-cell stack with 420 W was conducted by Tokyo Gas and cell stack tests with 100 to 300 W, respectively, were conducted by Murata Manufacturing Co., Fujikura Corporation and Mitsui Engineering & Shipbuilding Co. Osaka Gas is developing a high power density tubular SOFC and planning to test a 1 kW class tubular cell module in 1994.

The technical information exchange of SOFC in Japan is mostly made at the research meeting held quarterly by 'The Solid Oxide Fuel Cell Society of Japan'.

General status of SOFC cell stack

The description so far has considered the current development status of the cell stack, picking up each of four programmes in Europe, the USA and Japan, and the following is the general status of development:

• performance	200 to 300 $mA/cm^2 \cdot$0.6 to 0.7 V/cell
• power density	0.1 to 0.2 W/cm^2
• area of cell	20 to 200 cm^2 (maximum 400 cm^2)
• capacity of cell stack	to 1300 W (maximum a.c. 25 kW)
• type of cell	planar-type in most programmes (tubular-type in a few programmes)

Improved data have been obtained regarding the voltage degradation of a single cell, but the degradation of the cell stack still seems to be large at present and the cell stack is also not strong against thermal cycles.

Evaluation programme of tubular SOFC

Development of Westinghouse's SOFC

Since 1987, two Westinghouse Electric 3 kW generator units have been operated by Osaka Gas and Tokyo Gas for about 5000 h [5]. This programme has provided satisfactory technical evaluation. Prior to this stage of two-unit, 3 kW generators, H_2 and CO-mixed gas were used as fuel. However, since 1989, the internal reforming technique has been adopted. This reforms natural gas fuel inside the generator module. The generator module made in 1989 in the GRI's programme was operated for 5400 h and it was confirmed that the internal reforming was functioning properly. The multi kW generator (MKG) made in 1990 in the DOE's programme was operated with the output of about 20 kW for 1850 h with natural gas, 725 h with naphtha and

425 h with hydrogen, respectively. A prepilot manufacturing facility (PPMF) was built by Westinghouse in 1989, and then the manufacture of the cell was started at this PPMF. This facility provided the opportunity to move the SOFC technology from a laboratory environment to a manufacturing environment.

In 1992, two units of the 25 kW class system were manufactured using cells made at this PPMF and these have been in operation in Japan. The maximum d.c. output of this 25 kW class system is 44 kW. Also, one unit comprising a 20 kW system is currently under manufacture. It is expected to be run by Southern California Edison. Another unit, comprising a 100 kW cogeneration system, is being designed. It is scheduled to be manufactured with DOE fund, and to be operated by Southern California Gas. The basic structure of the cell has not been changed, but a continual improvement has been made by which the power generation per cell has been increased:

- up to 1988 — active length 36 cm, 2 mm thick porous support tube
- 1990 to 1993 — 50 cm long, 1.2 mm thick porous support tube
- 1993 — 100 cm long, air electrode supported (AES) cell

By means of such cell improvements, the d.c. output per cell has been increased from 20 to nearly 100 W.

TABLE 4

Specification 25 kW SOFC system, Westinghouse

a) Specifications generator		
Generator	Cell	Active length 50 cm (active area 185 cm^2) 576 cells (3 parallel × 192 series) × 2 modules
	Reforming	Internal (with prereformers)
	Operating temperature	1000 °C
	Operating pressure	Atmospheric
	Fuel	11000 kcal/Nm^3 natural gas
	Fuel utilization	85%
b) Specifications first and second system		
	First system (d.c. generator system)	Second system (a.c. cogeneration system)
Consortium	Kansai Electric Osaka Gas Tokyo Gas	Osaka Gas Tokyo Gas
Test site	Kobe	Osaka
Output	d.c. 36 kW at nominal 44 kW at maximum	a.c. or d.c. a.c. 25 kW at maximum electric efficiency a.c. 33 kW at maximum output Heat recovery as steam 27 kW (8 kg/cm^2) at maximum
Control	Automatic Each module can be operated independently	Automatic

Evaluation of 25 kW class SOFC system

The manufacture and evaluation of two units of the 25 kW class SOFC system are carried out as the joint project of Kansai Electric Power, Osaka Gas, Tokyo Gas and Westinghouse, and they are at Kobe and Osaka at present, Table 4. The output of this system at its maximum electrical efficiency is a.c. 25 kW (d.c. ~36 kW). The maximum d.c. output is about 44 kW. The system is composed of two generator module units each having 576 cells with 50 cm active length (1152 cells in two modules). These 576 cells are connected with three parallels ×192 series. The standard operating conditions are 85% for fuel utilization, 1000 °C for temperature and the pressure is atmospheric. This system is of the internal reforming type integrated with one simple and compact prereformer per 144 cells, which reforms fuel as much as 75%. The steam required for reforming is supplied through generation reaction by partial recirculation of depleted fuel. Heating of the catalyst layer is achieved by exhaust gas from the combustion zone. Accordingly, steam and heat required for fuel reforming are self-supplied and the system is simplified. A generator module is shown in Fig. 1.

The first system was installed in February 1992, at Rokko Test Center of Kansai Electric (Kobe City), Fig. 2. The output is d.c. and each of the generator modules can be independently operated. This first system was operated with about 35 kW (17.5 kW/one module) d.c. output, covering 2595 h for module A (four thermal cycles)

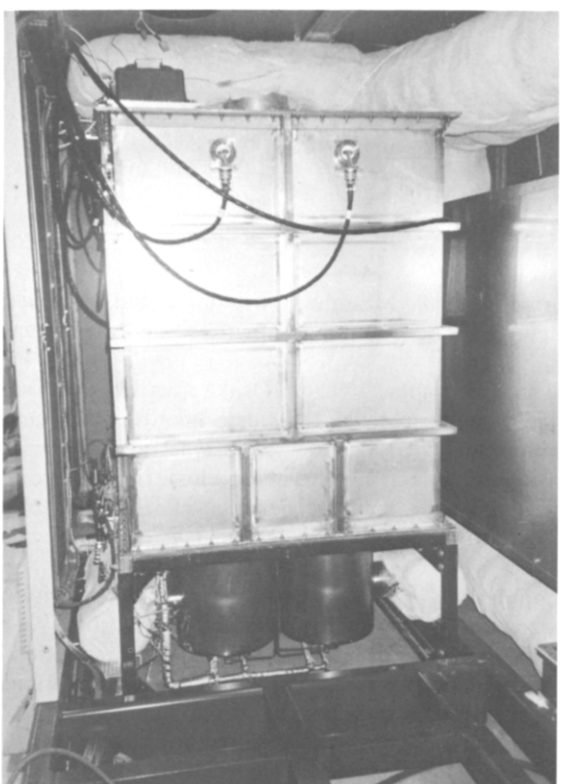


Fig. 1. Generator module of 25 kW class SOFC system.

Fig. 2. 25 kW class SOFC system (first system).

and 1576 h for module B (two thermal cycles). Module B was inspected, repaired and restarted at the end of March, 1993. The running time after the restart was 3016 h as from September 22, 1993, Table 5.

The second system was installed in September, 1992, at Osaka Gas Iwasaki Test Center (Osaka City). The system is designed to recover the waste heat as steam and outputs both by a.c. and d.c. are available. This second system was operated with maximum d.c. output of 30.6 kW and totally 817 h (four thermal cycles). In this second system, it was necessary to adjust the air-supply balance between the two modules after the initial operation. At present, a study is being made on how to inspect and repair modules, Table 6.

The voltage of the generator module has been rising since the initial operation and no degradation has resulted during the operating period, Fig. 3. Up to 2595 h the maximum measured *V–I* performance reached the design value in the first system. At the second system, it was lower by about 5% owing to shorter operating time, Fig. 4. The upper end of the operating range of each system was limited because of some leaking cells which appeared during the operation.

These systems are not only capable of the perfect automatic operation, but also of automated systematic functioning. No operation crews have been assigned on holidays and at night time. It takes 7 to 8 h from cold state to normal operation.

TABLE 5

Operation test summary 25 kW SOFC system Westinghouse — first system

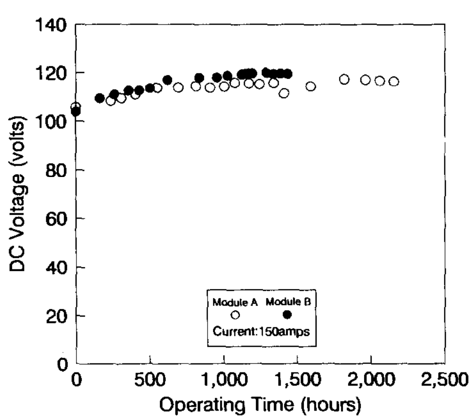
	First system (d.c. generation)		
	Module A	Module B	Module B (repaired)
Test period	11/29/91 (Pgh.)[a] 7/12/92 (Kobe)	12/19/91 (Pgh.)[a] 4/29/92 (Kobe)	3/31/93(Kobe) (as from 9/22/93)
Operating time	2595 h	1576 h	3016 h
Average load	16.8 kW	17.4 kW	16.9 kW
Startup/cooldown	4 times	2 times	1 time
Partial cooldown	9 times	3 times	2 times
Major problems	Air heater burnout Low string voltage	Period of excessively high fuel utilization	Air blower failure

[a]Phg. = Pittsburgh.

TABLE 6

Operation test summary 25 kW SOFC system, Westinghouse — second system

	Second system (a.c. cogeneration)
Test period	7/2/92(Pittsburgh) — 10/21/92(Osaka)
Operating time	817 h
Average load	30.6 kW
Startup/cooldown	4 times
Partial cooldown	8 times
Major problems	Module flow imbalance Hot spot in Quadrant A and low string voltage



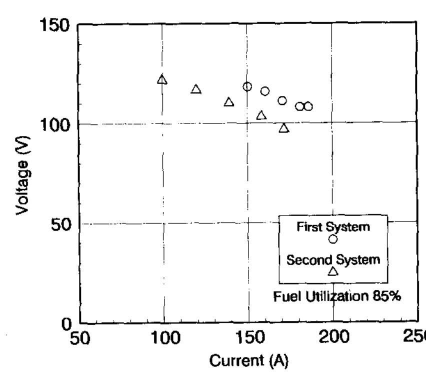


Fig. 3. Voltage vs. operating time (first system); 25 kW SOFC system, Westinghouse.

Fig. 4. Module operation results: 25 kW SOFC system, Westinghouse.

Since this 25 kW class system is small in capacity with a large percentage of parasitic power and envelop heat loss, as well as with porous support tube cell, the electrical efficiency is rather low. However, that of a 500 kW system using the AES cell and advanced generator technology can be estimated to be 50% even at maximum power on the basis of LHV (45% for HHV).

Conclusions

Worldwide the SOFC activities are gaining momentum. Various cell concepts related to materials, cell geometries, fabrication processes, etc., have been created and some of them have been developed up to 1 kW class stack tests.

In the Westinghouse SOFC, two units of 25 kW class system have been manufactured with a simple system design and operated for more than 2500 h. These units represent one of the significant milestones in the commercialization of the SOFC.

As the SOFC offers many advantages which include high efficiency, low maintenance and high-quality exhaust gas, the development programmes including fundamental research should be promoted more actively in future. In addition, by means of well-advanced technical exchange between the researchers and organizations, the duration for commercializing the SOFC can be shortened.

References

1 W. Drenkhalm and H.-E. Vollmar, *Ext. Abstr., Fuel Cell Seminar, Tucson, AZ, USA, Nov. 29–Dec. 2, 1992,* p. 419.
2 R. Diethelm, K. Honegger and B. Barp, *Proc. Int. Fuel Cell Conf., NEDO, Makuhari, Japan, Feb. 3-6, 1992,* p. 329.
3 M. Hsu and H. Tai, *Ext. Abstr., Fuel Cell Seminar, Phoenix, AZ, USA, Nov. 25–28, 1990,* p. 115.
4 D.T. Hooie, *Proc. 3rd Symp. Solid Oxide Fuel Cells, Honolulu, MI, USA, May 16–21, 1993,* p. 3.
5 S.C. Singhal, *Proc. 2nd Symp. Solid Oxide Fuel Cells, Athens, Greece, July 2–5, 1991,* p. 25.