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Progress in the planar CPn SOFC system design

L.J. Frost, R.M. Privette, A.C. Khandkar
SOFCo, 2425 South 900 West, Salt Lake City, UT 84119, USA

Abstract

A high efficiency, modular planar SOFC module using the patented CPn module has been demonstrated on pipeline natural gas. The results of this 1.4 kW thermally integrated module, along with stack/cell tests, have verified the multi-stage oxidation concept. Design and analysis of a 10 kW mobile electric power generating system using this technology predicts a final module with >40% system efficiency when operated on logistics fuel. However, this analysis also stresses the need for improved cell performance at lower temperature. Ceria-based planar single cells have been demonstrated at >300 mW/cm^2 at 750 °C.

Keywords: Solid oxide fuel cells; System design

1. Introduction

SOFCo, a Babcock and Wilcox/Ceramatec company, is developing the CPn module design, a compact multi-stack module configuration which enhances modularity, efficiency and reliability. The design features multi-stage oxidation wherein the fuel is consumed incrementally over several stages. Improved fuel efficiency is obtained by allowing each stack in the fuel series to operate independently at its optimal voltage while maintaining a uniform current density for the given fuel composition. The multi-stage fuel oxidation option has been previously discussed and has been shown to increase stack efficiency significantly [1–5]. A 1.4 kW module based on this patented design was demonstrated using pipeline natural gas. Several tests conducted on short stacks and modules operating on humidified H_2 have shown very good correlation to theoretical models and verify the predicted improvement in efficiency.

In a parallel program, planar fuel cells using ceria as an electrolyte operating at 700–800 °C are under development. High performance and endurance of ceria cells have been demonstrated.

A demonstrating program for a 10 kW mobile electric power generating system operating on military logistic fuel is currently in progress. Several system designs have been evaluated and the results indicate the possibility of using SOFCs to fulfill the requirements. Considerations of temperature, weight, performance, and logistic fuel processing options have all been evaluated and the results are outlined below.

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2. Status of SOFC technology at SOFCo

2.1. SOFC single cell

Single cells have been shown to produce power 200–300 mW/cm^2 at 900 °C on numerous occasions. Endurance testing of a cell operated at 200 mA/cm^2 and 1000 °C is shown in Fig. 1. The cell has exceeded 35 000 h under load with an overall degradation rate below 0.5%/1000 h. The cell has also experienced several deep thermal cycles to room temperature with minimal effect. Open-circuit voltage has also remained stable for the duration of the test indicating good seal integrity. Several advancements have been made in electrode microstructure enabling testing of improved cells with equivalent power operating at 900 °C. Endurance characteristics of these cells are shown in Fig. 2.

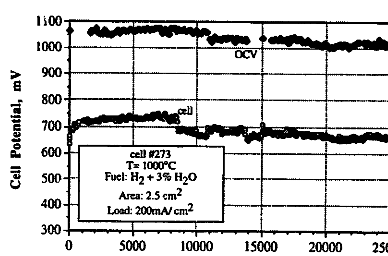

Fig. 1. Single cell endurance test at 1000 °C.

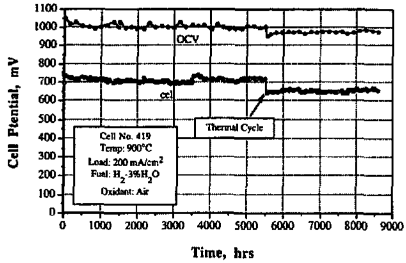

Fig. 2. Endurance characteristics of improved cells at 900 °C.

2.2. *Stack testing*

Stack tests using both 5 cm and 10 cm square components were conducted. Stack test results from a seven-cell stack fabricated using the ceramic interconnects are shown in Fig. 3. As can be seen, it achieved a performance 300 mA/ cm^2 at 0.65 V/cell at 50% fuel utilization. The operating temperature of the stack was 950 °C. The endurance characteristics of the stack are shown in Fig. 4. A more recent 31 cell 10 cm stack operating with an air inlet temperature of 850 °C produced 315 mA/cm^2 at 0.5 V.

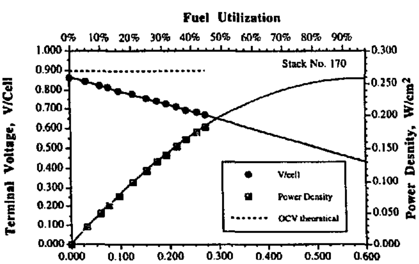

Fig. 3. Performance of a seven-cell stack at 950 °C.

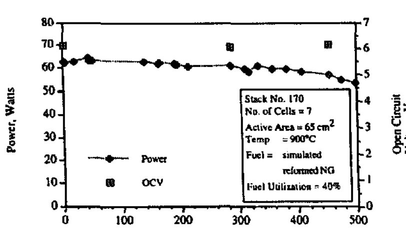

Fig. 4. Long-term endurance of a seven-cell stack at 900 °C.

2.3. *The CPn design*

The CPn module consists of a multi-stack arrangement that allows multi-stage oxidation of the fuel in a thermally integrated SOFC module, which houses the fuel cell stacks, heat exchanger, reformer tubes, and a spent fuel burner. Air, used as the fuel cell oxidant and coolant, is preheated through the counterflow heat exchanger with the stack air exhaust and delivered to the SOFC stacks. The heat exchanger is incorporated into the wall of the module housing. The fuel processing system is thermally coupled to the stacks within the insulated enclosure accomplishing indirect internal reformation of hydrocarbon fuels. A schematic of the stack arrangement is shown in Fig. 5.

2.3.1. *CPn design verification test*

A two-stage stack was conducted to verify the CPn design concept. It consisted of two nine-cell stacks with a cell area of 5 cm × 5 cm and an electrode active area of 22 cm^2/cell. The interconnects used in this test were made of an experimental metal alloy. The fuel, H_2 humidified by bubbling through a reservoir of water at room temperature to give approximately 3% water vapor, was fed through the upstream fuel inlet manifold, and passed through both stacks sequentially. The fuel test was maintained at a flow rate that corresponded to approximately 33% fuel utilization per stage at 10 A current per stack. The air was manifolded to flow in a single pass. The performance test consisted of testing the stack pairs in electrical series and of testing each of the stacks individually. The initial voltage of the downstream stack was about 60 mV/cell lower than the upstream stack possibly due to some leakage. The two stacks were initially tested individually and then tested in electrical series. The performance of both stacks under these conditions are shown in Fig. 6.

The module design was also verified in a multi-stack arrangement. The unit was operated at 900 °C air inlet with desulfurized pipeline natural gas. The power output of the unit was 1.4 kW. More recently a newer cell technology has been verified at a lower operating temperature of 850 °C. The power output of the unit was 850 W at an average cell voltage of 0.5–0.55 V /cell.

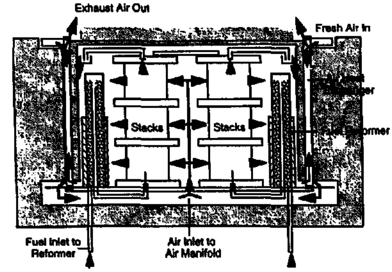

Fig. 5. Schematic of CPn module stack arrangement.

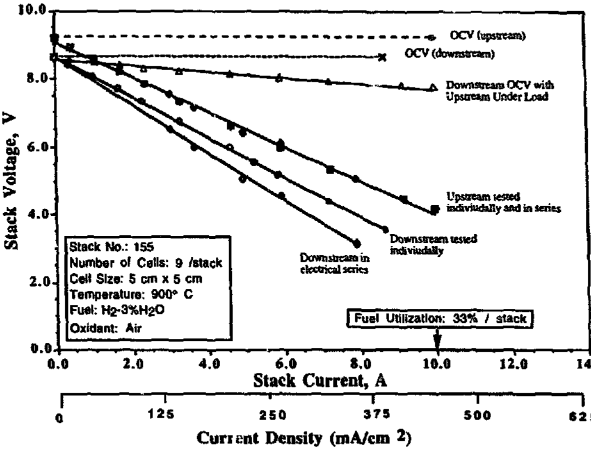

Fig. 6. Two-stage stack module: performance characteristics.

3. Mobile electric power generator

SOFCo plans to design a mobile electric generator based on the patented planar SOFC CPn staged oxidation design. The CPn design will be integrated with a proprietary steam reforming catalyst developed by the Institute of Gas Technology (IGT) and the Gas Research Institute (GRI). System integration will make use of the extensive Babcock and Wilcox (B and W) power generation system design experience. The integration of fuel processing equipment necessary to reform logistic fuel with SOFC stacks into a compact hardware configuration represents a significant advance in the state-of-the-art in SOFC system technology.

Toward this end, the introductory phase of a three-phase, four-year program with the objective of designing and demonstrating a 10 kW mobile electric power generator operating on logistic fuel has been recently completed. Objectives of Phase 1 included: the development of a preliminary system design based upon the target military application parameters, an assessment of technologies critical to system performance including integrated sulfur-tolerant fuel reforming processes, and the fabrication of multi-stack test units for performance evaluation.

One key aspect of this program is that military power systems must operate on logistic fuels (JP-8, DF-2). The use of sulfur-laden (0.3 wt.%) logistic fuel requires processing to convert the fuel to a hydrogen-rich, low-sulfur gas for use in the fuel cell stacks. SOFCo's reforming approach is to evaluate the IGT Sulfur Tolerant Reformer (STR) [6] which does not require the large equipment necessary for hydrodesulfurization, and avoids gas dilution common in other reforming strategies.

Another key feature is thermal integration of critical processes within an insulated generator enclosure. Heat from the fuel cells is used for both the fuel reforming and the preheating of incoming air. This approach results in high system efficiency, promotes a compact system design, and requires no external utilities for operation.

Phase 2 will focus on developing a 2–4 kW non-integrated breadboard system employing all key elements of the generator design. Completion of the 10 kW generator design and demonstration of a prototype system incorporating the integrated SOFC module concept will be performed in Phase 3.

3.1. Phase 1 Results

The US Army Lightweight Multipurpose Shelter (LMS) was chosen as the target application for this project. The SOFC generator fits within a small tunnel, measuring approximately 29 in × 25 in × 84 in, near the front of the shelter. The selection was based on the Army's interest in an advanced power supply for the LMS, and the suitable match between the LMS power requirement and the demonstration size for the current program.

In parallel with the selection of the LMS application, two competing process designs were analyzed and conceptual hardware design layouts were considered. Primary considerations for the system designs included complexity and technical risk, overall system efficiency, and size and weight. Both systems incorporate steam reforming of the JP-8 fuel, and post-reforming removal of sulfur in a ZnO bed. The primary difference between the schemes is the method for obtaining the steam required for the reforming. A single system was then selected from the competing designs and refined for the current application.

The first system, referred to as 'anode gas recycle', recycles a portion of the anode exhaust to supply steam for the reforming reaction. The recycle stream is mixed with the incoming JP-8 fuel prior to entering the reformer. The remaining anode exhaust is mixed with air from the cathode exhaust and burned to provide heat for fuel reforming and air preheating operations.

The second system termed 'anode gas condensation', incorporates a condenser in the fuel cell anode exhaust stream. The water vapor is first condensed, then separated and later reheated in a steam generator before ultimately being mixed with the incoming vaporized fuel. This system benefits from a smaller water vapor recycle stream and eliminates the need for a high temperature blower. It does, however, require the use of a condenser and small steam generator. Heat is provided to the steam generator by burning a combination of anode exhaust and incoming JP-8 fuel.

Analyses of both systems were completed using the ASPEN PLUS [7] process simulator. The results of these analyses are shown in Table 1. As can be seen, both systems were projected to achieve 40+% system net efficiency. One significant difference was the steam-to-carbon ratio that may be necessary to avoid coking as predicted by a thermodynamic equilibrium analysis.

The need for a small, high temperature blower and the increased potential for carbon formation in the 'anode gas recycle' system were the primary factors in the selection of the 'anode gas condensation' system for future development. Following selection, the 'anode gas condensation' configuration was refined to more closely match reformer performance demonstrated during Phase 1 of this program, and to optimize heat integration between the system components. In particular, the following refinements were made:

- the steam-to-carbon ratio was increased from 1.8 to 2.5
- a recuperative bayonet reformer design was incorporated
- the air preheater was modified to provide easier access and better control
- the use of a vertical condenser design was evaluated

Predicted performance of the refined system is shown in Table 2. Net power generation of 10.2 kW is expected at a net system efficiency of 40%. Reformer stream steam-to-carbon ratio is 2.5, and the system air flow is approximately seven times the stoichiometric flow requirement.

Table 1
Predicted performance using ASPEN simulator

	Scheme 1 Anode gas recycle	Scheme 2 Anode gas condensation
Net system efficiency (%)	45.3	43.8
Fuel flow (lb m/h)	3.65	3.76
Steam-to-carbon ratio	1.8	1.8
Fuel utilization (%)	82.6	93.3
Air flow (times stoichiometric air)	7.6	7.2
Operating voltage (V/cell)	0.68	0.73

Table 2
Refined performance model for anode gas condensation

	Scheme 2: refined Anode gas condensation
Number of cells	265
Net system efficiency	40.0
Net power (kW)	10.2
Fuel flow (lb m/h)	4.13
Steam-to-carbon ratio	2.5
Fuel utilization	95.4
Air flow (times stoichiometric air)	6.89
Operating voltage (V/cell)	0.71

3.2. *Future work*

While the preliminary design fits within the space envelope of the LMS, the weight of the SOFC system is higher than desired. Phase 2 system design work will focus on reducing system weight and refining component sizing and performance estimates.

Phase 2 work will build on the results of Phase 1 through the breadboard demonstration of a 2–4 kW non-integrated SOFC generator. The breadboard generator will provide valuable experience on fuel processing system scale-up, and fuel cell stack performance operating on logistic fuel reformate. Demonstration of the breadboard system is scheduled for July 1996.

4. Low temperature electrolyte development

The high operating temperature of SOFCs poses considerable challenges in cell operation. Thermochemical interactions of cell materials and morphological changes in electrode structure leading to performance degradation at high temperature operation suggest that lower operating temperature may be advantageous. Additionally, the lower temperature operation enables the use of inexpensive alloy for heat exchangers which will lower the system cost. Ceria-based electrolytes have been evaluated for performance and endurance at lower operating temperatures.

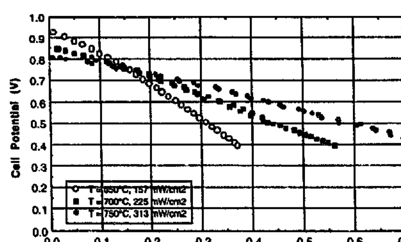

Fig. 7. Performance of rare earth-doped CeO_2 electrolyte.

Fig. 7 shows the performance of a rare earth-doped ceria-based single cell. The cell area was 2.5 cm^2 and was operated on air and 3% humidified H_2. The parasitic mixed conduction losses have been minimized and a peak performance of > 300 mW/cm^2 has been demonstrated at 750 °C. Endurance tests on these cells at 133 mA/cm^2 have exceeded 3000 h with < 0.5%/1000 h degradation rates.

5. Conclusions

Planar SOFCs have been operated with satisfactory performance for periods greater than 35 000 h. Performance has also been demonstrated with both ceramic and metal interconnects. A module design with multi-stage oxidation was tested and to have measured performance as expected from modeling. Efforts are underway to scale up this performance and size of SOFC modules.

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References

[1] M. Dokiya, N. Sakai, T. Kawada and H. Yokokawa, *Proc. Int. Fuel Cell Conf., Makuhari, Japan, 1992*, p. 309.
[2] R.A. Gaggioli and W.R. Dunbar, *Trans. ASME, 115* (1993) 100.
[3] A. Solheim, R. Tunold and R. Ødegard, in F. Gross, P. Zegers, S.C. Singhal and O. Yamamoto (eds.). *Proc. 2nd Int. Symp. Solid Oxide Fuel Cells*, Commission of the European Communities, L-2920, Luxembourg, *EUR-13546EN*, 1992, p. 297.
[4] D.G. Walhood and J.R. Ferguson, in F. Gross, P. Zegers, S.C. Singhal and O. Yamamoto (eds.), *Proc. 2nd Int. Symp. Solid Oxide Fuel Cells*, Commission of the European Communities, L-2920, Luxembourg, *EUR-13546EN*, 1991, p. 289.
[5] J. Hartvigsen, S. Elangovan and A. Khandkar, in S.C. Singhal and H. Iwahara (eds.), *Proc. 3rd Int. Symp. Solid Oxide Fuel Cells, 1993*, Proc. Vol. 93-4, The Electrochemical Society, Pennington, NJ, USA, 1993, p. 878.
[6] A.L. Lee, Catalytic steam reforming of diesel fuel for fuel cell hydrogen production, Final Rep. to Fort Belvoir, Contract No. *DAAK70-86-P-0810*, 1986.
[7] *Aspen Technology*, Inc. Cambridge, MA, USA.