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Status of tubular SOFC field unit demonstrations

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Abstract

Siemens Westinghouse is in the final stage of its tubular solid oxide fuel cell (SOFC) development program, and the program emphasis has shifted from basic technology development to cost reduction, scale-up and demonstration of pre-commercial power systems at customer sites. This paper describes our field unit demonstration program including the EDB/ELSAM 100-kW e combined heat and power (CHP) system, the Southern California Edison (SCE) 220-kW e pressurized SOFC/gas turbine (PSOFC/GT) power system, and the planned demonstrations of commercial prototype power systems. In the Spring of 1999, the EDB/ELSAM 100-kW e SOFC–CHP system produced 109 kW e net AC to the utility grid at 46% electrical efficiency and 65 kW t to the hot water district heating system, verifying the analytical predictions. The SCE 220-kW e PSOFC/GT power system will undergo factory startup in the Fall of 1999. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: SOFC; Fuel cells; Solid oxide fuel cells; Tubular SOFC

1. Introduction

Siemens Westinghouse (and previously Westinghouse Electric) has been developing tubular solid oxide fuel cell (SOFC) technology in earnest for nearly 20 years. Over this period, the basic cell design, materials and manufacturing processes, the basic cell stack configuration including depleted fuel gas recirculation and in-stack reformation, and the atmospheric pressure system design have all been developed and their performance verified through extensive test programs. A very important part of our test program is our field unit demonstrations, which have evolved from 3 kW e power systems in 1987 using 36 cm active length cells and fueled by H_2/CO to a 100-kW e combined heat and power (CHP) system in 1997 using 150 cm active length cells and fueled by natural gas. The next field unit will be the world's first pressurized SOFC/gas turbine (PSOFC/GT) power system rated at 220 kW e and scheduled to undergo factory startup in the Fall of 1999. The focus is on the design, operating history and lessons learned for the EDB/ELSAM 100-kW e SOFC–CHP system, and the design, build and predicted performance for the Southern California Edison (SCE) 220-kW e PSOFC/GT power system. It concludes with our planned demonstrations of commercial prototype power systems.

2. Field unit demonstrations

2.1. EDB/ELSAM 100-kW e SOFC–CHP system

In late 1997, Siemens Westinghouse delivered to EDB/ELSAM (a Dutch/Danish utility consortium), an atmospheric pressure 100-kW e SOFC–CHP system to a district heating substation in Westervoort, a town near Arnhem in The Netherlands. Through August 1999, it remains the largest operating SOFC system, producing between 105 and 110 kW e net AC to the utility grid and approximately 65 kW t to the hot water district heating system. In addition, this power system achieved an impressive 46% electrical efficiency (net AC/LHV) in the Spring/Summer of 1999.

2.1.1. Design description

The 100-kW e SOFC–CHP system is the first field unit to utilize the commercial prototype air electrode supported cells (22 mm diameter, 150 cm active length, 834 cm^2 active area) and in-stack reformers. The next level of fabrication hierarchy after the cell is the cell bundle, which consists of a 24-cell array arranged as eight cells in electrical series by three cells in electrical parallel as shown in Fig. 1. Four cell bundles are connected in series to form a bundle row, and 12 bundle rows are aligned side by side, interconnected in serpentine fashion with an in-stack reformer between each bundle row. This 48-bundle

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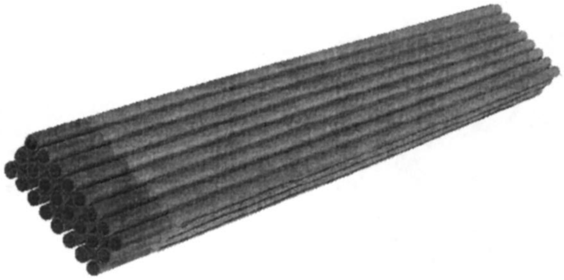

Fig. 1. Typical 24-cell bundle of tubular SOFCs.

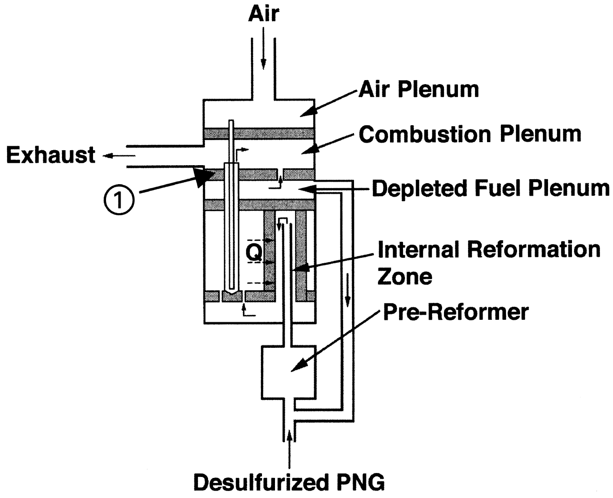

Fig. 3. The 100-kW e stack simplified flow schematic.

array along with the stack reformers and the ejector and pre-reformer assembly, is shown in Fig. 2. The simplified schematic in Fig. 3 shows the fluid flow features of the 100-kW e stack. The array of vertically aligned cells is separated horizontally into five zones by horizontal ceramic baffles that, except for the uppermost, are either porous or have clearance around the cells passing through them. The zones defined by the baffles are as follows: the fuel distribution plenum below the cell stack, the active cell space, the depleted fuel plenum, the combustion plenum above the cell stack, and the air plenum. Desulfurized natural gas at several atmospheres pressure above cell operating pressure is introduced as the primary fluid in an ejector or jet pump. This ejector withdraws depleted fuel from the depleted fuel plenum and mixes it with the incoming natural gas. The mixture passes through an adiabatic pre-reformer where higher hydrocarbons and a small percentage of methane are reformed. The primarily methane stream is then routed to the top of the in-stack reformers from where it flows downward through a catalytically active space to the fuel distribution plenum. The in-stack reformers are heated radiantly by the fuel cells. The fully reformed fuel passes over the exterior of the fuel cells where it is electrochemically reacted, generating electrical power and heat. The depleted fuel is passed to the depleted fuel plenum where a portion is recirculated and a portion passes to the combustion zone. Air is introduced into the air plenum and is routed to the interior and bottom of each tubular cell by an air feed tube. The air passes upward in the annular space between the cell cathode and the air feed tube. The vitiated air passes into the combustion zone where the depleted fuel is completely reacted. The hot gas in the combustion zone preheats the incoming air in the air feed tubes. From the combustion zone, the hot exhaust gas is routed out of the SOFC.

The 100-kW e SOFC–CHP system was designed in five major skids: SOFC module (described above), fuel supply, thermal management and electrical, power conditioning, and heat export. The fuel supply system desulfurizers the incoming natural gas and delivers regulated desulfurized natural gas to the ejectors in the SOFC module. The fuel supply system also provides purge gas for startup and shutdown, and a small amount of steam for startup only. The thermal management system consists of main and auxiliary air blowers, a recuperator, an electric air heater for startup only, and associated ducting and valving. The control and electrical distribution cabinets also reside on the thermal management system skid. The power conditioning system provides the interface with the utility grid, converting the DC power produced by the SOFC module

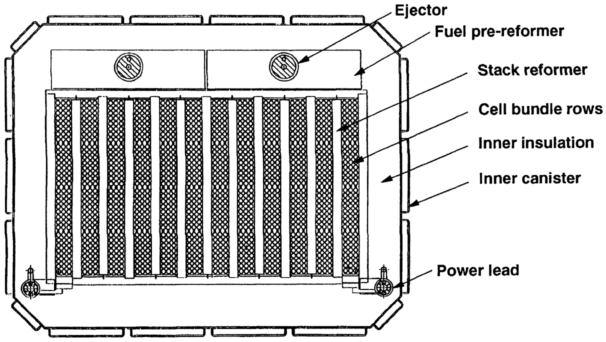

Fig. 2. The 100-kW e stack cross-section.

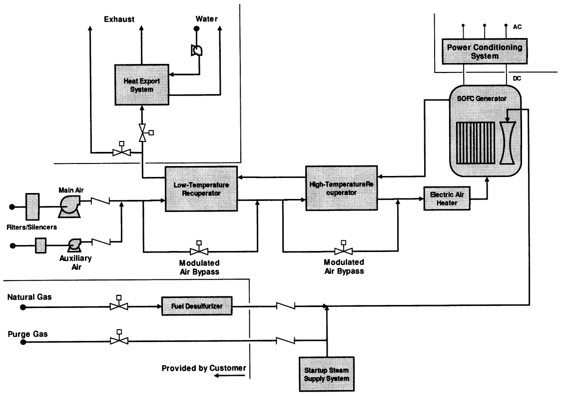

Fig. 4. The 100-kW e SOFC–CHP system simplified flow schematic.

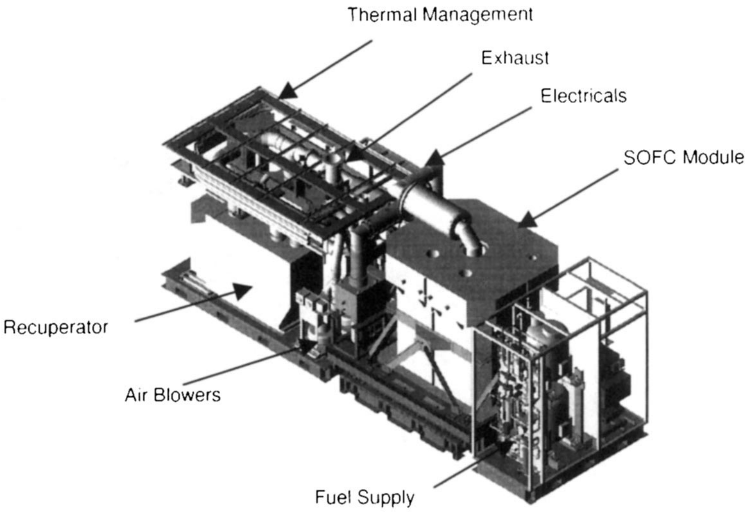

Fig. 5. Isometric of the 100-kW SOFC–CHP system showing major components.

to AC power required by the grid: 400 V, three-phase, 50 Hz. In case of grid interruptions or problems with the power conditioning system, a DC dissipator (i.e., variable resistance load bank) is also provided to permit continued system operation. The heat export system recovers heat from the exhaust gas exiting the recuperator by heating water to 56°C as part of the district heating system. Fig. 4 presents a simplified flow schematic of the 100-kW e SOFC–CHP system. Fig. 5 presents an isometric of the system excluding the power conditioning system and heat export system, and Fig. 6 presents a photograph of the installed system at the customer site also excluding the power conditioning system and heat export system.

2.1.2. Operating history

The 100-kW e field unit underwent factory testing in October 1997. It operated for 335 h at the factory prior to shutdown to prepare the unit for shipping to The Netherlands. The unit arrived in The Netherlands in November 1997 and startup occurred 19 days thereafter. The unit operated essentially unattended for a total of 3700 h, producing 105–110 kW e net AC to the grid at 42% electrical efficiency for about 1700 h. (At other times, it was either at part load or operating on the DC dissipator.) The measured electrical efficiency (42%) was significantly below the analytical prediction of 47%. In addition, temperature distribution and localized voltage anomalies were observed, and measured fuel gas compositions at the cell exit were indicative of air leakage to the fuel side. As a results of these observations, the unit was shutdown for inspection and repair on June 26, 1998. As can be seen from Fig. 7, the terminal voltage showed no signs of degradation over the 3700-h operating period except for a sulfur poisoning incident which was corrected by replacing the desulfurizer reagent, activated carbon. (One important lesson learned is that activated carbon is not an effective

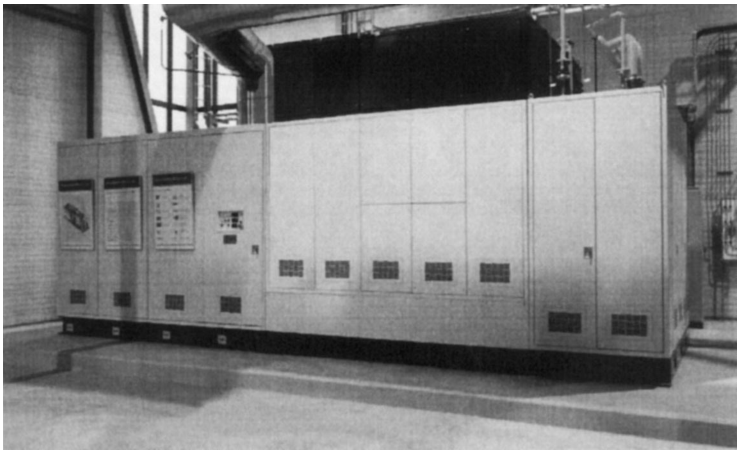

Fig. 6. Photograph of EDB/ELSAM 100-kW SOFC–CHP power system.

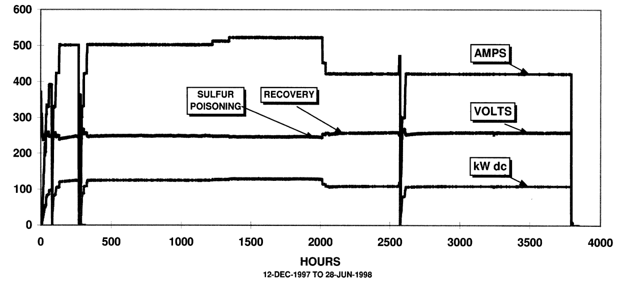

Fig. 7. EDB/ELSAM 100-kW e SOFC–CHP system Build 1 module performance.

desulfurizer in the presence of thiophene, requiring replacement every 1000–1200 h.)

The module was then returned to the factory for inspection where the problem was found to be failed baffle boards at the cell open ends, which allowed air leakage into the depleted fuel plenum (see Fig. 3, item 1). Since a portion of the gas in this plenum was recirculated by the natural gas-driven ejector, the incoming fuel was partially oxidized (approximately 5%) prior to reaching the cells. In addition, all the nickel components on the fuel side underwent surface oxidation during the cooldown since the gas in the depleted fuel plenum continued to be recirculated by the ejector now driven by purge gas instead of natural gas. The final observation was partial loss of electrical contact between a small number of adjacent bundles, explaining the localized voltage anomalies.

After design improvements were made to the baffle boards and the cell bundles replaced, the SOFC module was returned to the site and reinstalled in February 1999. The unit was restarted in early March. Almost immediately a significant improvement in performance was noted. The electrical efficiency improved from 42% for Build 1 to 46% for Build 2, very close to the analytically predicted value of 47%. Fig. 8 presents the Build 2 module DC performance, and Fig. 9 presents the system AC performance. Note, on Fig. 8, the stability of the terminal voltage (no voltage loss after 2200 h of operation) and the SOFC module DC efficiency of 53%. The difference between the DC efficiency of 53% and the net AC efficiency of 46% is attributed to the parasitic system loads (7–8 kW e) and the inverter efficiency (92.5%).

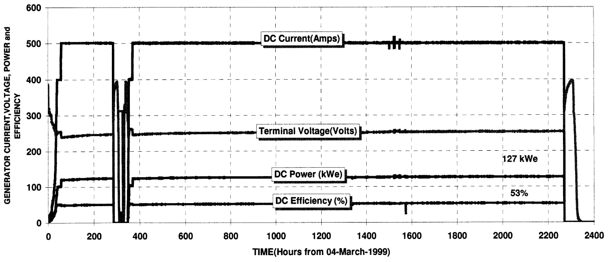

Fig. 8. EDB/ELSAM 100-kW e SOFC–CHP system, Build 2 module performance.

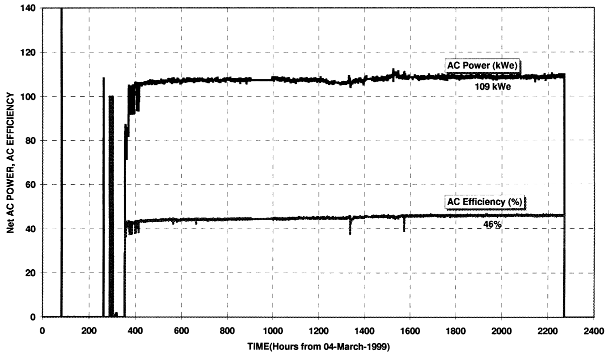

Fig. 9. EDB/ELSAM 100-kW e SOFC–CHP System, Build 2 AC performance.

After operating for nearly 2200 h following the rebuild, the unit went into STOP on July 9, 1999 due to a failure of the static switch which connects the power conditioning system output to the AC grid. The problem has been fixed and the unit awaits restart at or about the end of August 1999.

2.2. SCE 220-kW e PSOFC / GT power system

In July 1997, SCE contracted with Westinghouse Electric (now Siemens Westinghouse Power) to design, build and deliver for test the world's PSOFC/GT power system. As of the end of August 1999, the microturbine generator (MTG) has been received from the supplier, Northern Research and Engineering (NREC) and the system assembly is nearing completion.

2.2.1. Design description

The stack design is the same as that utilized in the EDB/ELSAM 100-kW e SOFC–CHP system. For the 220-kW e system, however, the stack is contained within a pressure vessel and will be operated at 3 atm absolute pressure.

The system design consists of five major subsystems: SOFC module, fuel supply, thermal management including the MTG, electricals, and power dissipation devices. As in the 100-kW e unit, the fuel supply system desulfurizes the incoming natural gas and delivers regulated desulfurized natural gas to the ejectors in the SOFC module. It also provides purge gases for startup and shutdown, and a small amount of steam for startup only. The thermal management system consists of a two shaft, recuperated, MTG, a startup duct burner for the MTG, a startup duct burner to preheat SOFC inlet air, an auxiliary air system for shutdown, and associated piping and valving. The controls and electrical distribution cabinets also reside on the thermal management skid. Because of the experimental nature of this power system, it was decided not to connect the power system to the grid to avoid grid initiated transients. Therefore, power dissipators are provided to dissipate the SOFC

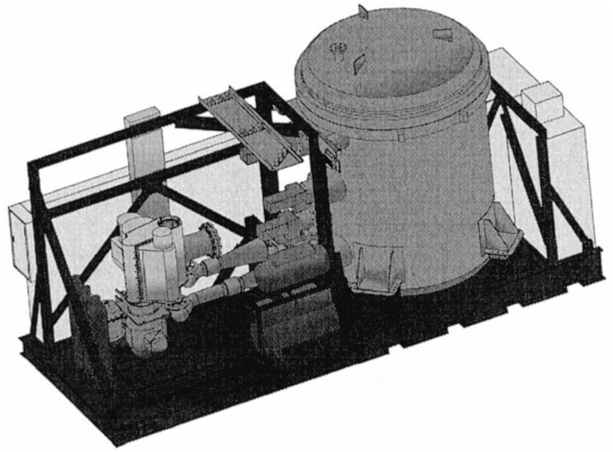

Fig. 10. SCE 220-kW e PSOFC/GT power system assembly.

DC power and the MTG AC power. The system assembly exclusive of the power dissipators is illustrated in Fig. 10.

Fig. 11 presents a flow schematic for the 220-kW e PSOFC/GT power system. Air is drawn through a filter, increased in pressure by the gasifier compressor, heated by the power turbine exhaust gas in a recuperator, routed to an air heater (duct burner C1), then to the SOFC air inlet. Fuel is compressed to increase its pressure, desulfurized and then routed to the SOFC fuel inlet (ejectors). The SOFC exhaust at an operating pressure of about 3 atm absolute and at 850°C is routed to the gasifier expander driving the gasifier compressor, then to the power turbine driving the AC generator, then through the recuperator and to the exhaust stack.

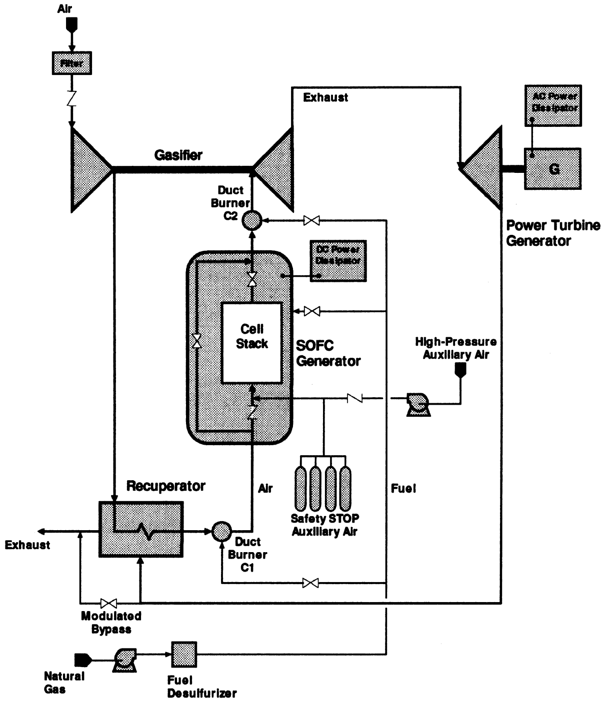

Fig. 11. SCE 220-kW e PSOFC/GT power system flow schematic.

Table 1
SCE 220-kW e PSOFC/GT power system predicted performance summary

Cell current	267 A
Cell voltage	0.610 V
Pressure ratio	2.9
Compressor air intake rate	1.3 lb/s
Turbine inlet temperature	840°C
SOFC DC power	187 kW e
SOFC gross AC power	176 kW e
GT AC power	47 kW e
System net AC power	220 kW e
Efficiency (net AC/LHV)	57%

Table 1 presents the predicted performance summary for the SCE 220-kW e PSOFC/GT power system. As shown the total system output and electrical efficiency, if it were grid connected, is predicted to be 220 kW e (176 kW e from the SOFC plus 47 kW e from the MTG minus 3-kW e system loads) and 57% (net AC/LHV), respectively. For the same number of fuel cells as the 100-kW e SOFC–CHP, the system power output is roughly doubled (from 110 to 220 kW e net AC) and the electrical efficiency is increased from 46% to 57%.

2.2.2. Test schedule

A process and control test of the system without the cell stack but with all other components in place including the pressure vessel and its internal insulation will be conducted in September/October 1999 at the factory in Pittsburgh, PA. Once the system functionality has been verified and the control loops tuned, the cell stack will be inserted in the pressure vessel in preparation for the Factory Acceptance Test (FAT) to be conducted in late October/November 1999. Following the FAT, the unit will be shipped to the customer site at the University of California, Irvine. System installation will occur in December 1999/January 2000, and site testing should begin January/February 2000.

2.3. Planned demonstrations

Following the SCE 220-kW e PSOFC/GT proof-of-concept demonstration, four to six additional pre-commercial demonstrations are planned. Siemens Westinghouse intends to design, build and test in collaboration with development partners and customers the following commercial prototype systems: one or two 250-kW e SOFC–CHP systems, one or two 320-kW e PSOFC/GT power systems, and two 1-MW e PSOFC/GT power systems. The design of these units will benefit from the lessons learned from the 100-kW e SOFC–CHP system and 220-kW e PSOFC/GT power system demonstrations, and the cost reduction and design simplification programs that have been ongoing in earnest over the last couple of years. Siemens Westinghouse is actively negotiating with identified customers concerning four of the above demonstration systems. In addition to the demonstrations identified above, Siemens Westinghouse has performed a conceptual design for Shell Oil concerning a ‘‘zero-emission’’ SOFC power system employing CO_2 sequestration. Shell is currently evaluating our proposal to design, build and test such a system. The SOFC field unit demonstration phase is expected to continue through 2002. Sufficient test data will have been generated by 2002 to verify our readiness for commercialization.

3. Summary and conclusions

Given that the EDB/ELSAM 100-kW e SOFC–CHP system was our first field unit to employ our commercial prototype cells and our internally developed stack reformers, Siemens Westinghouse is very pleased with its performance to date. Late 1999 and early 2000 will prove very enlightening and exciting concerning the performance of the world’s first PSOFC/GT power system. Notwithstanding, development of this hybrid system represents a major extrapolation from the company’s experience base, hence schedule slippages have occurred during resolution of unexpected design issues. One thing is for certain, we will learn much. Our pathway to commercialization seems to be well lit and hopefully the trip will not be too bumpy.

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