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PRESSURIZED SOLID OXIDE FUEL CELL/GAS TURBINE COMBINED CYCLE SYSTEMS

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SUMMARY

Over the last 10 years, Westinghouse Electric Corporation has made great strides in advancing tubular solid oxide fuel cell (SOFC) technology towards commercialization by the year 2001. In 1993, Westinghouse initiated a program to develop pressurized solid oxide fuel cell/gas turbine (PSOFC/GT) combined cycle power systems because of the ultra-high electrical efficiencies, 60-75% (net AC/LHV CH4), inherent with these systems. This paper will discuss SOFC technology advancements in recent years, and the final phase development program which will focus on the development and demonstration of PSOFC/GT power systems for distributed power applications.

KEYWORDS:
Fuel Cells, SOFC, Combined Cycles, Distributed Power

INTRODUCTION

Since 1958, when the high temperature, oxygen ion conductivity of zirconium oxide was first discovered, Westinghouse Electric Corporation has been the world leader in the development of solid oxide fuel cell (SOFC) technology. SOFCs offer a clean, pollution-free technology to electrochemically generate electricity at high efficiencies. These fuel cells provide high efficiency, reliability, modularity, fuel adaptability, low noise levels, and very low levels of NO_x, SO_x, and CO_2 emissions. Furthermore, because of the high temperature of operation (~1000°C), SOFC generators can be operated directly on natural gas eliminating the need for an expensive, external reformer system. These SOFC generators also produce high temperature exhaust gases which can be used for process heat or a bottoming electric power cycle to further increase the overall efficiency. In particular, pressurized SOFC (PSOFC) generators can be successfully used as replacements for combustors in gas turbines (GT); such integrated PSOFC/GT power systems are expected to have electrical efficiencies in the range 60-75%.

TECHNICAL DESCRIPTION

Over the last 10 years of tubular SOFC development, Westinghouse Electric Corporation has made great strides in advancing this technology towards commercialization. Significant advancements have been made in the areas of cell power output, cell voltage stability and lifetime, thermal cycle toughness, and scale-up of SOFC generators and power systems. Figure 1 presents the evolution of SOFC power output since 1986. As can be observed, cell power output has been increased by nearly a factor of 12 primarily as a result of material changes and size scale-up to our commercial size cell (22 mm O.D., 1500 mm active length). Concerning voltage stability and lifetime, two cells were operated for 69,000 hours (7.9 years) with a voltage degradation rate of 0.4% per 1000 hours, and a 25 kWe SOFC generator consisting of

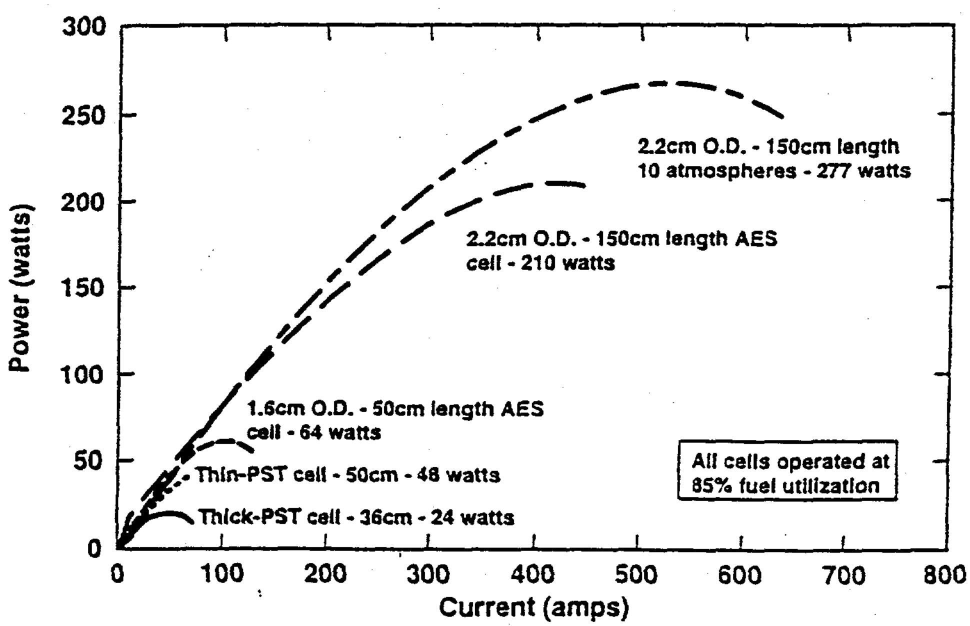

Figure 1 - Advancements in Tubular SOFC Power Output.

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576 cells of 500 mm active length was operated for 13,000 hours with a voltage degradation rate of 0.2% per 1000 hours. Concerning thermal cycle performance, Westinghouse thermal cycled 2 cells over 100 times from 1000°C (operating temperature) to room temperature and back; Kansai Electric thermal cycled 4 other Westinghouse cells again over 100 times; and the above mentioned 25 kWe generator experience 10 thermal cycles. These cells showed no signs of performance loss or damage as a result of these thermal cycles.

In addition to the above cell advancements, significant advancements in SOFC generators and power systems have also been made. Beginning in 1987, 3 kWe SOFC power systems were tested by Tokyo Gas and Osaka Gas on H_2/CO. Beginning in 1990, 25 kWe class SOFC power systems were tested by Kansai Electric, Osaka/Tokyo Gas, Southern California Edison, and Westinghouse primarily on pipeline natural gas. In addition testing on naphtha, jet fuel, and diesel fuel was also successfully performed. Design features of the 25 kWe class SOFC generator include 1) seal-less generator design, 2) internal, exhaust gas heated reformer, and 3) spent fuel recirculation to eliminate external steam supply. Starting in 1997, a 150 kWe (net AC) SOFC power system will be tested by EDB/ELSAM, a Dutch and Danish Utility Consortium. The SOFC generator for this power system produces 170 kWe DC and contains 1152 commercial size cells. A flow schematic of this generator is shown in Figure 2. The internal, exhaust gas heated reformer of the 25 kWe class generator was replaced with stack reformer boards (SRB's) as shown in Figure 2. The cells radiate directly to the SRB's providing the heat for reformation.

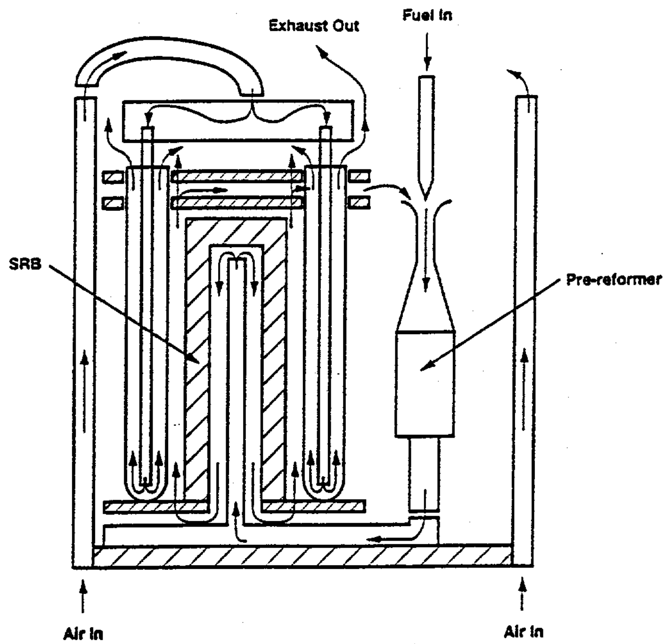

Figure 2 - Flow Schematic Within the 170 kWe DC SOFC Generator.

The final phase of the tubular SOFC development program will focus on the development and demonstration of pressurized solid oxide fuel cell/gas turbine (PSOFC/GT) combined cycle power systems for distributed power applications. The commercial PSOFC/GT product line will cover the power range 200 kWe to 50 MWe, and the electrical efficiency for these systems will range from 60% to 75% (net AC/LHV CH_4), the highest of any known fossil fueled power generation technology. Figure 3 illustrates the features of this combined cycle. The compressor portion of the gas turbine delivers pressurized and recuperated air to the SOFC module(s). Except for startup, the natural gas fuel is fed only to the SOFC module(s). The fuel and oxygen in the air electrochemically react within the module(s) to produce DC electrical power and hot exhaust gas. The hot exhaust gas is directed to the expander portion of the gas turbine driving the air compressor and an electric generator. The SOFC exhaust gas temperature is typically 850°C and the operating pressure, at least for the early commercial units, will be in the range 3 to 7 atm absolute, which are very compatible with existing industrial gas turbine technology.

The first demonstration of a pressurized solid oxide fuel cell/gas turbine combined cycle will be a proof-of-concept 250 kWe PSOFC/MTG power system consisting of a single 200 kWe PSOFC module and a 50 kWe microturbine generator (MTG). This system, which is being designed and built with funds from the U.S. Department of Energy (DOE), a U.S. Utility, and Westinghouse Electric Corporation, is scheduled for initial startup in third quarter, 1998 at a U.S. Utility selected site. Table 1 presents performance estimates for a 250 kWe PSOFC/MTG power system. Note that an electrical efficiency of 62% is achievable at a power output rating of only 250 kWe. This demonstration will provide valuable "lessons learned" in the design, build and operation of such systems applicable to the subsequent "MWe-Class" combined cycle demonstration described below.

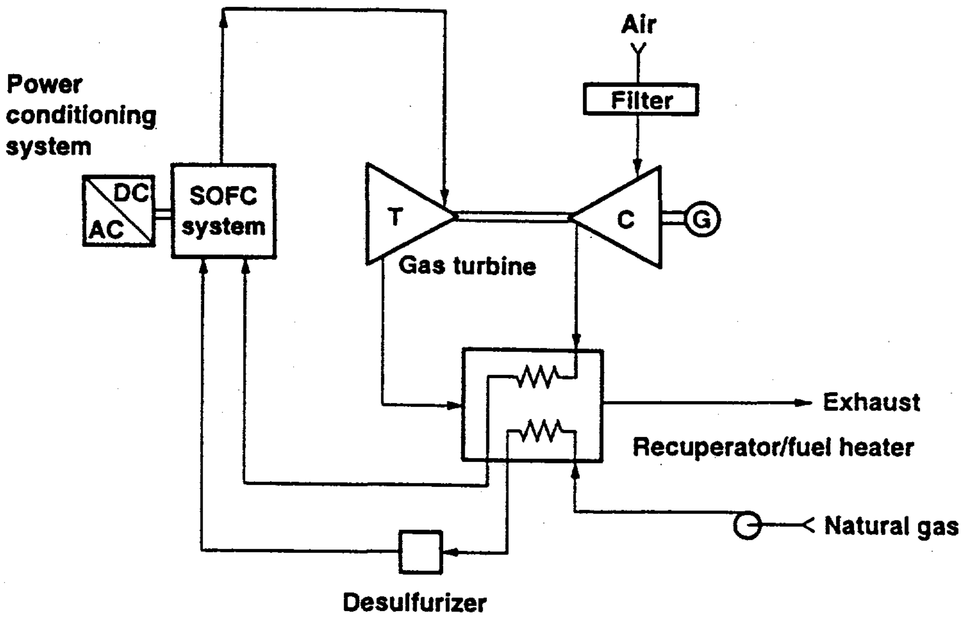

Figure 3 - Simplified PSOFC/GT Schematic.

Table 1. 250 kWe PSOFC/MTG System Performance Estimates

Parameter	Design Point
Pressure ratio	3.5
Compressor air flow rate, lb/hr	3720
Turbine inlet temperature, °F	1524
SOFC current density, mA/cm^2	327
Cell current, amps	281
Cell voltage, volts	0.695
SOFC fuel utilization, %	80
SOFC stoichs	3.7
SOFC fuel flow rate, lb/hr	70.1
MTG combustor fuel flow rate, lb/hr	0
SOFC bypass air flow	0
Electric heater power	0
SOFC ac power, kWe	214.9
MTG ac power, kWe	46.6
Plant ac power output, kWe	261.5
Plant ac efficiency (ac/LHV), %	62.3

The second demonstration of this combined cycle will be 1.3 MWe fully packaged, commercial prototype PSOFC/GT power system consisting of two 500 kWe PSOFC modules and a 300 kWe gas turbine. The program plan and funding consortium, tentatively consisting of one or more Electric Utilities, DOE, Westinghouse, an industrial gas turbine manufacturer, and the Environmental Protection Agency (EPA), are currently being organized with the objective of initiating testing at EPA's new laboratory located at Fort Meade, Maryland by first quarter 2000. This system will produce electrical power with a 63% electrical efficiency, and will be very representative of early commercial units to be offered in the market place starting in the year 2001.

The final demonstration phase is less well developed but conceptually will consist of upgrading the 63% efficient, 1.3 MWe system to a 70% efficient, 2.5 MWe system and initiating testing in late 2000/early 2001. This will be accomplished by adding two more 500 kWe PSOFC modules, and changing the gas turbine from a single shaft 300 kWe engine to a dual shaft (gas generator and power turbine) 500 kWe system. As shown in Figure 4, two of the four 500 kWe PSOFC modules will provide the turbine inlet gas to the gas generator at 9 atm absolute. The gas generator exhaust will be at 3 atm absolute and be reheated by the other two 500 kWe PSOFC modules prior to entering the power turbine. This dual shaft concept in combination with the SOFC reheat feature allows the attainment of previously unimaginable electrical efficiencies exceeding 70%.

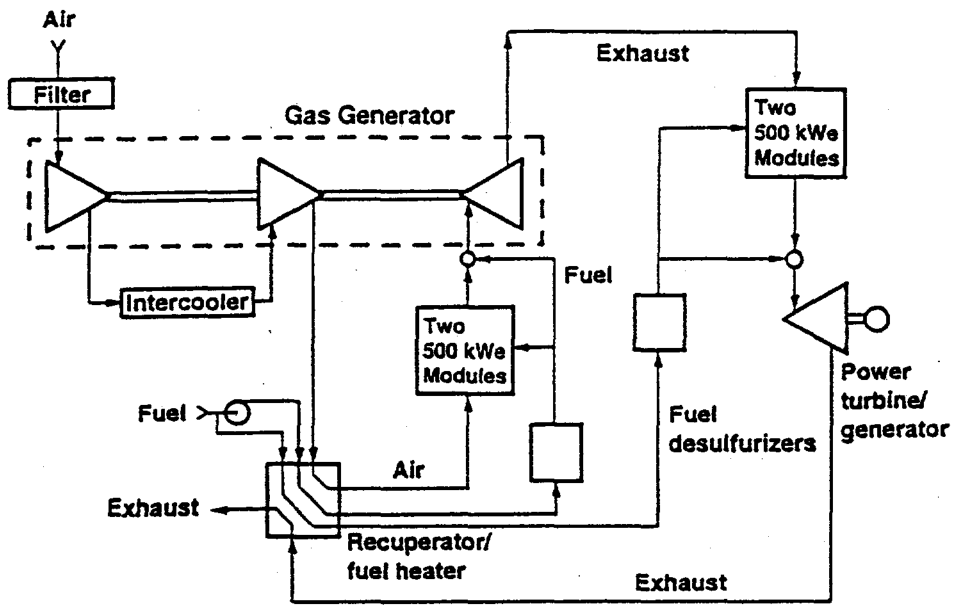

Figure 4 - 2.5 MWe PSOFC/GT System Schematic.

Our commercialization plan calls for delivering the first commercial PSOFC/GT power system in late 2001. These early systems will have ratings in the 1-3 MWe range, electrical efficiencies in the 60-65% range, and NO_x, SO_x emissions below the limits of detectability. In addition, two detailed cost studies on the Westinghouse PSOFC/GT system performed by consultants to DOE have concluded that a total installed cost of $1000/kWe is achievable under large production volume assumptions. Based upon the system performance attributes and cost studies, Westinghouse believes that PSOFC/GT power systems will play an important role in the power generation mix of the 21st century.

CONCLUSIONS

The development of SOFC technology for power generation applications has come a long way from those early research days when the oxygen ion conductivity of zirconium oxide was first investigated. Westinghouse has successfully develop its commercial size SOFC, and has demonstrated long life, stable voltage performance, and the ability to endure many thermal cycles. In addition, the atmospheric SOFC generator technology including the seal-less design, integrated natural gas reformers, and spent fuel recirculation, has been developed nearly to the point of commercial readiness. Cost reduction and design adaptation for pressurized operation are the remaining tasks to be performed. The SOFC power system technology including automatic control without operator assistance and rapid, transient response capability has been reliably demonstrated many times. The final SOFC development phase will focus on the development of PSOFC/GT combine cycle power system technology. Such systems will be capable of electrical efficiencies in the range 60-75%. Commercialization is expected in 2001 with the offering of a MWe-class PSOFC/GT combined cycle power system.

ACKNOWLEDGMENTS

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