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Solid Oxide Fuel Cell Combined Cycles

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Author:

F.P. Bevc
W.L. Lindberg
D.M. Bachovchin

Contractor:

Westinghouse Electric Corporation
1310 Beulah Road
Pittsburgh, Pennsylvania 15235-5098

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Frank P. Bevc
Power Generation Business Unit
Westinghouse Electric Corporation
Orlando, Florida

Wayne L. Lundberg and Dennis M. Bachovchin
Science & Technology Center
Westinghouse Electric Corporation
Pittsburgh, Pennsylvania

ABSTRACT

The integration of the solid oxide fuel cell (SOFC) and combustion turbine technologies can result in combined-cycle power plants, fueled with natural gas, that have high efficiencies and clean gaseous emissions. Results of a study are presented in which conceptual designs were developed for three power plants based upon such an integration, and ranging in rating from 3 to 10 MW net ac. The plant cycles are described, and characteristics of key components are summarized. In addition, plant design-point efficiency estimates are presented, as well as values of other plant performance parameters.

INTRODUCTION

The development of SOFC power plant concepts has been based to date on atmospheric-pressure SOFC technology. That is, fuel and air pressures within the SOFC system are generally within 0.1 atm of the atmospheric-air pressure. However, increasing attention is being focused on SOFC power plants in which the SOFC system is operated at elevated pressure levels. At Westinghouse, this is due to the results of cell performance analyses, and cell testing, which indicate that cell voltage increases with the cell's operating pressure. Consequently, operating an SOFC at elevated pressures leads to increased power output for a given cell current, and to increased cell efficiency as well. In addition, the elevated operating pressure will also enable SOFC integration with a combustion turbine cycle, and in large plants, this integrated system could still be combined with a steam turbine bottoming cycle. Preliminary studies indicate that such three-level combined-cycle power plants are capable of power generation efficiencies in the 65-75% (LHV) range, values that are significantly higher than those projected for atmospheric-pressure SOFC/steam turbine combined cycles, and for state-of-the-art and advanced combustion turbine combined cycles. With its characteristically high exhaust temperature (1120K), the SOFC technology is extremely well suited for application in systems that integrate it with thermal power generating systems.

Due to the increasing availability of efficient, low-power, combustion turbines, and to the modular nature of the SOFC technology, power plants based on the integration of pressurized-SOFC and combustion turbine technologies potentially will also work well when deployed in small, distributed-power applications. Such applications, typically needing power in the 1 to 20 MW range, require low emissions, small footprints, quiet operation, and high efficiency, and they may, or may not, utilize a steam bottoming cycle. SOFC/combustion turbine power plants can meet such requirements, and distributed-power generation is potentially a very attractive, early-market-entry application for the SOFC technology. To enable an assessment of the performance of SOFC/combustion turbine power plants in this application, we recently completed a conceptual design study of three distributed-power plants - one rated at 3 MW net ac, one at 4.5 MW net ac, and the third, at 10 MW net ac. In each case, a cycle was configured, assuming a specific combustion turbine, and plant performance was estimated. It is the purpose of this paper to summarize study results.

Background on SOFC power generation and on Westinghouse SOFC development was provided by Bevc and Parker (1995).

THE PRESSURIZED-SOFC/COMBUSTION TURBINE POWER PLANT

Effect of Pressure on SOFC Performance

Cell performance analyses and experiments indicate that cell voltage, for a given cell current, increases with increasing cell operating pressure. Predictions of the relationship between cell voltage and pressure are presented in Figure 1. These predictions are corroborated in tests (Ray et al., 1995) being performed by Westinghouse and Ontario Hydro Technologies on small fuel cell bundles. The effect of pressure on cell voltage is clearly significant. A typical cell operating voltage is 600 mV, and the figure indicates that operation at 10 to 15 atmospheres, a common combustion turbine pressure range, will result in a voltage increase of at least 60 mV, or 10%, and for a given cell current, the cell power output and its efficiency will increase by the same percentage. The development of more power from the same hardware, at higher efficiency levels, are key advantages of SOFC pressurization. Another is the opportunity pressurization provides for enhanced exhaust heat utilization, and this contributes additionally to the achievement of increased power plant efficiencies.

Description of the Pressurized-SOFC/Combustion Turbine Cycle

A cycle integrating the SOFC and combustion turbine technologies is depicted in Figure 2. Variations on this cycle have been studied by others; for example, see Rokni (1993), and Harvey and Richter (1993, 1994). In our cycle, the SOFC system is composed of one or more SOFC modules arranged in flow parallel. The system receives pressurized, preheated air and desulfurized natural gas fuel, and it produces dc power and a hot (~1120K) exhaust stream. The exhaust, with an oxygen composition of 14-17%, can serve as a preheated oxidant for the combustion turbine; if its temperature matches turbine inlet requirements, the SOFC exhaust could be expanded directly by the combustion turbine, with the need for no fuel addition at the turbine combustor.

Air for the SOFC system is provided by the turbine compressor. The temperature required at the SOFC inlet (~770K) is achieved by the recuperator, utilizing heat recovered from the turbine exhaust. For maximum cycle efficiency, the recuperator effectiveness should be maximized consistent with plant design requirements relating to component physical size and economic performance.

The power plant fuel is natural gas. The gas will contain naturally-occurring sulfur-bearing compounds, or sulfur-bearing odorants that are added for safety purposes. To preclude a sulfur reaction with SOFC materials, the fuel's sulfur concentration must be reduced to the 1 ppmv (ppm, volume basis) level before SOFC entry.

Cycle Feature Alternatives

To enhance power plant performance, or to serve particular customer needs, the cycle could be equipped with features in addition to those identified in the simple cycle diagram of Figure 1. Choosing among them will depend on the application, and on a careful evaluation of plant economics. Among the alternative cycle features are compressor intercooling, combustion turbine steam injection, a steam turbine bottoming cycle, and combustion turbine reheat.

Pressurized SOFC Module

The SOFC system in an SOFC/combustion turbine power plant is composed of SOFC generator modules, in a parallel flow arrangement, with the number of standard, factory-produced modules being set by the plant power requirement and by economics. A single pressurized SOFC module consists of a horizontal pressure vessel, the length of which can be set to house a desired number of SOFC submodules. For this study, each submodule is composed of 2496 cells and has a peak dc power capability of 675 kW; each cell is of the Westinghouse tubular, air-electrode-supported design, and has a diameter and active length of 22 mm and 1500 mm, respectively. Due to the near equalization of pressures on the air and fuel sides of each cell, the cell technology developed for use in atmospheric-pressure power plants is completely applicable in the pressurized power plant.

A pressurized SOFC module designed to house three submodules is depicted in Figure 3. The module operates at 10 atm (absolute), and its design features the internal reformation of the natural gas fuel. A gas recirculation loop inside the module pressure vessel serves each submodule. The loop provides water for the fuel reforming reaction, and the required reforming heat is supplied by the exothermic SOFC electrochemical reaction.

The dimensions of each submodule are 2900 mm(w), 2400 mm(h), and 2900 mm(l). The overall dimensions of the SOFC module pressure vessel are 4200 mm(d), and 9300 mm(l).

PRESSURIZED-SOFC POWER PLANT DESCRIPTIONS

10 MW Power Plant

This plant is intended for industrial/commercial application. It is dispatched in the baseload mode to applications that require quality power with high plant availability.

The baseline cycle for the 10 MW SOFC/combustion turbine power plant is shown in Figure 4. It is based on the Figure 2 cycle concept, but some additional detail is shown. Fuel desulfurization is accomplished by a zinc oxide-based desulfurizer unit. The desulfurizer operates at 673K, a temperature level that is achieved by heating fuel using a relatively small amount of heat recovered from the turbine exhaust. Desulfurized fuel is also supplied to the combustor. This is not required, but designing for it will result in plant sulfur oxide emissions that are virtually zero.

The Allison Engine Company combustion turbine product line, and specifically an Allison 501-KB4, may provide a suitable combustion turbine basis for the power plant. A summary of KB4 characteristics is presented in Table 1.

TABLE 1. ALLISON 501-KB4 COMBUSTION TURBINE PARAMETERS

Compressor Air Flow	15.4 kg/s
Combustor Outlet Temperature	1314K
Compressor Pressure Ratio	10:2
Fuel Flow Rate	0.26 kg/s
Shaft Power	3580 kW

The plant includes four SOFC modules of the design depicted in Figure 3. The modules could be installed individually, or they could doubled, resulting in the housing of six SOFC submodules in each of two horizontal pressure vessels.

Performance estimates for a 10 MW SOFC/combustion turbine power plant based on the Allison 501-KB4 are presented in Table 2. For all performance estimates discussed herein, ISO ambient air is assumed, and the assumed power conditioning efficiency is 96%.

TABLE 2. 10 MW SOFC/COMBUSTION TURBINE POWER PLANT PERFORMANCE ESTIMATES

SOFC Fuel Flow	0.29 kg/s
Combustor Fuel Flow	0.07 kg/s
SOFC Power	6.8 MW ac
Turbine Power	3.6 MW ac
Plant Power	10.3 MW net ac
Plant Efficiency (LHV)	60%
Plant Exhaust Flow Rate	15.6 kg/s
Plant Exhaust Temperature	630K

Of critical importance is the power plant's NOx emission performance. NOx generation will occur in this plant at two locations - in the SOFC system, where the electrochemically-unreacted fuel mixes with the depleted-air stream and burns, and at the turbine combustor. A significant fraction of the heat required to serve the combustion turbine is SOFC-generated. The majority of this SOFC heat is produced as a byproduct of the electrochemical process, and in the absence of nitrogen. Thus, its generation is accompanied virtually by zero NOx formation. However, the remainder of the SOFC heat is produced by the combustion of depleted SOFC fuel as it exits the fuel cell anode and mixes with excess air exiting the cathode. Nitrogen is involved in this process, but the process is still a low NOx producer. The combustion of the depleted fuel occurs at many sites in the form of small (0.25 mm) diffusion flames. The flame residence time at each site is very short, and substantial NOx generation is therefore precluded. NOx measurements (Ray et al., 1995) on atmospheric-pressure field units, that utilize a similar combustion zone design, show exhaust NOx concentrations of less than 1 ppmv, and early measurements on the exhaust from a pressurized SOFC test stand are indicating concentrations of 2 ppmv.

The other plant NOx source is the turbine combustor in which vitiated air, the 1120K SOFC exhaust, supports the combustion of natural gas that is fired to achieve the required turbine inlet temperature. The combustor for this power plant would be patterned after the Westinghouse multi-annular swirl burner (MASB), Domeracki et al., (1995), which was designed originally for burning synthetic fuel gas, with high fuel-bound nitrogen (FBN), in a high-temperature oxygen-depleted air stream. The FBN is converted in the combustor to N_2, rather than to NOx, by employing a long-residence-time (45 ms) fuel-rich zone. The process temperature is 1860K, and combustion is followed by rapid quench and dilution to minimize the formation of thermal NOx. In the SOFC power plant application, utilizing natural gas fuel, there is no FBN, and the MASB design would therefore produce NOx only by the prompt-NOx mechanism. Based on chemical kinetics analysis, it is estimated that designing for a rich-zone temperature and residence time of 1590K and 25 ms will result in a NOx generation rate of approximately 3 ppmv. This, in addition to the 2 ppmv NOx estimate for the SOFC system, results in a power plant NOx estimate of approximately 5 ppmv.

3 MW and 4.5 MW Power Plants

The 3 MW plant is designed for baseloaded substation support. It is based on the Heron combustion turbine (Hendriks, 1993), an engine being developed and marketed by the Dutch firm, Heron Exergy B.V.. The Heron cycle is illustrated in Figure 5. The turbine, a two-shaft engine, is intercooled, recuperated, and reheated. Its rating is 1.4 MW net ac, and a cycle efficiency of 42.9% (LHV) is achieved. Values of key cycle parameters are provided in Table 3.

TABLE 3. HERON COMBUSTION TURBINE PARAMETERS

Compressor Air Flow	5.15 kg/s
HP Combustor Exhaust Temperature	1134K
LP Combustor Exhaust Temperature	1136K
Compressor Pressure Ratio	8.8:1
Power Turbine Exhaust Temperature	893K
Power Plant Exhaust Temperature	498K
Recuperator Effectiveness	88.3%

One possibility for integrating an SOFC system with the Heron turbine is shown schematically in Figure 6. In this cycle, Cycle 3-1, the SOFC system, consisting of one SOFC module of the Figure 3 design, is placed ahead of the high-pressure (HP) combustor. To accommodate the SOFC system, the cycle is again equipped with a desulfurizer to process the SOFC natural gas fuel. It is found that an operating point can be selected such that SOFC heat is sufficient to provide the inlet temperature required at the compressor turbine inlet, with the need for zero fuel flow to the HP combustor.

A variation on this cycle, Cycle 3-2, is illustrated in Figure 7. A single SOFC module is again positioned ahead of the HP combustor, but the new feature is a second SOFC module, of the same design, that is located upstream of the low-pressure (LP) combustor. This module too is supplied with desulfurized natural gas fuel, but its oxidant stream is vitiated air from the compressor-turbine exhaust. Again, depending on the selection of the SOFC operating point, the heat produced by this SOFC system can be sufficient to result in the need for zero fuel flow at the LP combustor. Performance estimates for Cycles 3-1 and 3-2 are presented in Table 4.

TABLE 4. 3 MW-CLASS SOFC/COMBUSTION TURBINE POWER PLANT PERFORMANCE ESTIMATES

	Cycle 3-1	Cycle 3-2
HP SOFC Fuel Flow, kg/s	0.079	0.078
HP Combustor Fuel Flow, kg/s	0	0
LP SOFC Fuel Flow, kg/s	-	0.063
LP Combustor Fuel Flow, kg/s	0.030	0
SOFC Power, MW ac	1.7	3.1
Turbine Power, MW ac	1.4	1.4
Plant Net ac Power, MW	3.1	4.5
Plant Efficiency (LHV), %	61	67
Plant Exhaust Flow Rate, kg/s	5.26	5.29
Plant Exhaust Temperature, K	485	489
Exhaust NOx Concentration, ppmv	< 5	< 4

Design-point NOx emissions for Cycle 3-1 are estimated at 5 ppmv or less, based upon the assumption of 2 ppmv NOx generation at the SOFC system, and achieving 3 ppmv or less at the power turbine combustor through the application of advanced combustor technology. For Cycle 3-2, no fuel is fired at either combustor at the plant design point. Thus, the plant NOx will be due to the two SOFC systems alone, and is not expected to exceed 4 ppmv. This highlights a key advantage of SOFC integration with the Heron turbine - the turbine inlet temperatures match well with the temperatures that are anticipated at the exhausts of pressurized SOFC generator modules.

CONCLUSION

Cycles that integrate the SOFC and combustion turbine technologies promise to be the basis for very attractive power plants at the small, distributed-power level. The cycles described herein take advantage of the natural synergism that exists between the two technologies. When pressurized by the turbine compressor, the SOFC system produces more power at higher efficiency, and the system's hot exhaust can be utilized directly by the combustion turbine such that combustor fuel requirements are reduced or eliminated. These effects combine and contribute to the achievement of high cycle efficiencies. In addition, plants based on the pressurized-SOFC/combustion turbine cycle will generate NOx at very low levels, particularly when the SOFC and turbine systems are carefully matched such that minimal or no fuel is required at the turbine combustor(s).

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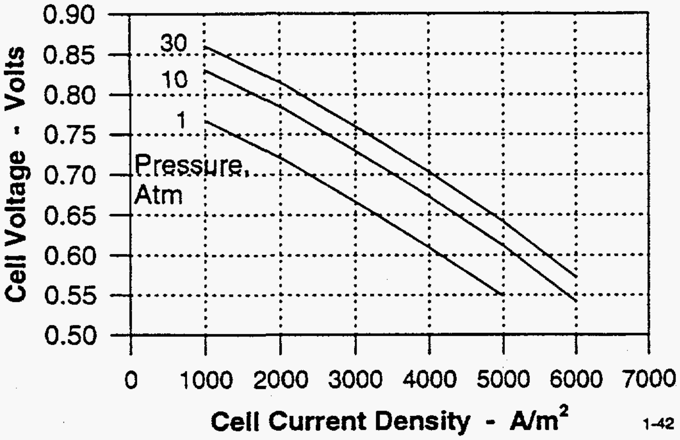

FIGURE 1. SOFC PERFORMANCE ESTIMATES

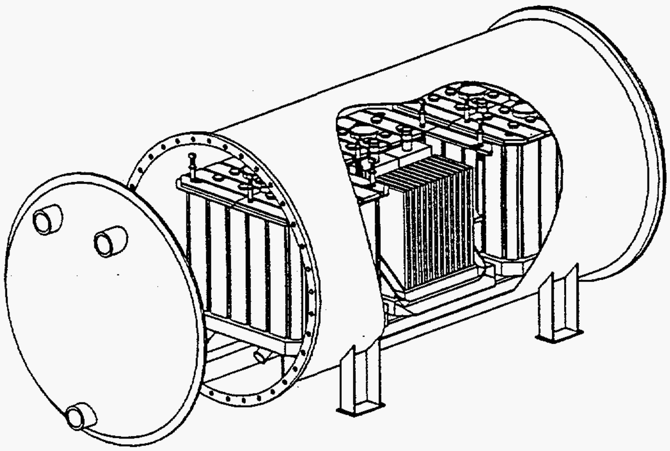

FIGURE 3. PRESSURIZED SOFC MODULE

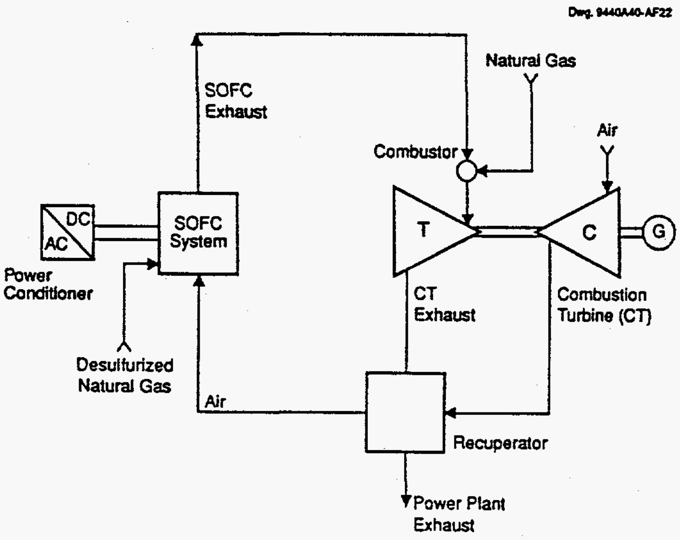

FIGURE 2. SIMPLIFIED SOFC/COMBUSTION TURBINE CYCLE DIAGRAM

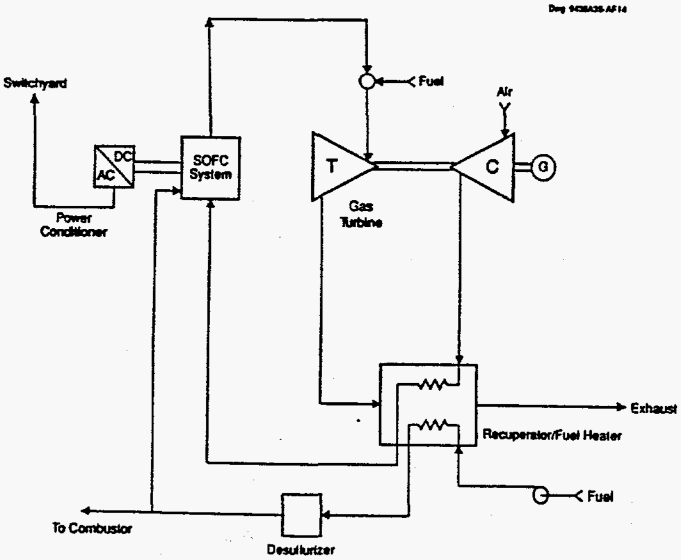

FIGURE 4. SOFC/COMBUSTION TURBINE POWER PLANT CYCLE

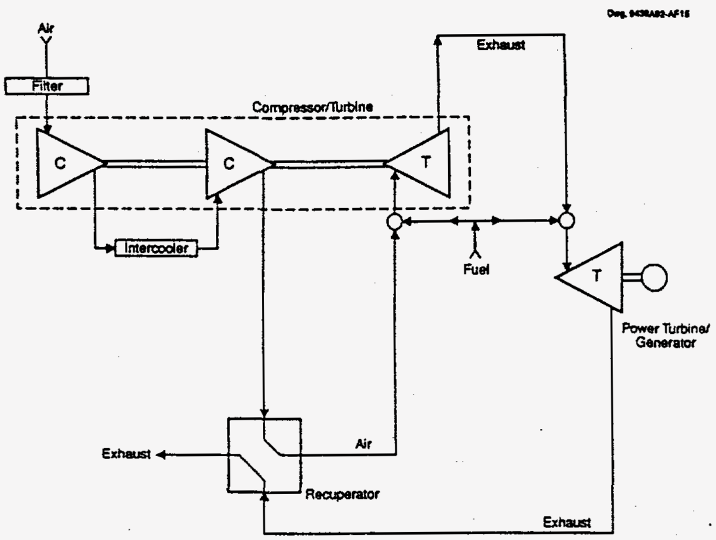

FIGURE 5. HERON COMBUSTION TURBINE CYCLE

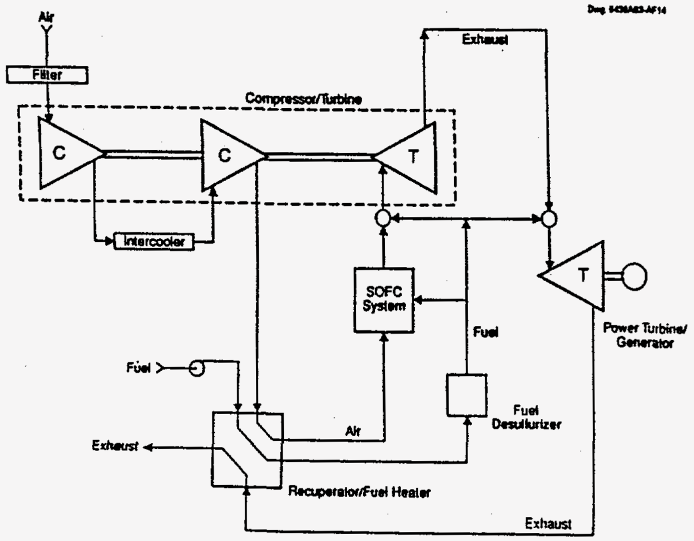

FIGURE 6. SOFC/HERON COMBUSTION TURBINE CYCLE,CYCLE 3-1

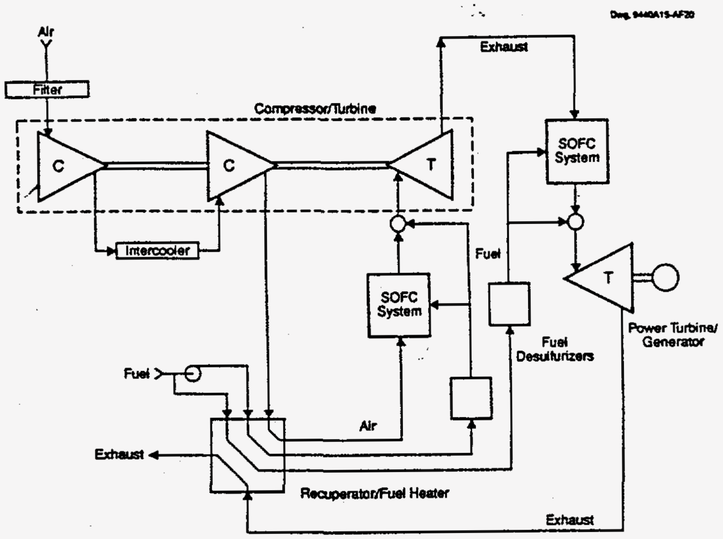

FIGURE 7. SOFC/HERON COMBUSTION TURBINE CYCLE, CYCLE 3-2