

Paper Number:
DOE/MC/28055-97/C0780

CONF-961232--4

Title:
Solid Oxide Fuel Cell/Gas Turbine Power Plant Cycles and Performance Estimates

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Contract Number:
DE-FC21-91MC28055

Conference:
Power-Gen International 1996 Conference

Conference Location:
Orlando, Florida

Conference Dates:
December 4-6, 1996

Conference Sponsor:
U.S. Electrical Power Industries

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Introduction

A solid oxide fuel cell (SOFC) module is supplied with natural gas fuel and preheated oxidant air, and it produces dc electric power and a hot, non-polluting, exhaust stream. The nominal operating temperature of the module cell stack is 1000°C, and the module design exhaust temperature is typically 850°C. The heat contained in the exhaust stream can be utilized to supplement or supplant the fuel energy that is added to a gas turbine combustor, and operating the SOFC at elevated pressure levels by providing it with air directly from a gas turbine compressor serves to enhance the power and efficiency performance of the fuel cell. Thus, cycles that integrate the two technologies can be synergistic, and they can provide the basis for very efficient power plants. Westinghouse has been engaged in studies of such cycles and plants to assess their performance potential and to help define applications for the Westinghouse tubular SOFC technology. It is the objective of this paper to discuss several pressurized SOFC/gas turbine (PSOFC/GT) cycle options that have been considered during this work, and to present performance estimates for power plant concepts that are based on those cycles. The capacities of these plants are less than 10 MWe, which provides a very good fit with distributed-power applications.

Pressurized SOFC Module Basis

The SOFC system of a PSOFC/GT power plant is composed of one or more pressurized SOFC generator modules, with the number of standard, factory-produced modules to be included in the plant design being set by plant capacity requirements. A single module consists of a horizontal pressure vessel, the length of which is set to house a desired number of SOFC submodules. Each submodule is composed of 2496 cells and has a peak dc power capability of 675 kW (at ten atmospheres); 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.

A pressurized SOFC module designed to house three submodules is illustrated in Figure 1. A depleted-fuel recirculation loop within each submodule provides water vapor for the fuel reforming reaction, and the required reforming heat is supplied by the exothermic SOFC electrochemical reaction. Thus, all reformation of the natural gas fuel occurs within the module, and steam and heat from external sources to support the reformation process are not needed. Each power plant concept discussed in this paper incorporates one such module. The overall dimensions of the module pressure vessel are 4200 mm(d), and 9300 mm(l), and the dimensions of each submodule are 2900 mm(w), 2400 mm(h), and 2900 mm(l).

Effect of Pressure on SOFC Performance

Cell performance analyses indicate, and experiments being performed by Westinghouse and Ontario-Hydro Technologies corroborate, that cell voltage, for a given cell current, increases with increasing pressure. Predictions of the relationship between cell voltage and pressure are presented in Figure 2, and the estimated effect of pressure on voltage is clearly significant. A typical cell operating voltage is 600 mV, and the figure indicates that operation at 10 atmospheres will result in a cell voltage increase of 10-12% relative to the voltage at atmospheric pressure. The estimated effect of pressure on the cell efficiency/power relationship is indicated in Figure 3, which was constructed directly from the data presented in Figure 2. More power, developed from the same cell hardware, and at higher efficiency levels, are key advantages of SOFC pressurization. Another advantage is the opportunity pressurization provides for enhanced exhaust-heat utilization.

Effect of Pressure on SOFC/GT Cycle Performance

A cycle that integrates a pressurized SOFC system (module) as a topping cycle with a gas turbine is illustrated in Figure 4. A power plant based upon this cycle would be all-electric, producing only electric power, and recovering no heat for application to customer thermal needs. The SOFC module receives pressurized, preheated air and desulfurized natural gas, and it produces dc power and the hot exhaust. For best cycle performance, the gas turbine is selected such that its required inlet temperature matches the temperature of the exhaust that exits the SOFC module. Normally, that temperature will be in the 850-925°C range. Thus, at the plant design point, the hot SOFC exhaust can be expanded directly by the gas turbine, with no need for the combustion of additional fuel at the turbine inlet. Consequently, Figure 4 shows no gas turbine combustor. However, it is likely that the plant would be equipped with such a combustor for use during part-load operations and startup. Air for the SOFC module is supplied by the turbine compressor, and the air temperature required at the SOFC inlet, typically 500°C, is provided by the recuperator, utilizing heat recovered from the gas turbine exhaust.

The power plant fuel is natural gas. The fuel will generally contain naturally-occurring sulfur-bearing compounds, or sulfur-bearing odorants that are purposely added for safety reasons. To preclude a sulfur reaction with SOFC materials, the fuel sulfur concentration must be reduced to less than 1 ppm (volume basis) before SOFC entry. In the plant concepts discussed in this paper, fuel desulfurization is accomplished via a zinc-oxide-based desulfurizer unit. The relatively small amount of heat needed to elevate the reagent-bed temperature is recovered from the turbine exhaust.

Performance estimates for a power plant based upon this pressurized-SOFC cycle are presented in Figure 5. To obtain points for the curve, calculations were done for several cell current densities between 200 mA/cm², at the low-power point, and 550 mA/cm² at the highest power. For each estimate, the SOFC exhaust temperature was fixed at 850°C, and the SOFC stoichs/compressor pressure ratio combination was found which produced the highest plant efficiency, and for which the required recuperator effectiveness did not exceed 93%. The calculations represent plant design-point performance estimates for which the SOFC part of the plant was fixed (one pressurized SOFC module), but the turbine/recuperator design was variable from point-to-point, depending upon the SOFC stoichs, the SOFC current density, and the compressor pressure ratio. As the curve indicates, this PSOFC/GT system could serve an application whose maximum demand for power lies in the 1 - 2.5 MWe range, and efficiencies in the 60%-70% range will be achieved. The selection of the preferred design point and turbine design conditions will depend upon an evaluation of plant economics, which were not considered in this assessment of plant thermal performance.

Figure 6 shows a cycle diagram for an SOFC/GT power plant that integrates an atmospheric-pressure SOFC module as a bottoming cycle with a gas turbine, and we can compare plant performance estimates for this cycle with those for the pressurized-SOFC cycle (Figure 5) to gauge the plant performance boost that SOFC pressurization can provide. In the atmospheric-pressure SOFC cycle, the turbine working fluid is air, and the turbine inlet temperature requirement is met by the recovery of heat, at the recuperator, from the atmospheric-pressure SOFC exhaust. Air for the SOFC module comes from the turbine exhaust at a pressure that is above atmospheric by the sum of pressure drops across the SOFC module and the recuperator gas side, and at the required temperature by designing for a specific pressure ratio, given a design turbine inlet temperature. The pressure drop sum will be less than 1 psi. An engineering challenge posed by this cycle is the recuperator; ideally, its gas side must operate at inlet temperatures in the 850°C range.

Performance estimates for the atmospheric-pressure SOFC/GT cycle are presented in Figure 7. This power plant uses the same SOFC module as in the previous calculation, except that the module is not pressurized, and the SOFC exhaust temperature has the same value (850°C) as in the analysis of the pressurized plant. For each point on the curve, the

stoichs/pressure ratio combination was found for which the highest estimate of plant efficiency was achieved, and the recuperator effectiveness did not exceed 93%. A comparison of these efficiency estimates with those for the pressurized-SOFC plant indicate a clear preference, on the basis of thermal performance, for the pressurized plant.

Pressurized-SOFC/GT Cycle Options with Heat Recovery

Cogeneration

A cycle that includes the recovery of exhaust heat for the production of steam and hot water for site use is shown in Figure 8. It is developed by adding a single-pressure heat recovery steam generator (HRSG) and hot water heater to the all-electric PSOFC/GT cycle. If they are justified economically, a double or triple-pressure HRSG could of course be applied in place of the single-pressure unit.

Design-point performance estimates for the single-pressure cogeneration system are presented in Figure 9. As in the previous analyses, the SOFC system consists of the single pressurized SOFC module, but the gas turbine and HRSG designs vary from point-to-point with the changing mass flow rate.

The HRSG steam pressure is 10 atm (abs), and the steam is generated with 10°C superheat. The HRSG could be designed for higher pressures, and much higher steam temperatures could be achieved to meet specific user requirements by bypassing air around the recuperator, or by placing the superheater ahead of the recuperator. The gas temperature at the hot water heater inlet is approximately 180°C. Thus, the potential exists to generate hot water over a wide range of temperatures. The temperature at the HRSG exhaust is 70°C.

In Figure 9, system performance is characterized by three heat recovery efficiencies and fuel effectiveness in addition to the system's electric efficiency. Two heat recovery efficiencies represent the fraction of the incoming fuel energy (LHV) that is used directly in the production of steam and hot water, and the fuel effectiveness is the sum of the total heat recovery and electric efficiencies; it represents the percentage of the fuel energy that the system is able to convert to useful product.

Gas Turbine Steam Injection

Utilizing recovered heat to generate steam for injection at the gas turbine inlet represents an approach that can be applied to derive more power from a plant with a fixed SOFC system and turbine basis. A cycle diagram for a steam-injected PSOFC/GT power plant is presented in Figure 10. A single-pressure HRSG is again employed, although a two or three-pressure design could be used, and the steam produced is returned to the turbine inlet. In the evaluation of this system, it has been assumed that fuel would be burned at the gas turbine combustor to maintain a turbine inlet temperature of 850°C. The HRSG steam pressure is set at two atmospheres above the turbine inlet pressure, and the steam superheat is 10°C.

To see the effect of steam injection on plant performance, a reference point was taken from Figure 5 for an all-electric PSOFC/GT power plant. Then, for the steam injection case, the SOFC operating point from the reference case was retained, and the SOFC system was unchanged, but the SOFC stoichs parameter was allowed to increase as needed to keep the recuperator design effectiveness at 93%. This means there is more mass flow through the system, and a physically-larger recuperator would be required at the new power plant design point. Further, the compressor pressure ratio was increased, consistent with the change in mass flow through the turbine, and it was considered that the same turbine would be used, as modified to permit the injection of steam. Table 1 compares steam-injected plant performance with that for the reference case; it shows that the generation and injection of steam at the

rate of 0.165 kg/s, representing a 4.5% increase in mass flow relative to the reference case, results in a 11% increase in total plant power output.

It is noted that while the plant power output increased due to steam injection, the plant efficiency did not, due to the need to fire fuel at the gas turbine combustor. Thus, the steam injection option could be an attractive alternative in applications where the cost of fuel is relatively low, the plant capital cost is the major cost-of-electricity driver, and where the added plant complexity can be tolerated.

Table 1. Effect of Gas Turbine Steam Injection on PSOFC/GT Power Plant Performance.

Parameter	Reference Case No Steam Injection	With Steam Injection
Plant type	All-electric	All-electric
SOFC current density, mA/cm ²	400	400
Steam injection rate, kg/s	0	0.165
SOFC stoichs	4.0	4.76
SOFC fuel utilization, %	90	80
Compressor air flow rate, kg/s	3.70	4.40
Compressor pressure ratio	3.7	4.4
SOFC fuel flow, kg/s	0.0625	0.0703
Gas turbine fuel flow, kg/s	0	0.0055
SOFC ac power, MW	1.55	1.63
Gas turbine ac power, MW	0.44	0.58
Plant power output, MW net ac	1.96	2.17
Plant efficiency (net ac/LHV), %	66.2	60.3

Performance and Cost Estimates for a Specific Power Plant Design

A conceptual design has been developed at Westinghouse for a 3 MW-class, all-electric PSOFC/GT power plant. The design utilizes the pressurized SOFC module depicted in Figure 1, and it employs an engine similar to the Solar Turbines Saturn-20 gas turbine, but with a slightly reduced air flow to provide a good match with the SOFC module. The turbine operates with a pressure ratio of 6.36:1, and its firing temperature is less than 870°C. Thus, the SOFC module and the turbine can be integrated to require no fuel firing at the turbine combustor.

Performance estimates for this power plant are presented in Table 2. Note that the plant generates more power relative to the Figure 5 cases. This is due mainly to the use of higher compressor and turbine efficiencies in the analysis of this larger turbine. It is anticipated that Westinghouse will offer all-electric SOFC/GT plants of this or similar design and performance early in the next decade, and that such plants will fit very well in distributed-power applications. The estimated mature-market total installed cost of this particular power plant is in the range of \$1100-1500/kW ac.

Table 2. PSOFC/GT Power Plant Performance Estimates.

Parameter	
Compressor air flow rate	5.23 kg/s
Compressor pressure ratio	6.36:1
Turbine inlet temperature	869°C
SOFC fuel flow rate	0.0967 kg/s
Gas turbine fuel flow rate	0
SOFC ac power	1.95 MW ac
Gas turbine ac power	1.03 MW ac
Plant power output	2.93 MW net ac
Plant efficiency (net ac/LHV)	63.7%

Conclusions

- SOFC pressurization enhances SOFC efficiency and power performance. It enables the direct integration of the SOFC and gas turbine technologies which can form the basis for very efficient combined-cycle power plants.
- PSOFC/GT cogeneration systems, producing steam and/or hot water in addition to electric power, can be designed to achieve high fuel effectiveness values. A wide range of steam pressures and temperatures are possible due to system component arrangement flexibility.
- It is anticipated that Westinghouse will offer small PSOFC/GT power plants for sale early in the next decade. These plants will have capacities less than 10 MW net ac, and they will operate with efficiencies in the 60-65% (net ac/LHV) range.

Acknowledgments

Tubular SOFC development is sponsored by Westinghouse and the United States Department of Energy, Morgantown Energy Technology Center (DOE-METC), under cooperative agreement DE-FC21-91MC28055. Pressurized SOFC testing is supported by: DOE-METC; Westinghouse; and Ontario Hydro Technologies and their Canadian funding partners. In addition, the analysis of pressurized cell test data is sponsored by the preceding plus the New Energy and Industrial Technology Development Organization (NEDO) of Japan and its participating Japanese Electric Power Companies.

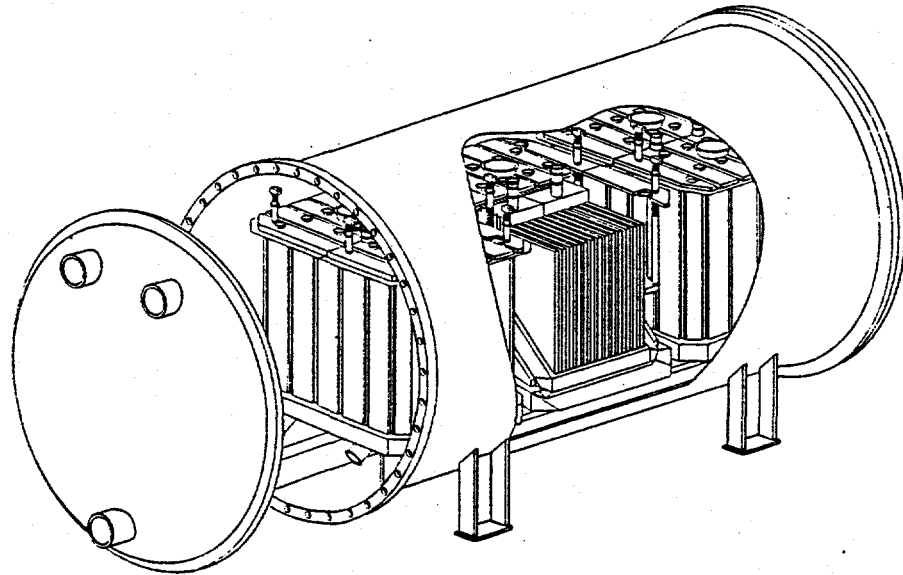


Figure 1. Pressurized SOFC module

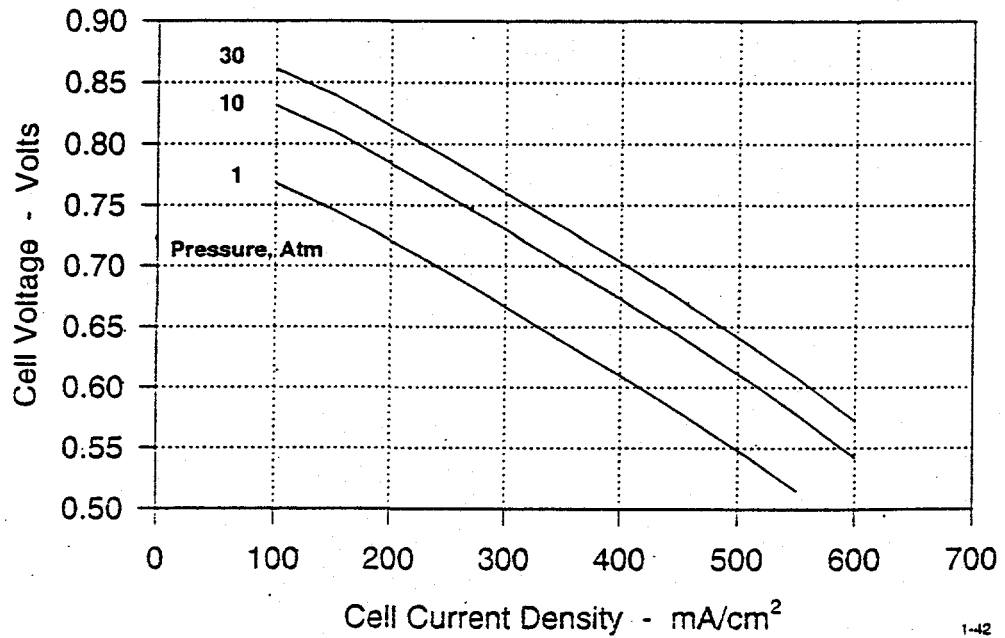


Figure 2. SOFC voltage-current estimates

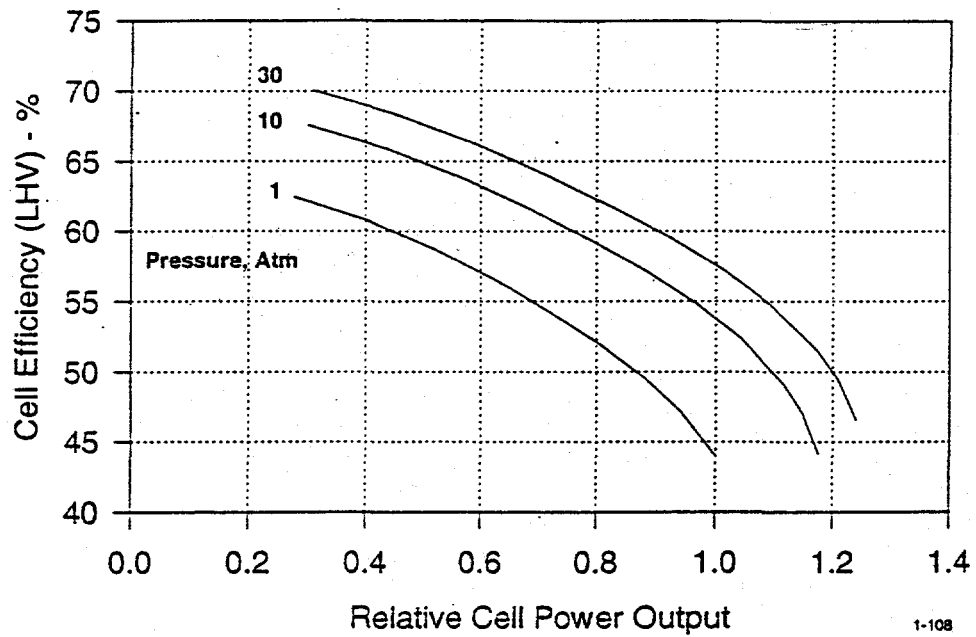


Figure 3. SOFC efficiency-power estimates

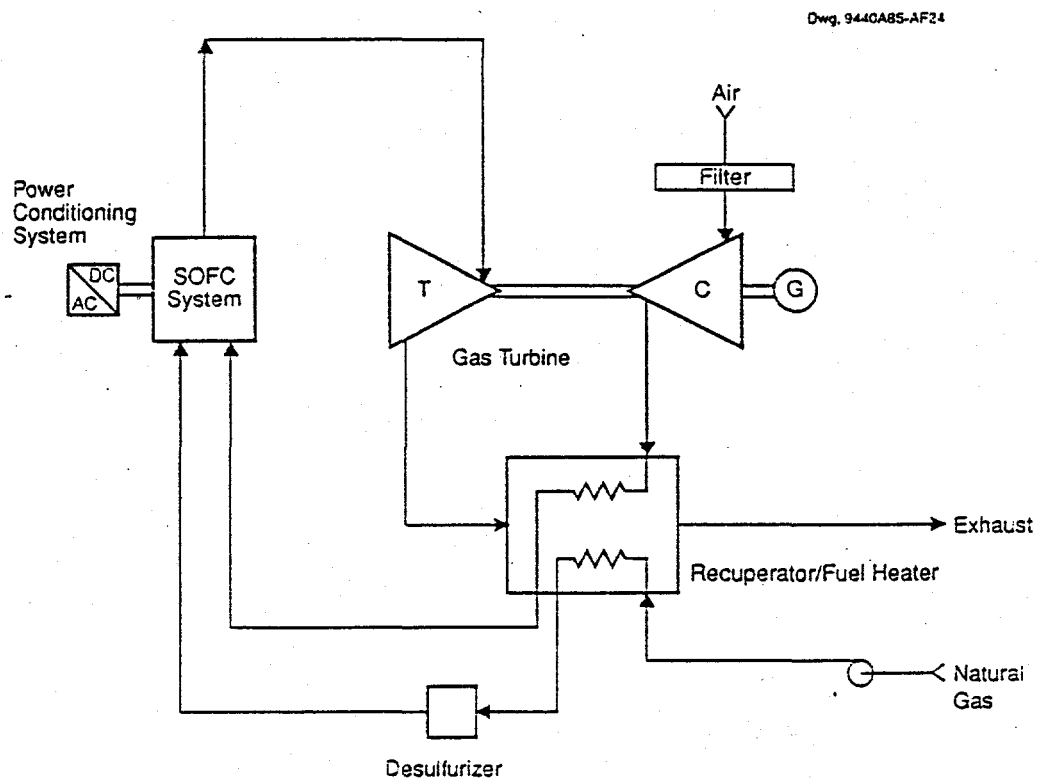


Figure 4. PSOFC/GT power plant cycle

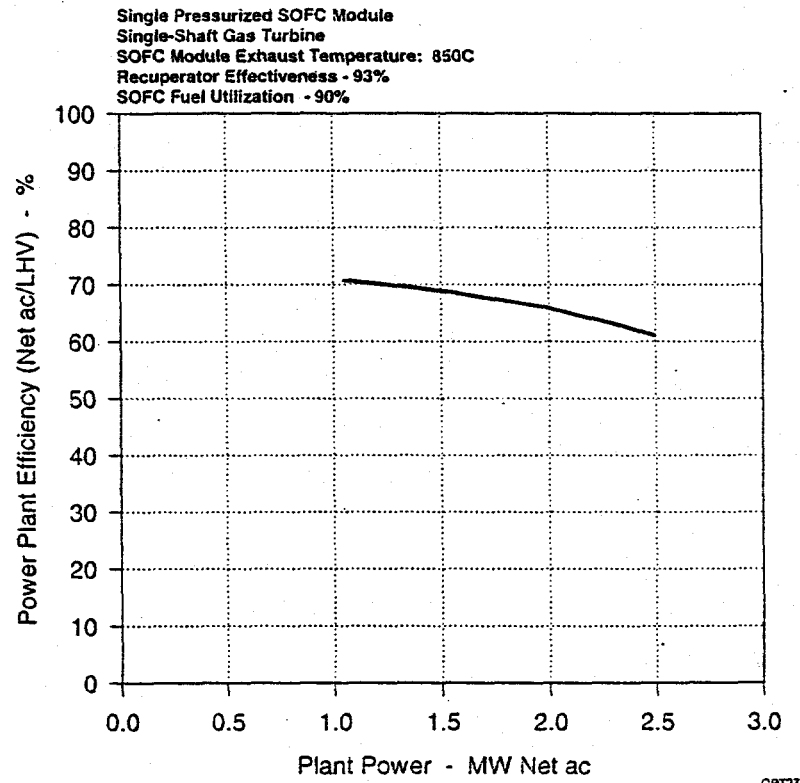


Figure 5. PSOFC/GT power plant performance estimates

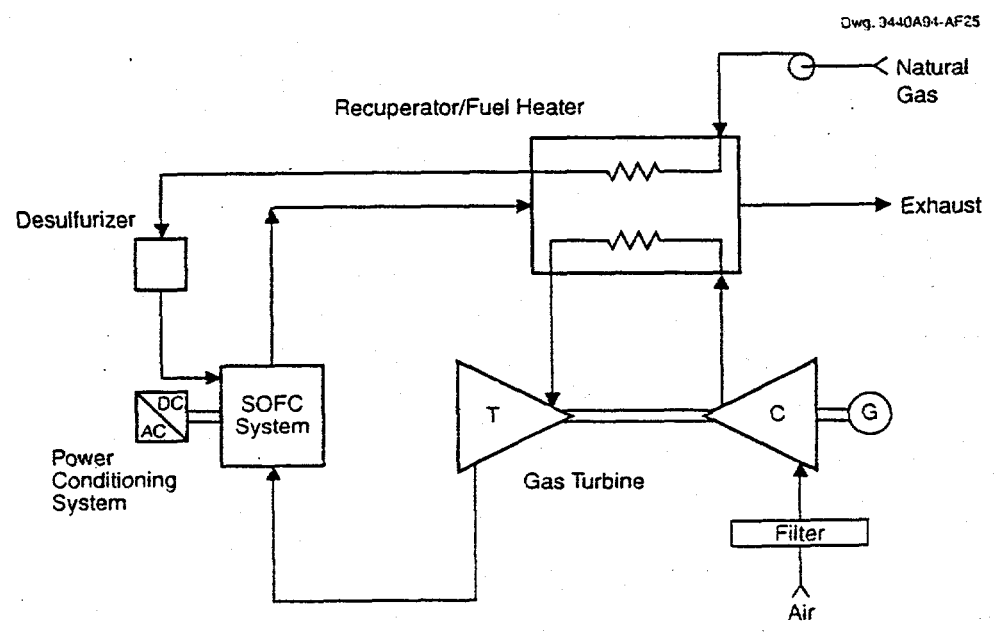


Figure 6. Atmospheric-pressure SOFC/GT power plant cycle.

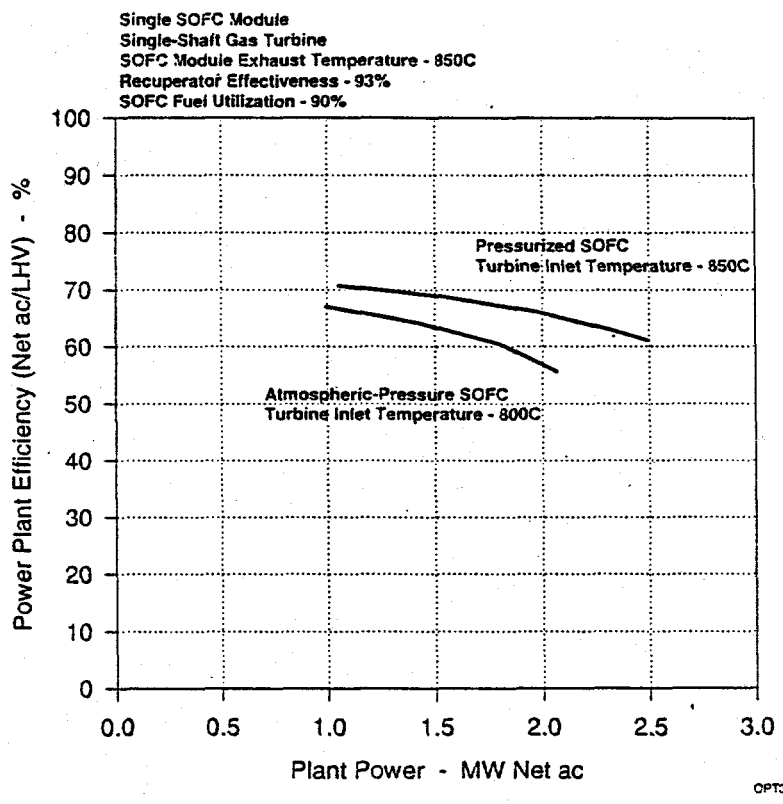


Figure 7. Effect of SOFC pressurization on power plant performance.

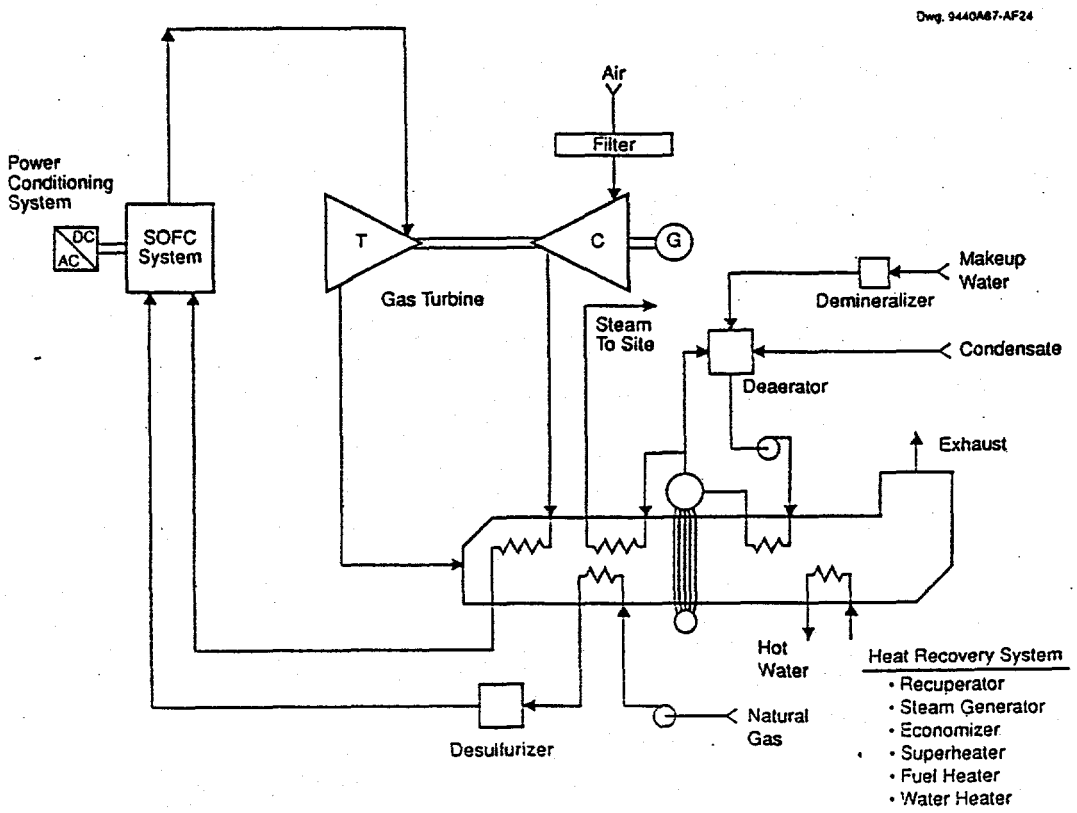


Figure 8. PSOFC/GT cogeneration system cycle.

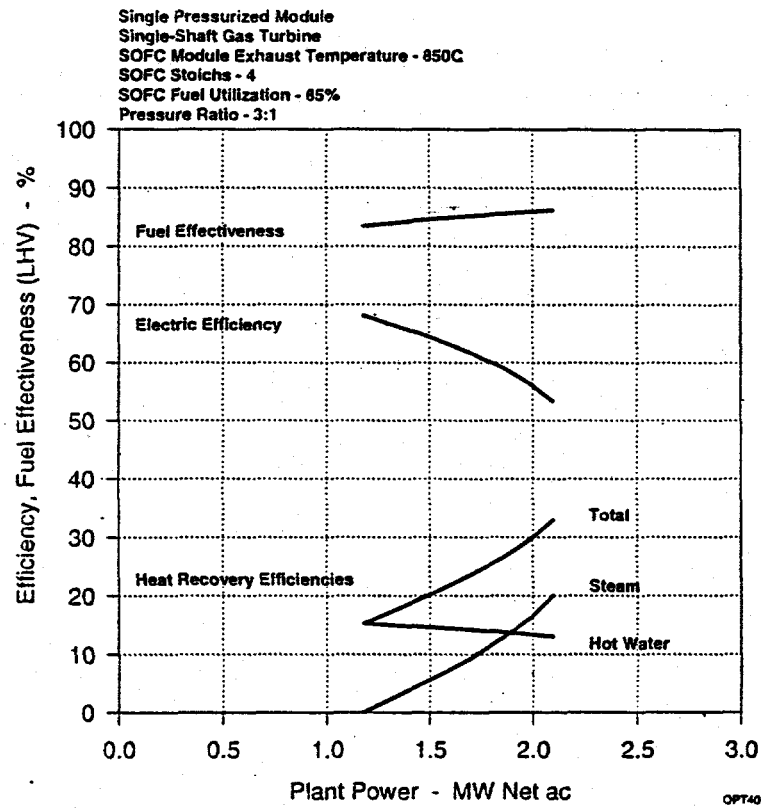


Figure 9. PSOFC/GT cogeneration system performance estimates.

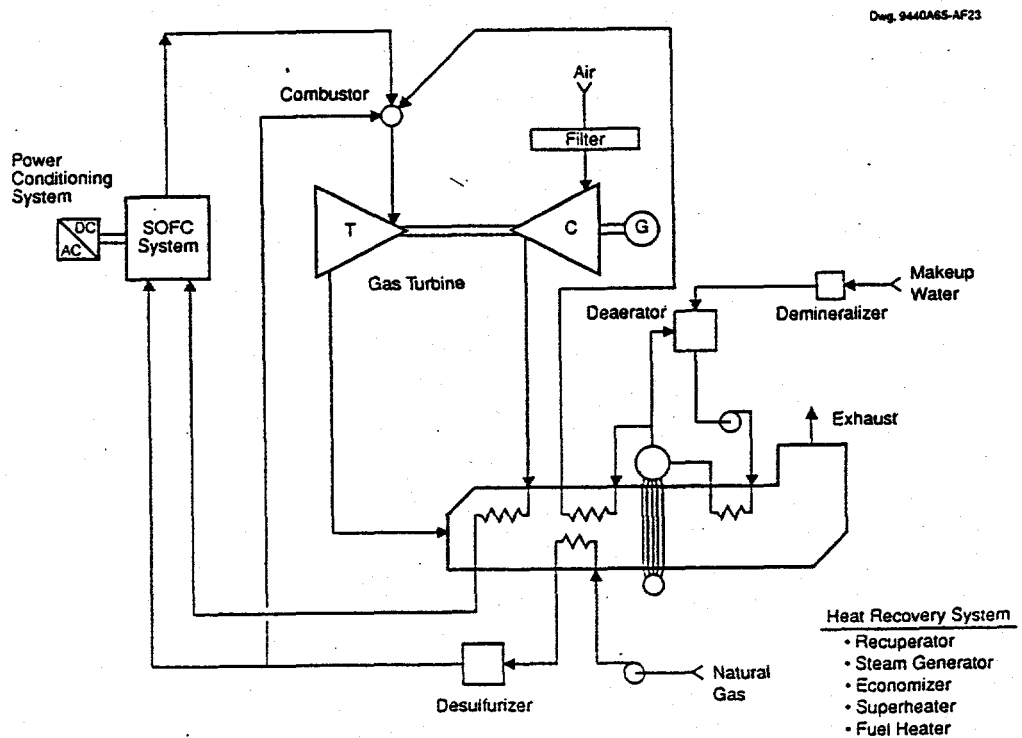


Figure 10. PSOFC/steam-injected GT power plant cycle.

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1310 Beulah Road, Pittsburgh, PA 15235

A. CONTRACTOR INFORMATION (CONTRACTOR COMPLETES PART A. 1-5)

- Document Title: SOFC/Gas Turbine Power Plant Cycles and Performance Estimates
- Type of Document: Technical Progress Report Topical Report Final Technical Report
 Abstract Technical Paper Journal Article Conference Presentation
 Other (please specify): _____
- Date clearance needed: Before Nov 22, 1996
- Results of review for possible inventive subject matter (Subject Inventions):
a. No Subject Invention is believed to be disclosed therein. per E. R. Ray
b. Describes a possible Subject Invention relating to _____
i. Contractor Docket No. _____
ii. A disclosure of the invention was submitted on _____
iii. A disclosure of the invention will be submitted by the following date: _____
iv. A waiver of DOE's patent rights to the contract: has been granted, has been applied for, or will be applied for by the following date: _____

5. Remarks:
Signed LaVerne Roidt Date 11/19/96
(Contractor)

Name & Position LaVerne R. Roidt, Contract Analyst
Address Westinghouse STC 1310 Beulah Road Pittsburgh, PA 15235

B. PATENT COUNSEL ACTION (PATENT COUNSEL COMPLETES PART B. 6-7)

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Signed Lisa A. Jarr Date 11/20/96
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Gas Turbine Steam Injection

Utilizing recovered heat to generate steam for injection at the gas turbine inlet represents an approach that can be applied to derive more power from a plant with a fixed SOFC system and turbine basis. A cycle diagram for a steam-injected PSOFC/GT power plant is presented in Figure 10. A single-pressure HRSG is again employed, although a two or three-pressure design could be used, and the steam produced is returned to the turbine inlet. In the evaluation of this system, it has been assumed that fuel would be burned at the gas turbine combustor to maintain a turbine inlet temperature of 850°C. The HRSG steam pressure is set at two atmospheres above the turbine inlet pressure, and the steam superheat is 10°C.

To see the effect of steam injection on plant performance, a reference point was taken from Figure 5 for an all-electric PSOFC/GT power plant. Then, for the steam injection case, the SOFC operating point from the reference case was retained, and the SOFC system was unchanged, but the SOFC stoichs parameter was allowed to increase as needed to keep the recuperator design effectiveness at 93%. This means there is more mass flow through the system, and a physically-larger recuperator would be required at the new power plant design point. Further, the compressor pressure ratio was increased, consistent with the change in mass flow through the turbine, and it was considered that the same turbine would be used, as modified to permit the injection of steam. Table 1 compares steam-injected plant performance with that for the reference case; it shows that the generation and injection of steam at the

rate of 0.165 kg/s, representing a 4.5% increase in mass flow relative to the reference case, results in a 11% increase in total plant power output.

It is noted that while the plant power output increased due to steam injection, the plant efficiency did not, due to the need to fire fuel at the gas turbine combustor. Thus, the steam injection option could be an attractive alternative in applications where the cost of fuel is relatively low, the plant capital cost is the major cost-of-electricity driver, and where the added plant complexity can be tolerated.

Table 1. Effect of Gas Turbine Steam Injection on PSOFC/GT Power Plant Performance.

Parameter	Reference Case No Steam Injection	With Steam Injection
Plant type	All-electric	All-electric
SOFC current density, mA/cm ²	400	400
Steam injection rate, kg/s	0	0.165
SOFC stoichs	4.0	4.76
SOFC fuel utilization, %	90	80
Compressor air flow rate, kg/s	3.70	4.40
Compressor pressure ratio	3.7	4.4
SOFC fuel flow, kg/s	0.0625	0.0703
Gas turbine fuel flow, kg/s	0	0.0055
SOFC ac power, MW	1.55	1.63
Gas turbine ac power, MW	0.44	0.58
Plant power output, MW net ac	1.96	2.17
Plant efficiency (net ac/LHV), %	66.2	60.3

Performance and Cost Estimates for a Specific Power Plant Design

A conceptual design has been developed at Westinghouse for a 3 MW-class, all-electric PSOFC/GT power plant. The design utilizes the pressurized SOFC module depicted in Figure 1, and it employs an engine similar to the Solar Turbines Saturn-20 gas turbine, but with a slightly reduced air flow to provide a good match with the SOFC module. The turbine operates with a pressure ratio of 6.36:1, and its firing temperature is less than 870°C. Thus, the SOFC module and the turbine can be integrated to require no fuel firing at the turbine combustor.

Performance estimates for this power plant are presented in Table 2. Note that the plant generates more power relative to the Figure 5 cases. This is due mainly to the use of higher compressor and turbine efficiencies in the analysis of this larger turbine. It is anticipated that Westinghouse will offer all-electric SOFC/GT plants of this or similar design and performance early in the next decade, and that such plants will fit very well in distributed-power applications. The estimated mature-market total installed cost of this particular power plant is in the range of \$1100-1500/kW ac.

Table 2. PSOFC/GT Power Plant Performance Estimates.

Parameter	
Compressor air flow rate	5.23 kg/s
Compressor pressure ratio	6.36:1
Turbine inlet temperature	869°C
SOFC fuel flow rate	0.0967 kg/s
Gas turbine fuel flow rate	0
SOFC ac power	1.95 MW ac
Gas turbine ac power	1.03 MW ac
Plant power output	2.93 MW net ac
Plant efficiency (net ac/LHV)	63.7%

Conclusions

- SOFC pressurization enhances SOFC efficiency and power performance. It enables the direct integration of the SOFC and gas turbine technologies which can form the basis for very efficient combined-cycle power plants.
- PSOFC/GT cogeneration systems, producing steam and/or hot water in addition to electric power, can be designed to achieve high fuel effectiveness values. A wide range of steam pressures and temperatures are possible due to system component arrangement flexibility.
- It is anticipated that Westinghouse will offer small PSOFC/GT power plants for sale early in the next decade. These plants will have capacities less than 10 MW net ac, and they will operate with efficiencies in the 60-65% (net ac/LHV) range.

Acknowledgments

Tubular SOFC development is sponsored by Westinghouse and the United States Department of Energy, Morgantown Energy Technology Center (DOE-METC), under cooperative agreement DE-FC21-91MC28055. Pressurized SOFC testing is supported by: DOE-METC; Westinghouse; and Ontario Hydro Technologies and their Canadian funding partners. In addition, the analysis of pressurized cell test data is sponsored by the preceding plus the New Energy and Industrial Technology Development Organization (NEDO) of Japan and its participating Japanese Electric Power Companies.

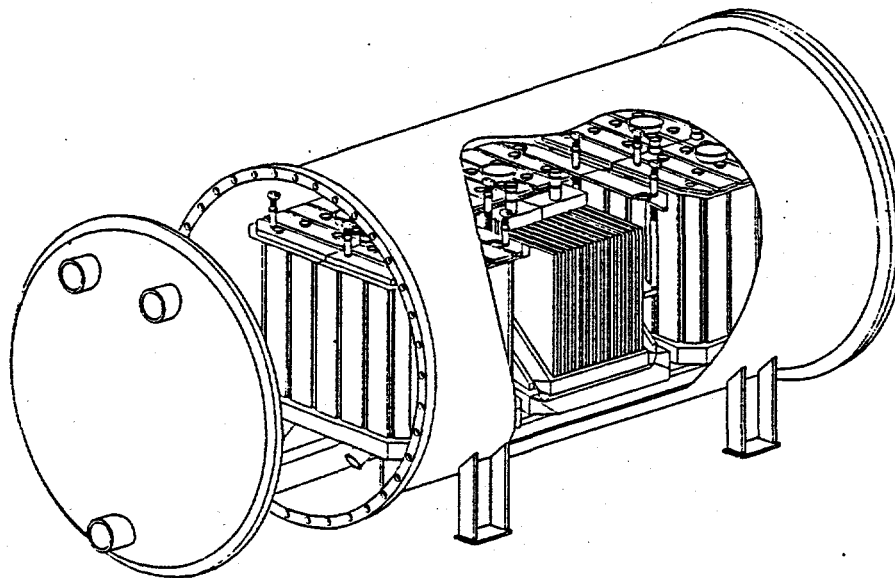


Figure 1. Pressurized SOFC module

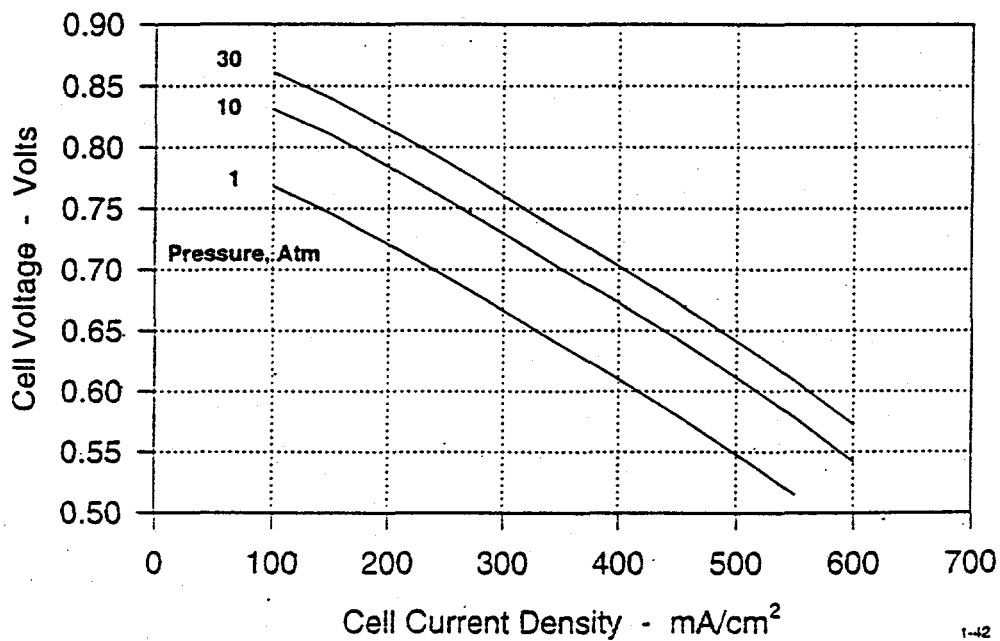


Figure 2. SOFC voltage-current estimates

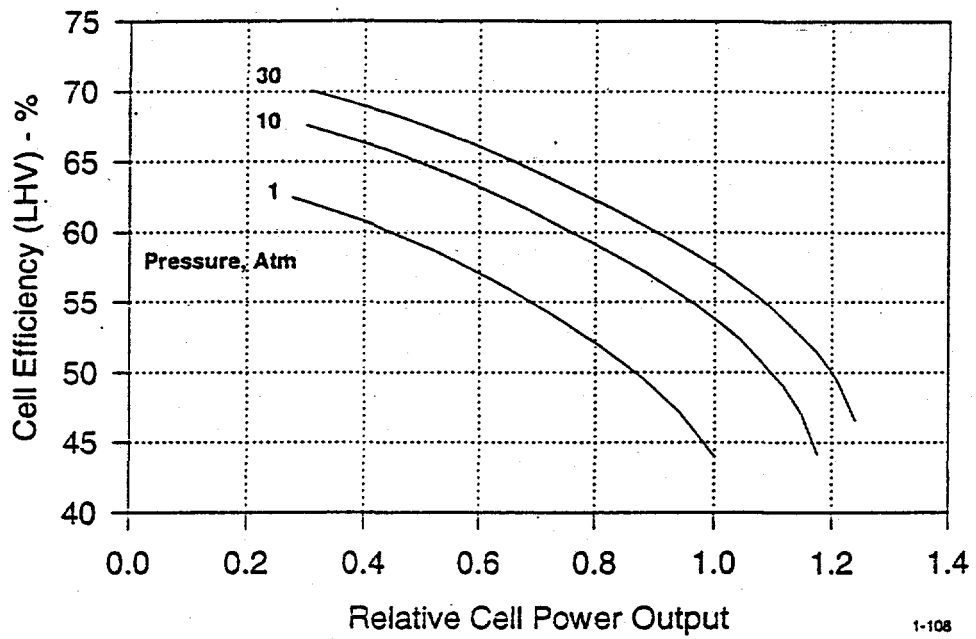


Figure 3. SOFC efficiency-power estimates

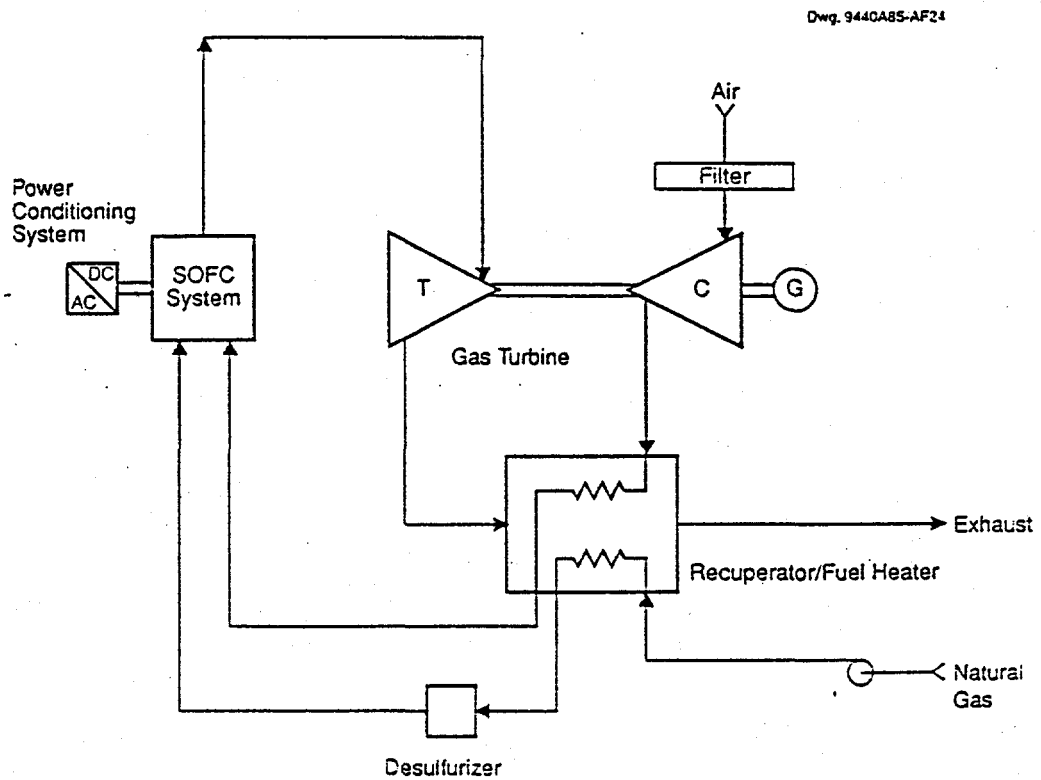


Figure 4. PSOFC/GT power plant cycle

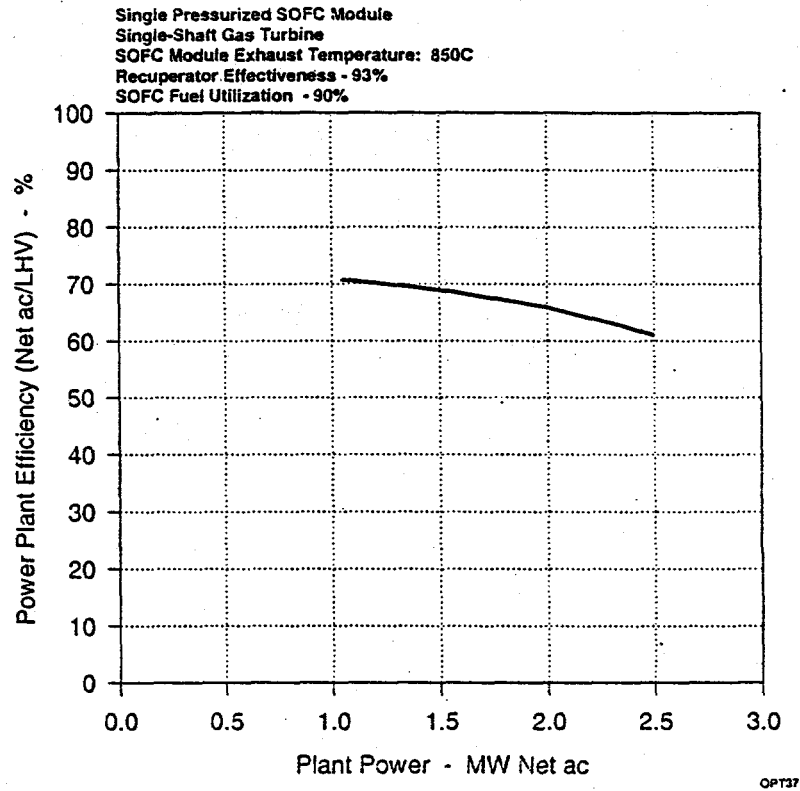


Figure 5. PSOFC/GT power plant performance estimates

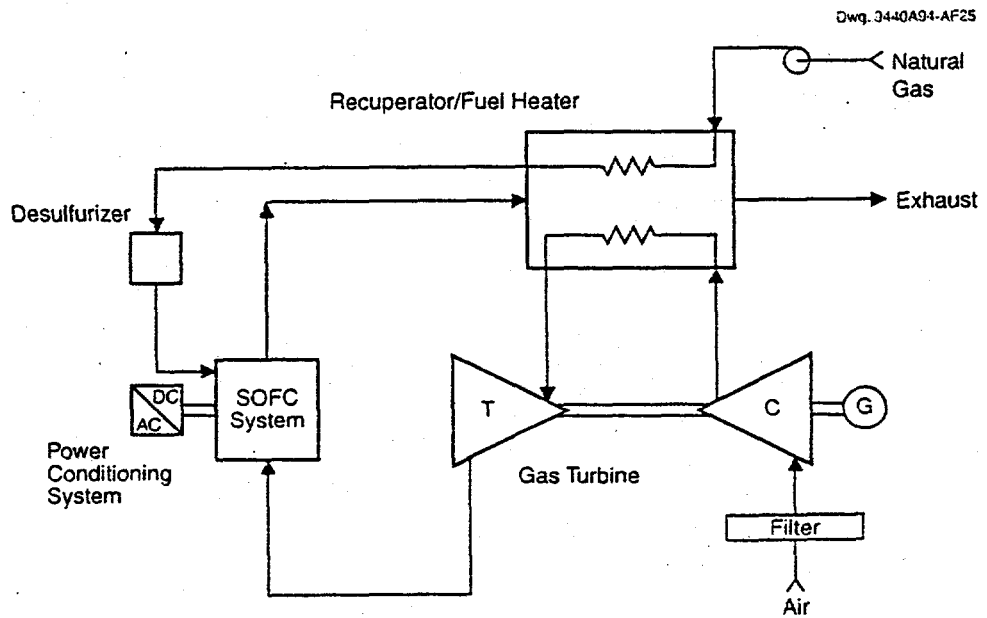


Figure 6. Atmospheric-pressure SOFC/GT power plant cycle.

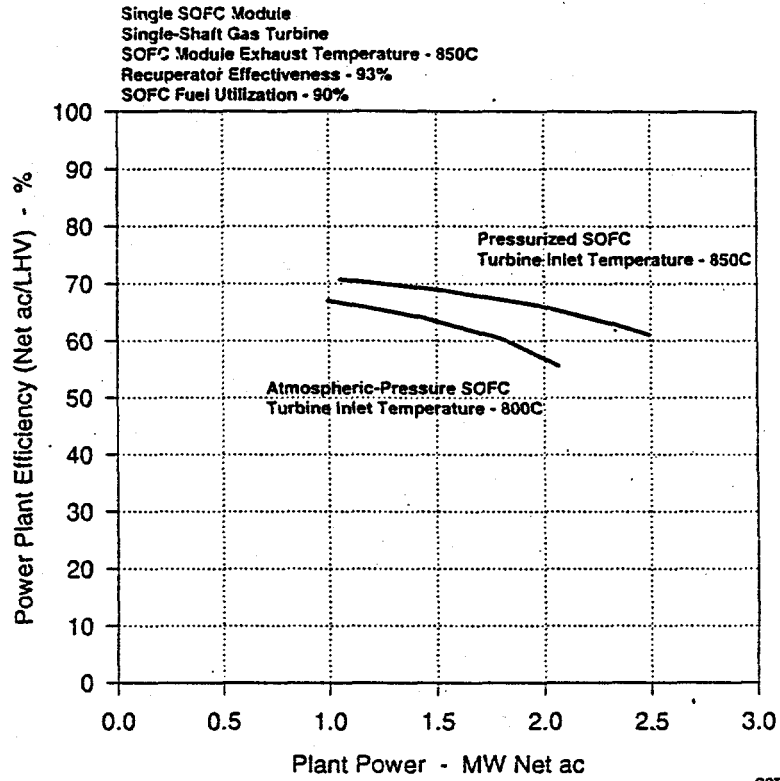


Figure 7. Effect of SOFC pressurization on power plant performance.

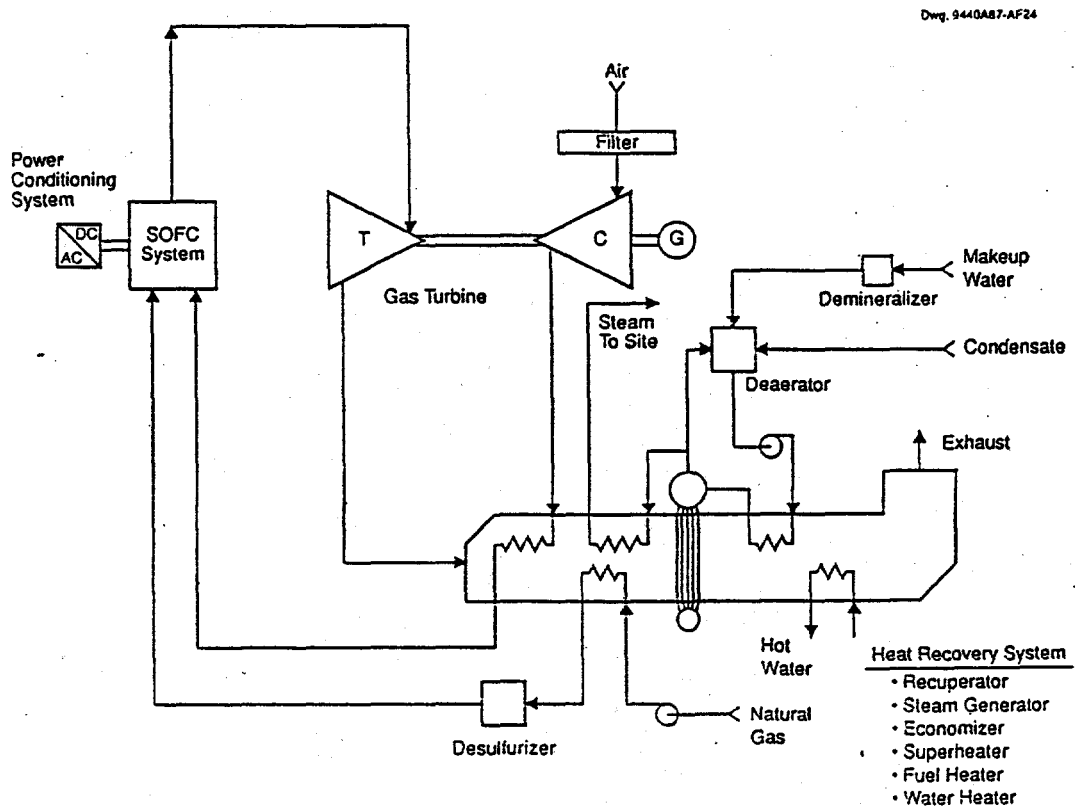


Figure 8. PSOFC/GT cogeneration system cycle.

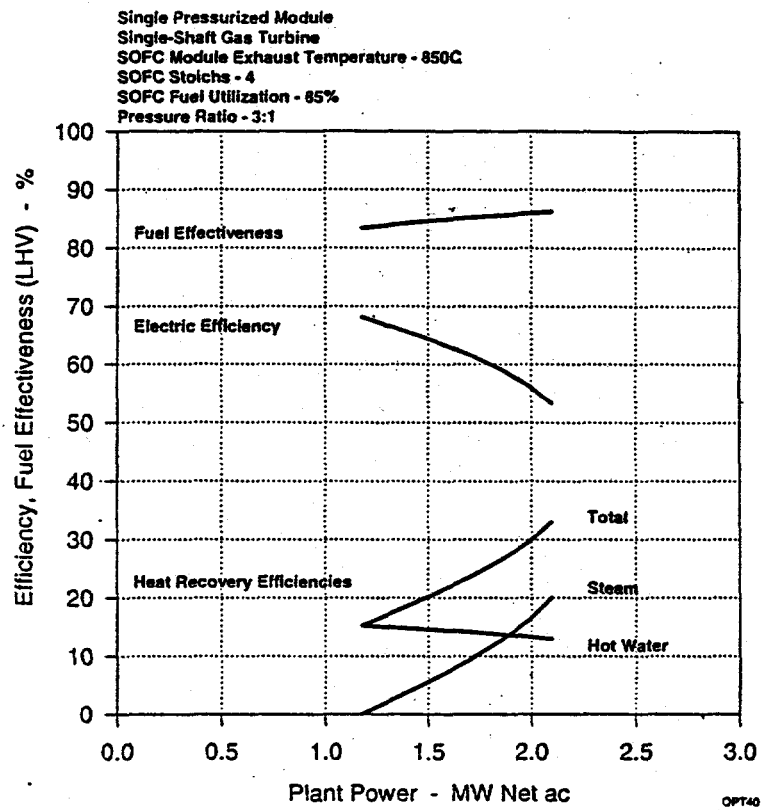


Figure 9. P-SOFC/GT cogeneration system performance estimates.

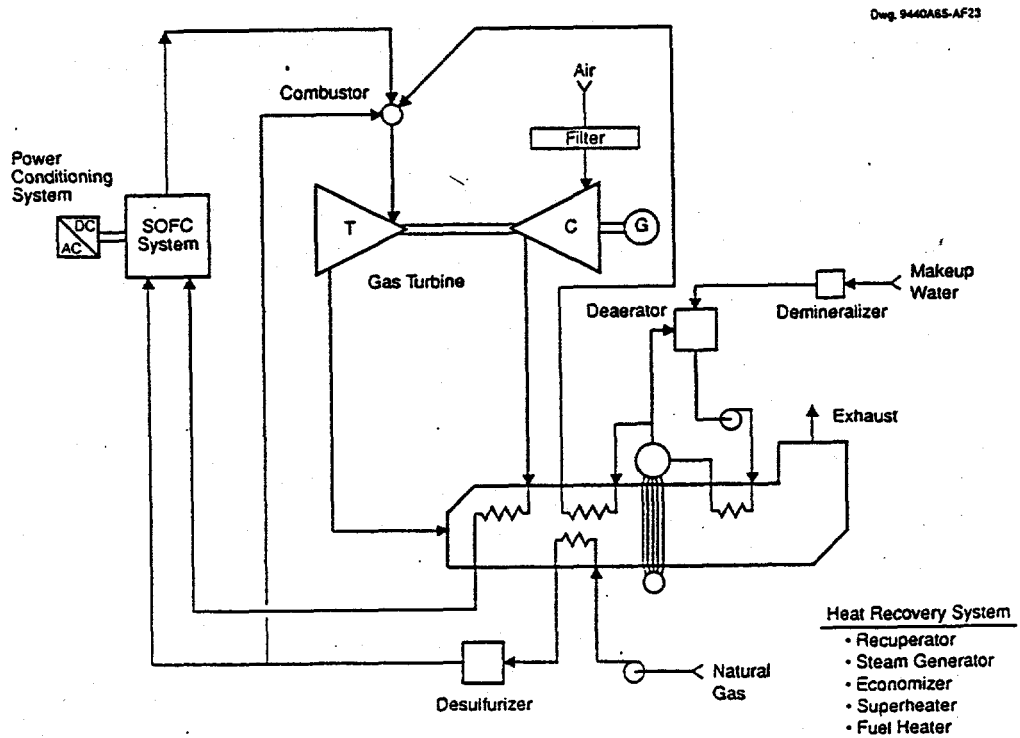


Figure 10. P-SOFC/steam-injected GT power plant cycle.

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FROM: Westinghouse Science & Technology Center
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A. CONTRACTOR INFORMATION (CONTRACTOR COMPLETES PART A. 1-5)

- Document Title: SOFc/Gas Turbine Power Plant Cycles and Performance Estimates
- Type of Document: Technical Progress Report Topical Report Final Technical Report
 Abstract Technical Paper Journal Article Conference Presentation
 Other (please specify): _____
- Date clearance needed: Before Nov 28, 1996
- Results of review for possible inventive subject matter (Subject Inventions):
a. No Subject Invention is believed to be disclosed therein. per E. R. Ray
b. Describes a possible Subject Invention relating to _____
i. Contractor Docket No. _____
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iii. A disclosure of the invention will be submitted by the following date: _____
iv. A waiver of DOE's patent rights to the contract: has been granted, has been applied for, or will be applied for by the following date: _____

5. Remarks:
Signed LaVerne Roidt Date 11/19/96
(Contractor)
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Address Westinghouse STC 1310 Beulah Road Pittsburgh, PA 15235

B. PATENT COUNSEL ACTION (PATENT COUNSEL COMPLETES PART B. 6-7)

- Patent clearance for release of the above-identified document is granted.
- Please defer release of document until advised by this office.
Signed Lisa A. Jarr Date 11/20/96
(Patent Advisor)