SOFC SYSTEM ANALYSIS

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A preliminary design and cost estimate of a 500 kW SOFC commercial unit was conducted to assess its economic potential for distributed power generation. The stacks used were of planar design based on the thin electrolyte technology. The study results indicate that the optimum operating temperature for the thin electrolyte is 800C, the product can be produced at $700-800/kW with 55-60% overall electric efficiency (LHV), and the cost of electricity (5-6 cents/kWh based on $4/MMBtu retail natural gas price and 25% annual capital recovery) is sufficiently low to capture the distributed generation market.

This study is funded by the Gas Research Institute (GRI). Bechtel Corporation is the prime contractor, responsible for the overall system design and cost estimate. TDA Research provided the stack performance and cost estimate.

INTRODUCTION

The planar SOFC has the potential to be more efficient and lower cost than the tubular design because the cells used have shorter current path and are simpler to manufacture. However, it is difficult to find suitable low cost materials for the sealant and interconnect at the 1000C cell operating temperature. To overcome this technical barrier, Gas Research Institute (GRI) has been funding research for developing thin electrolyte cells to reduce the operating temperature. TDA Research, in a recent GRI funded stack cost study (1, 2), showed the thin electrolyte stack could be manufactured at a very low cost of $230/kW due to the use of metallic instead of ceramic interconnects. However, the stack cost typically represents only 20-40% of the total system cost. To determine its commercial viability for distributed power generation, GRI has engaged Bechtel to conduct a cost analysis of the entire system. In this study, TDA Research assisted Bechtel in estimating the stack performance and cost.

In this system analysis, a system simulation model was built and tradeoffs were performed to select the optimum operating parameters and system configuration. The tradeoffs were geared to address the issues such as:

- Will the increased cathode polarization resistance at the reduced operating temperature significantly penalize the overall system efficiency? How much can the increased Nernst potential at the reduced temperature help improve the system efficiency? Will the reduced temperature also reduce the supporting facility cost, such as the air preheater? What would be the optimum operating temperature when all the factors are considered?
- Is it beneficial to operate the cell at higher current density?
- Is it beneficial to operate the cell at higher fuel utilization?
- Is there any advantage to use pressurized operation?
- What is the best integration scheme between the stacks and supporting facilities?

This paper summarizes the preliminary results of this study.

STUDY CASES

Twenty five study cases divided into seven groups were analyzed as shown in Table I.

Groups 1-5 are ambient pressure operation cases. Groups 6 and 7 are pressurized operation cases. A comparison of them establishes the relative advantages between the ambient pressure operation and pressurized operation.

Groups 1-4 search for the optimum current density at the stack operating temperatures of 700, 800, 900, and 1000C, respectively. Three or four different current densities were analyzed in each of these groups. All the cases are based on a fuel utilization of 85%. The optimum case in each temperature group is then selected for comparison to establish the effects of operating temperature.

Group 5 searches for the optimum fuel utilization. Three different fuel utilization levels were analyzed under the condition of 800C stack operating temperature and 300 mA/cm2 current density. Case 5B is actually a duplicate of Case 2B.

Group 6 searches for the optimum operating pressure under the condition of 800C stack operating temperatures, 300 mA/cm2 current density, and 85% fuel utilization. Four different pressure levels were analyzed. Group 7 also searches for the optimum operating pressure. The current density and fuel utilization used are the same as Group 6 but the stack temperature is increased to 1000C to determine the benefits of a hotter gas for a more efficient operation of the downstream turbogenerator. Five different operating pressures were analyzed in Group 7.

All the cases were designed for a minimum excess air level of 30% to ensure there is adequate oxygen concentration available in the cathode. This minimum excess air requirement has forced the high stack temperature cases in Groups 3 and 4 to operate at high current densities. For example, the minimum current density that a 1000C stack can operate is 600 mA/cm2. Below this current density level, the stack is too efficient and the waste heat generated is not sufficient to heat up a large amount of air to the stack operating temperature.

SYSTEM CONFIGURATIONS

Ambient Pressure Operation

All the atmospheric pressure cases (Groups 1-5) are based on the system configuration shown in Figure I.

The natural gas feed is desulfurized and fed to the ejector as the motive gas to induce an anode gas recycle. The anode gas recycle provides an internal steam supply for the pre-reformer by using the cell reaction product water in the anode exhaust gas. In the pre-reformer, the natural gas is partially reformed to ensure there is hydrogen available for the cell reactions at the cell entrance to generate sufficient heat for the highly endothermic internal reforming reaction. An anode preheater is included as an extended part of the pre-reformer to heat the pre-reformed gas to the anode inlet temperature. Heat required for the pre-reforming and anode preheating is provided by a waste heat recovery from the fuel cell stack flue gas.

Multiple stacks (only one shown in Figure I) made of small size (10 cm diameter) cells are used. The stack heat is removed by a direct heat dissipation to the air preheater coils (only one shown in Figure I) placed in between the stacks. The small cell size was chosen to facilitate this type of heat removal. It prevents the cells from developing a large temperature gradient between the center and edge. A blower supplies the air feed to the air preheater coils. The preheated air is further heated to the cathode inlet temperature by a direct combustion in a “pre-burner” with the spent fuel in the anode exhaust gas. In other SOFC system designs, the anode exhaust is usually burned off with the cathode exhaust gas in an “after-burner”.

An effective heat integration between the stack heat removal and air preheating has been a major system design challenge for the SOFC. A standard heat integration scheme employed by many SOFC developers uses the cathode gas for the heat removal and preheat the air feed by heat exchange with the cathode exhaust gas. As the temperature rise of the cathode gas in the stacks is limited (usually less than 100C), the required flow is very large. Typically, a stoichiometric air ratio of 4-5 is necessary for the heat removal. This large air flow significantly increases the air preheater size. The large size, in conjunction with the high air discharge temperature required, significantly increases the air preheater cost. This has been one major reason that the SOFC system cost is high. The large air flow also increases the system pressure drop. The combined effect of large flow and high pressure drop increases the air blower size and the auxiliary power consumption. As a result, the system efficiency is reduced.

The present design does not depend on the cathode gas for the stack heat removal. The air flow required is substantially smaller. Thus, the air preheater is much smaller and the auxiliary power consumption is reduced. Also, a much hotter stack flue gas is available for downstream generation of steam, hot water, or additional power because the cathode exhaust gas is no longer used to preheat the air feed.

The “pre-burner” used in the present design reduces the duty requirement and air discharge temperature of the air preheater. As a result, the air preheater can be even smaller and constructed of a lower cost material. The “pre-burner”, however, decreases the oxygen concentration in the cathode feed by one to two percentage points. This was found to generate no substantial efficiency penalty in the present study.

The anode exhaust gas from the stacks is split into two streams: one to the ejector and other one to the “pre-burner”. The cathode exhaust gas, after heat recovery for the pre-reformer/anode preheater, is discharged to the atmosphere. As indicated previously, plenty of high temperature heat is available in this stream for further generation of steam, hot water, or power, if desired. All the high temperature system components are housed in a vessel to minimize high temperature pipe penetration through the vessel. The DC power produced from the stacks is converted to AC power in the inverter. Not shown in Figure I but included in the cost estimate are a startup boiler, a nitrogen system, and a control system.

Pressurized Operation

All the pressurized operation cases (Groups 6 and 7) are based on the system configuration shown in Figure II. It is essentially the same as that for the atmospheric pressure cases except a turbogenerator is included to produce additional power and to supply the compressed air feed by expansion of the stack flue gas.

The fuel cell/turbine integration described above is only one of many schemes commonly postulated. One other possible scheme is to have the gas turbine placed upstream of the fuel cell unit. The turbine exhaust becomes the cathode feed with the fuel cell flue gas to preheat the air feed to the turbine combustor. In this case, the fuel cell stacks can be operated at atmospheric pressure. Another possible scheme is to generate steam or hot air in the air preheater coils for expansion in a steam or gas turbine. These schemes will be investigated in the future in this study.

SYSTEM SIMULATION MODEL

The system simulation model used in this study performs an overall heat and material balance to determine the process stream flows and conditions, sizes the major equipment, estimates the capital and maintenance costs, and analyzes the cost of electricity. In the heat and material balance, the stack performance was estimated based on use of the following cell components:

- Anode: Ni/Zr cermet, 100 micron thick
- Electrolyte: YSZ, 5 micron thick
- Cathode: Sr-doped La Manganite, 100 micron thick
- Interconnect: stainless steel for the 700C and 800C operating temperatures, high alloy metal for the 900C operating temperature, and La Chromite for the 1000C operating temperature; all materials are 1000 micron thick

The stack costs previously estimated by TDA Research (2) based on 200 MW/yr production were \$43/ft2, \$70/ft2, and \$98/ ft2 cell area for the 700/800, 900, and 1000C operating temperatures, respectively. The ionic resistance of electrolyte used are 0.048, 0.017, 0.007, and 0.003 Ohm-cm2 at the 700, 800, 900, and 1000C operating temperatures, respectively. The corresponding total area specific resistances, which also include ohmic and polarization resistances of electrodes and ohmic and contact resistances of the interconnect, are 1.01, 0.68, 0.401, and 0.284 Ohm-cm2, respectively. The ionic resistances are seen to be a very small fraction of the total cell resistances due to the use of the thin electrolyte. The compressor and expander of the turbogenerator were assumed to have 76% and 86% polytropic efficiencies, respectively. The inverter was assumed to have 95% efficiency.

STUDY RESULTS

A summary of the system performance for all the cases, including feed requirements, a breakdown of the cell voltage drops, cell area required, amounts of power generated and consumed, and electric and cogeneration efficiencies, is shown in Table II.

A cost summary of all the cases is shown in Table III. The O&M cost component of the cost of electricity consists of maintenance cost, stack replacement cost, and catalyst consumption. As the fuel cell unit was designed for unattended operation, there is no operating labor cost. The annual maintenance cost, including both materials and labor, was assumed to be 1% of the capital cost. The stack replacement cost was based on a 5-year stack life with a salvage value equal to 1/3 of the original stack cost. The cost of electricity was calculated based on \$4/MM Btu natural gas price and 25% annual capital recovery (or 4 year payback) which are the typical values anticipated in the United States for the distributed power generation. Results of the specific tradeoff analysis are discussed below.

Optimum Current Density (Groups 1-4)

At higher current density, the cell voltage drops, the stacks are less efficient, and the system electric efficiency is reduced. The larger amount of heat generated from the stacks increases the stoichiometric air ratio and the air preheater size. On the other hand, the power density is increased and the total cell area required is reduced. The optimum current densities at 700, 800, 900, and 1000C operating temperatures are 200, 300, 500, and 600 mA/cm2, respectively.

Optimum Stack Operating Temperature

As the operating temperature increases, the stacks become more efficient but also more expensive. A comparison of the optimum current density cases from Groups 1-4 (Cases 1A, 2B, 3B, and 4A) in Figure III shows that the optimum stack temperature is 800C. This optimum temperature is a result of the tradeoff between the efficiency and stack cost. It should be noted that, due to the use of the “pre-burner”, the air preheater temperatures, even in the 1000C stack operating temperature cases, never exceed 660C. As a result, none of the study cases needs to use high alloy metals or ceramic materials for the air preheater. The optimum operating temperature will decrease if the cell resistance is further reduced in the future.

Optimum Fuel Utilization (Group 5 Cases)

The stacks are more efficient as the fuel utilization increases, even after taking into account the cell voltage reduction due to the lower fuel concentration in the anode. The more efficient stacks release less heat and, thus, the stoichiometric air ratio and the air preheater size are reduced. The total cell area, on the other hand, increases due to the lower power density. Overall, the total capital cost is not sensitive to the fuel utilization level. The higher efficiency is the main reason that the higher fuel utilization case is more economical. However, there is an upper limit for the practical fuel utilization level. Beyond that, certain areas of the cells could be deprived of fuel if a mal-distribution of gases develops due to the stack design imperfection, stack aging, or other reasons. Only the stack developers based on their actual operating experience can determine whether the upper limit is 85%, 90% or some other values.

Optimum Operating Pressure (Groups 6 and 7)

As the operating pressure increases, the turbogenerator has to compress the air to a higher pressure and this results in a hotter air feed to the fuel cell unit. The hotter air is less effective in removing the stack heat. Thus, the stoichiometric air ratio and air preheater size are increased. Due to the larger air flow and higher working pressure, a larger size turbogenerator is also required. The stacks, on the other hand, are more efficient because of the higher reactant partial pressure available. The expander gas of the turbogenerator for the cases studied is in a temperature region that the turbogenerator produces less power as the pressure increases. To compensate for this lower power production, the stacks have to produce more power. Therefore, the cell area required does not necessarily decrease when the stack efficiency increases with the operating pressure. Overall, the capital cost increases as the operating pressure increases.

The stacks become more efficient and turbogenerator becomes less efficient as the operating pressure increases. Due to these two opposing effects, the overall electric efficiency slightly increases and then decreases as the operating pressure increases. As the efficiency variation is very small, the cost of electricity reflects the change of capital cost with the operating pressure.

A comparison between Groups 6 and 7 indicates that the higher stack operating temperature, even though offers a higher electric efficiency, has no net economical advantage for pressurized operation. The major reason is that stack cost is substantially higher at 1000C than at 800C.

A comparison of the best pressurized case (Case 6A) with the best atmospheric pressure case (Case 2B) under the same current density and fuel utilization indicates the pressurization offers no major economical advantage. Given the same cost of electricity, the atmospheric pressure operation is preferred because the lack of high temperature rotating equipment can make the unit more reliable, less noisy, and safer to operate. Also, the atmospheric operation is less likely to need feed gas compression if the natural gas supply pressure is not sufficiently high.

CONCLUSIONS

This study shows that a properly designed planar thin electrolyte SOFC unit can be produced at $700-800/kW with 55-60% efficiency (LHV). The cost of electricity based on the retail natural gas price and capital recovery rate anticipated for the distributed power generation is around 5 cents/kW. In comparison, the retail electricity cost in the United States, ranges from 6 to 12 cents/kW. Thus, the SOFC can be commercially viable for capturing the distributed power generation market.

REFERENCES

1. K. Krist, J. D. Wright, and C. Romero, “Manufacturing Costs for Planar Solid Oxide Fuel Cells”, Proceedings of the 4th International Symposium on Solid Oxide Fuel Cells, Osaka, Japan, The Electrochemical Society, p. 24-32, 1995
2. C. Romero, J. D. Wright, “The Value and Manufacturing Costs of Solid Oxide Fuel Cell Stacks”, GRI Report No. GRI-96/0210, 1996

Table I Study Cases

Group 1	**Ambient Pressure 85% Fuel Utilization 700 C Stack Temperature**	**Case 1A: 200 mA/cm2 current density Case 1B: 300 mA/cm2 current density Case 1C: 400 mA/cm2 current density**
Group 2	**Ambient Pressure 85% Fuel Utilization 800 C Stack Temperature**	**Case 2A: 200 mA/cm2 current density Case 2B: 300 mA/cm2 current density Case 2C: 400 mA/cm2 current density Case 2D: 500 mA/cm2 current density**
Group 3	**Ambient Pressure 85% Fuel Utilization 900 C Stack Temperature**	**Case 3A: 400 mA/cm2 current density Case 3B: 500 mA/cm2 current density Case 3C: 600 mA/cm2 current density**
Group 4	**Ambient Pressure 85% Fuel Utilization 1000 C Stack Temperature**	**Case 4A: 600 mA/cm2 current density Case 4B: 700 mA/cm2 current density Case 4C: 800 mA/cm2 current density**
Group 5	**Ambient Pressure 300 mA/cm2 current density 800 C Stack Temperature**	**Case 5A: 80% fuel utilization Case 5B (2B) : 85% fuel utilization Case 5C: 90% fuel utilization**
Group 6	**Pressurized 85% Fuel Utilization 300 mA/cm2 Current Density 800 C Stack Temperature**	**Case 6A: 3 atm operating pressure Case 6B: 4 atm operating pressure Case 6C: 5 atm operating pressure Case 6D: 6 atm operating pressure**
Group 7	**Pressurized 85% Fuel Utilization 300 mA/cm2 Current Density 1000 C Stack Temperature**	**Case 7A: 5 atm operating pressure Case 7B: 6 atm operating pressure Case 7C: 7 atm operating pressure Case 7D: 8 atm operating pressure Case 7E: 9 atm operating pressure**

Table II Summary of System Performance

Study Case	1A	1B	1C	2A	2B	2C	2D	3A	3B	3C	4A	4B	4C
Operating Pressure, atm	1	1	1	1	1	1	1	1	1	1	1	1	1
Stack Operating Temp., C	700	700	700	800	800	800	800	900	900	900	1000	1000	1000
Fuel Utilization, %	85	85	85	85	85	85	85	85	85	85	85	85	85
Current Density, mA/cm2	200	300	400	200	300	400	500	400	500	600	600	700	800
Natural Gas Feed (HHV), MMBtu/h	3.32	3.84	4.57	3.15	3.41	3.72	4.09	3.50	3.71	3.94	3.76	3.93	4.11
Stoichiometric Air Ratio	1.66	1.99	2.32	1.32	1.49	1.65	1.82	1.35	1.44	1.54	1.31	1.37	1.43
Cell Voltage, Volt	0.741	0.642	0.542	0.779	0.721	0.662	0.602	0.702	0.664	0.625	0.653	0.626	0.598
Stack Power Density, kW/m2	1.48	1.92	2.17	1.56	2.16	2.65	3.01	2.81	3.32	3.75	3.92	4.38	4.79
Total Cell Area Required, ft2	3,867	2,975	2,653	3,657	2,639	2,159	1,901	2,030	1,720	1,524	1,456	1,303	1,193
Power from Inverter, kW	503.9	505.5	507.6	503.0	503.6	504.4	505.3	503.4	503.8	504.3	503.5	503.8	504.2
Power from Turbogenerator, kW	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Power Consumed for Blower, kW	3.9	5.5	7.6	3.0	3.6	4.4	5.3	3.4	3.8	4.3	3.5	3.8	4.2
Net Power Export, kW	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0
Electric Efficiency, % (LHV)	57.0	49.2	41.4	60.1	55.5	50.9	46.3	54.1	51.1	48.1	50.3	48.2	46.1
Cogeneration Potential, % (LHV)	35.2	42.6	50.0	32.7	37.2	41.6	46.1	39.0	41.9	44.9	43.1	45.2	47.3
Cogeneration Efficiency, % (LHV)	92.2	91.8	91.4	92.8	92.7	92.5	92.4	93.1	93.0	93.0	93.4	93.4	93.4

Table II Summary of System Performance (continued)

Study Case	5A	5B	5C	6A	6B	6C	6D	7A	7B	7C	7D	7E
Operating Pressure, atm	1	1	1	3	4	5	6	5	6	7	8	9
Stack Operating Temp., C	800	800	800	800	800	800	800	1000	1000	1000	1000	1000
Fuel Utilization, %	80	85	90	85	85	85	85	85	85	85	85	85
Current Density, mA/cm2	300	300	300	300	300	300	300	300	300	300	300	300
Natural Gas Feed (HHV), MMBtu/h	3.56	3.41	3.26	3.02	2.97	2.95	2.95	2.82	2.80	2.79	2.78	2.78
Stoichiometric Air Ratio	1.56	1.49	1.42	1.71	1.82	1.94	2.07	1.34	1.39	1.45	1.50	1.56
Cell Voltage, Volt	0.733	0.721	0.711	0.735	0.739	0.742	0.745	0.758	0.762	0.765	0.767	0.770
Stack Power Density, kW/m2	2.20	2.16	2.13	2.20	2.22	2.23	2.24	2.27	2.28	2.29	2.30	2.31
Total Cell Area Required, ft2	2,595	2,639	2,673	2,337	2,301	2,286	2,285	2,184	2,166	2,155	2,150	2,149
Power from Inverter, kW	504.0	503.6	503.3	454.5	450.1	449.4	451.0	438.4	436.8	436.4	436.9	438.1
Power from Turbogenerator, kW	0.0	0.0	0.0	45.5	49.9	50.6	49.0	61.6	63.2	63.6	63.1	61.9
Power Consumed for Blower, kW	4.0	3.6	3.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Net Power Export, kW	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0	500.0
Electric Efficiency, % (LHV)	53.1	55.5	58.0	62.7	63.7	64.1	64.1	67.1	67.6	68.0	68.1	68.2
Cogeneration Potential, % (LHV)	39.5	37.2	34.7	29.4	28.1	27.4	27.1	25.8	25.1	24.6	24.3	24.1
Cogeneration Efficiency, % (LHV)	92.6	92.7	92.7	92.1	91.8	91.5	91.2	92.9	92.7	92.6	92.4	92.3

Table III Cost Summary, 1996 Pricing

Study Case	1A	1B	1C	2A	2B	2C	2D	3A	3B	3C	4A	4B	4C
Operating Pressure, atm	1	1	1	1	1	1	1	1	1	1	1	1	1
Stack Operating Temp., C	700	700	700	800	800	800	800	900	900	900	1000	1000	1000
Fuel Utilization, %	85	85	85	85	85	85	85	85	85	85	85	85	85
Current Density, mA/cm2	200	300	400	200	300	400	500	400	500	600	600	700	800
Capital Cost, $/kW													
Stacks	331	254	227	313	226	185	162	285	241	214	284	254	233
Air Preheater/Vessel	93	114	149	76	81	92	107	74	80	88	74	80	86
Air Blower/Turbogenerator	2	2	3	2	2	2	2	2	2	2	2	2	2
Inverter & Control System	200	200	200	200	200	200	200	200	200	200	200	200	200
Desulfurizer, Ejector, Prereformer	25	28	32	24	25	26	28	25	26	27	26	27	27
Other Support Facilities	155	155	155	155	155	155	155	155	155	155	155	155	155
Total	806	754	766	769	689	660	656	741	705	687	741	718	703
Cost of Electricity, Cent/kWh (a)													
Capital Recovery (25% annualy)	2.42	2.27	2.30	2.31	2.07	1.98	1.97	2.22	2.12	2.06	2.23	2.16	2.11
Natural Gas ($4/MMBtu)	2.66	3.07	3.66	2.52	2.73	2.98	3.27	2.80	2.97	3.15	3.01	3.14	3.29
O&M	0.69	0.57	0.55	0.66	0.51	0.45	0.42	0.62	0.55	0.50	0.62	0.57	0.54
Total	5.77	5.91	6.50	5.49	5.31	5.41	5.66	5.64	5.63	5.72	5.85	5.87	5.94

Table III Cost Summary, 1996 Pricing (continued)

Study Case	5A	5B	5C	6A	6B	6C	6D	7A	7B	7C	7D	7E
Operating Pressure, atm	1	1	1	3	4	5	6	5	6	7	8	9
Stack Operating Temp., C	800	800	800	800	800	800	800	1000	1000	1000	1000	1000
Fuel Utilization, %	80	85	90	85	85	85	85	85	85	85	85	85
Current Density, mA/cm2	300	300	300	300	300	300	300	300	300	300	300	300
Capital Cost, $/kW												
Stacks	222	226	228	200	197	195	195	426	423	420	419	419
Air Preheater/Vessel	83	81	78	78	81	84	87	62	63	65	66	68
Air Blower/Turbogenerator	2	2	2	64	85	105	125	78	90	101	112	124
Inverter & Control System	200	200	200	200	200	200	200	200	200	200	200	200
Desulfurizer, Ejector, Prereformer	25	25	25	21	21	21	21	20	20	20	19	19
Other Support Facilities	155	155	155	201	201	201	201	201	201	201	201	201
Total	688	689	688	764	784	806	829	988	997	1007	1019	1032
Cost of Electricity, Cent/kWh (a)												
Capital Recovery (25% annualy)	2.07	2.07	2.07	2.30	2.36	2.42	2.49	2.97	2.99	3.03	3.06	3.10
Natural Gas ($4/MMBtu)	2.85	2.73	2.61	2.42	2.38	2.36	2.36	2.26	2.24	2.23	2.22	2.22
O&M	0.51	0.51	0.51	0.47	0.47	0.47	0.47	0.86	0.85	0.85	0.85	0.85
Total	5.42	5.31	5.19	5.18	5.20	5.25	5.32	6.08	6.09	6.11	6.14	6.18

(a) Based on 95% On-Stream Factor

Figure I System Configuration (Ambient Pressure Operation)

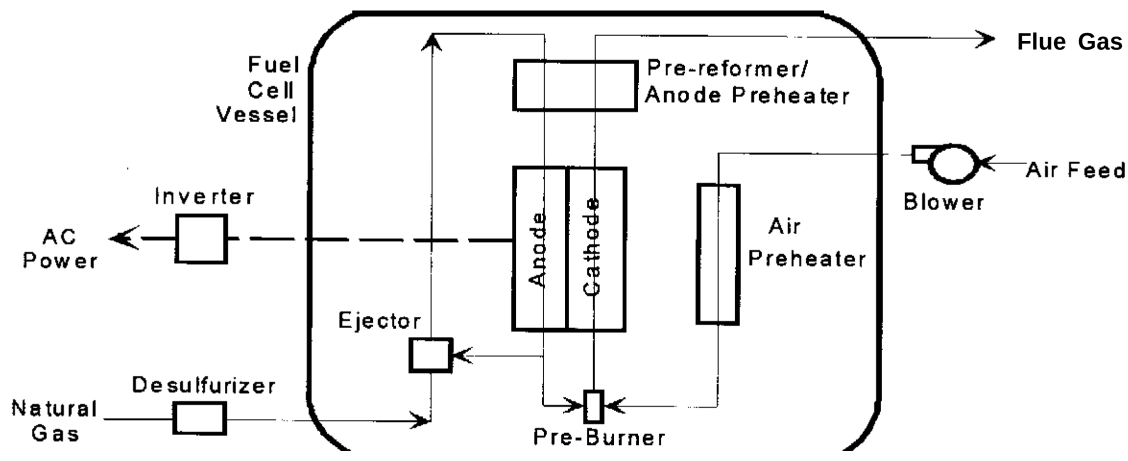

Figure II System Configuration (Pressurized Operation)

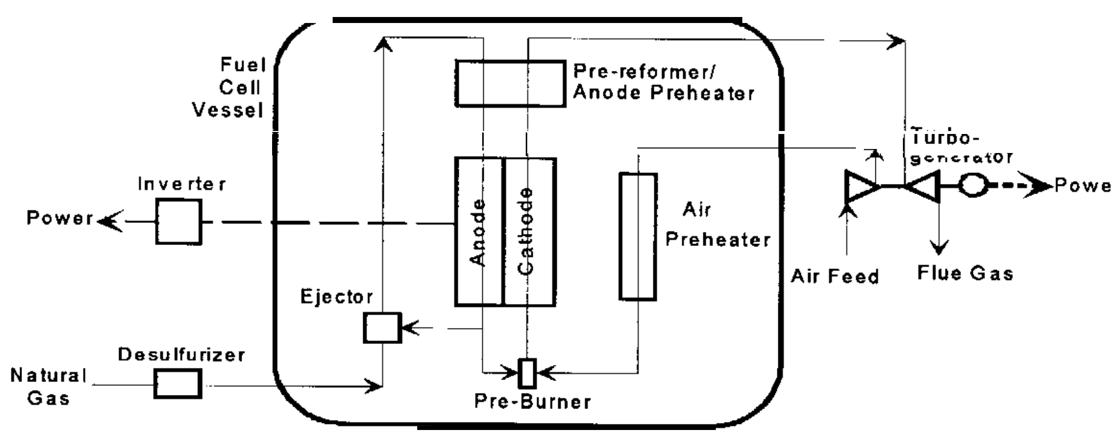

Figure III
Effect of Stack Operating Temperature on Electricity Cost