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High Efficiency Carbonate Fuel Cell/Turbine Hybrid Power Cycle

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HIGH EFFICIENCY CARBONATE FUEL CELL/TURBINE HYBRID POWER CYCLE

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ABSTRACT

Energy Research Corporation conducted studies of hybrid power cycles in cooperation with the U.S. Department of Energy, Morgantown Energy Technology Center (METC) to identify a high efficiency, economically competitive system. A hybrid power cycle which generates power at an LHV efficiency in excess of 70% was identified that includes an atmospheric pressure direct carbonate fuel cell, a gas turbine and a steam cycle. In the hybrid power cycle, natural gas fuel is mixed with recycled fuel cell anode exhaust, providing water for reforming fuel. The mixed gas then flows to a direct carbonate fuel cell which generates about 70% of the power. The portion of the fuel cell anode exhaust which is not recycled is burned and heat is transferred through a heat exchanger to the compressed air from a gas turbine. The heated compressed air is then heated further in the gas turbine burner and expands through the turbine generating 15 % of the power. Half the exhaust from the turbine provides air for the anode exhaust burner. All of the turbine exhaust eventually flows through the fuel cell cathodes providing the O_2 and CO_2 needed in the electrochemical reaction. Exhaust from the fuel cell cathodes flows to a steam system that includes a heat recovery steam generator and staged steam turbine which generates 15% of the hybrid cycle power.

Simulation studies of a 200 MW plant with a hybrid power cycle showed an LHV efficiency of 72.6%. The hybrid cycle power output and efficiency are relatively insensitive to ambient temperature, compared to a gas turbine combined cycle. The NO_x emissions from the hybrid power cycle are 75% lower than the level from a combined cycle. The estimated cost of electricity for a 200 MW with a hybrid power cycle is 46 mills/kWh, which is competitive with a combined cycle for installations where fuel cost is above $5.8/MMBTU. A key technology requirement in the hybrid power cycle is the heat exchanger which transfers heat to the compressed air from a gas turbine. In the 200 MW plant studies, a heat exchanger that operates at 1094°C was assumed to take advantage of high temperature heat exchanger technology currently under development by METC for coal gasifiers.

Studies of a near term high efficiency direct carbonate fuel cell/turbine hybrid power cycle have also been completed and are the subject of a paper to be presented at the Fuel Cell Seminar in Orlando, Florida in November 1996. These later studies were focused on a 20 MW hybrid power cycle for near term application.

INTRODUCTION

Direct carbonate fuel cells developed by Energy Research Corporation (ERC) generate power at an efficiency approaching 60%. A 2 MW power plant demonstration of this technology is presently under way at an installation in the city of Santa Clara in California. A 2.85 MW commercial configuration, shown in Figure 1, is presently being developed. The complete plant includes the carbonate fuel cell modules, power conditioning equipment, a heat recovery unit and supporting instrument air and water treatment systems. The emission levels for this 2.85 MW plant are orders of magnitude below existing or proposed standards. The 30 year levelized cost of electricity, without inflation, is projected to be under 52 mills/kWh assuming a capital cost for the carbonate fuel cell system of $1000/kW.

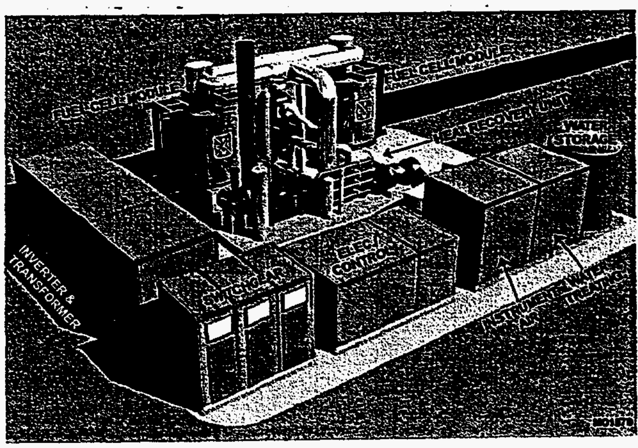

FIGURE 1. 2.85 MW POWER PLANT:
The Basic Direct Fuel Cell Technology for 200 MW Hybrid Cycle

ERC conducted studies of hybrid power cycles in cooperation with the U.S. Department of Energy, Morgantown Energy Technology Center (METC) to identify a higher efficiency, economically competitive system. A hybrid power cycle which integrates fuel cell and turbine technology generating power at an LHV efficiency in excess of 70% was identified. This paper describes the direct carbonate atmospheric pressure fuel cell/turbine hybrid power cycle and presents the results of studies on the application of this new cycle to a 200 MW power plant.

HYBRID POWER CYCLE DESCRIPTION

The direct carbonate atmospheric pressure fuel cell/turbine hybrid power cycle is shown in Figure 2. The system includes a direct carbonate fuel cell, a gas turbine, and a steam cycle. Natural gas flows to the fuel cell and the gas turbine. Air flows to the gas turbine, and exhaust from the gas turbine flows to the fuel cell. Fuel exhaust from the fuel cell is oxidized providing heat to the gas turbine. Exhaust from the fuel cell flows to the steam cycle.

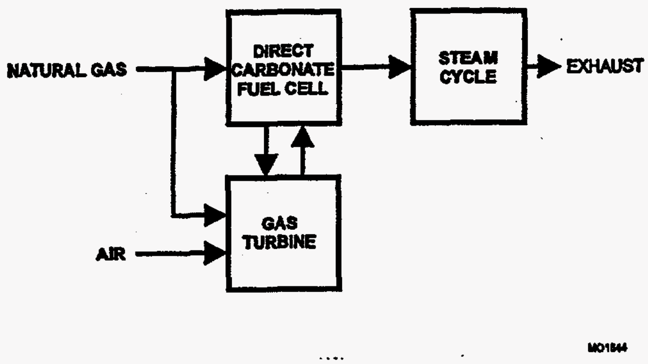

FIGURE 2. MAJOR ELEMENTS OF HYBRID POWER CYCLE:
An Integrated System to Maximize Electrical Efficiency

In the direct carbonate fuel cell system water vapor is mixed with the natural gas and is internally steam reformed producing CO and H_2 as follows:

(1) $CH_4 + 1.5\,H_2O + \text{Heat} \rightarrow CO + 3H_2 + 0.5\,H_2O$ Reform

(2) $CO + H_2O \rightarrow CO_2 + H_2$ Shift

(3) $H_2 + CO_3^{=} \rightarrow H_2O + CO_2 + 2e^-$ Anode Reaction

(4) $O_2 + 2CO_2 + 2e^- \rightarrow 2CO_3^{=}$ Cathode Reaction

The CO is shifted with water vapor produced at the cell anodes providing additional H_2, as shown in Reaction 2. The H_2 reacts electrochemically (with the carbonate ion) in the fuel cell anode. In the cathode, CO_2 reacts with oxygen from air producing a carbonate ion (Reaction 4) which migrates to the anode electrode through the electrolyte.

(5) $CH_4 + 2O_2 \rightarrow CO_2 + 2\,H_2O + \text{Electricity} + \text{Heat}$ Overall Reaction

The overall Reaction 5 results in electrochemical oxidation of the fuel producing CO_2 and H_2O. Heat generated in the fuel cells provides more than enough heat for the reforming process (Reaction 1) which occurs within the fuel cell stack.

200 MW PLANT SYSTEM

A system schematic for a 200 MW plant with the hybrid power cycle is shown in Figure 3. In this system, about 95% of the methane fuel flows to near atmospheric pressure direct internal reforming carbonate fuel cells. The methane is internally reformed to H_2 and CO. The water required for reforming is recycled from the fuel cell anode exit. About 80% of the H_2 and CO is consumed in the cell anodes generating DC power. The unreacted H_2 and CO flows to a burner which operates at 1094°C.

Five percent of the methane fuel is compressed and flows to the gas turbine combustor. The gas turbine compressor delivers air at 360 psia to a high temperature heat exchanger which heats the air to 982°C. The heated air then flows to the gas turbine combustor where it is heated further to 1094°C before flowing through the turbine. Turbine exhaust containing O_2 and CO_2 is split with 50% of the stream flowing to the fuel cell cathodes and 50% flowing to the anode exhaust burner. Exhaust from the cathode recycle burner heats the compressed air in the high temperature heat exchanger before joining the stream to the fuel cell cathodes. Exhaust from the cathodes at 677°C flows to the steam bottoming system. The steam bottoming system includes a Heat Recovery Steam Generator (HRSG) high, intermediate and low pressure steam turbines, a condenser and condensate pump. The HRSG includes a reheater, superheater, high pressure boiler, economizer, and a low pressure boiler. The system also includes a condensate reheater, deaerator, boiler feed pump and exhaust blower not shown on the simplified schematic.

This system is self-sufficient in its water management. There is no net requirement for process water other than for make-up of blow-down from the boilers. Exhaust from the system is at 67°C, with a dew point of about 54°C.

In the system described above, water is provided for the reforming process by *anode recycle* in which a portion of the fuel cell anode exhaust is recycled back to the inlet of the process. An alternative way is to provide the water vapor for the reforming process in the fuel cell stacks from the steam bottoming cycle. Both of these options were explored in studies of the hybrid power cycle for a 200 MW power plant.

200 MW HYBRID POWER CYCLE PLANT PERFORMANCE

The performance of the 200 MW plant with a hybrid power cycle was analyzed using a CHEMCAD[1] system model with an ERC developed fuel cell model. The results are shown in Table 1 for a system in which water vapor for the reforming is by anode recycle and for a system in which the water comes as steam from the steam system.

In the hybrid power cycle, about 70% of the power is produced by the fuel cell system, about 15 % comes from a generator driven by the gas turbine, and the remaining 15% comes from generators driven by the three steam turbines. There is about 5% parasitic power for pumps and blowers in the system.

PERFORMANCE SENSITIVITY TO SITE CONDITIONS

In the performance studies of the hybrid power cycle presented above, the assumed site conditions are sea level and 15°C ambient air. The effect of ambient temperature above 15°C and elevations above sea level was also investigated. The results indicate that the hybrid power cycle system is relatively insensitive to changes in ambient temperature or elevation. The effect of ambient temperatures at 35°C and 49°C on the performance of the hybrid power cycle system with anode recycle is shown in Table 2. An ambient temperature of 49°C results in only 4.2% reduction in the net power generation.

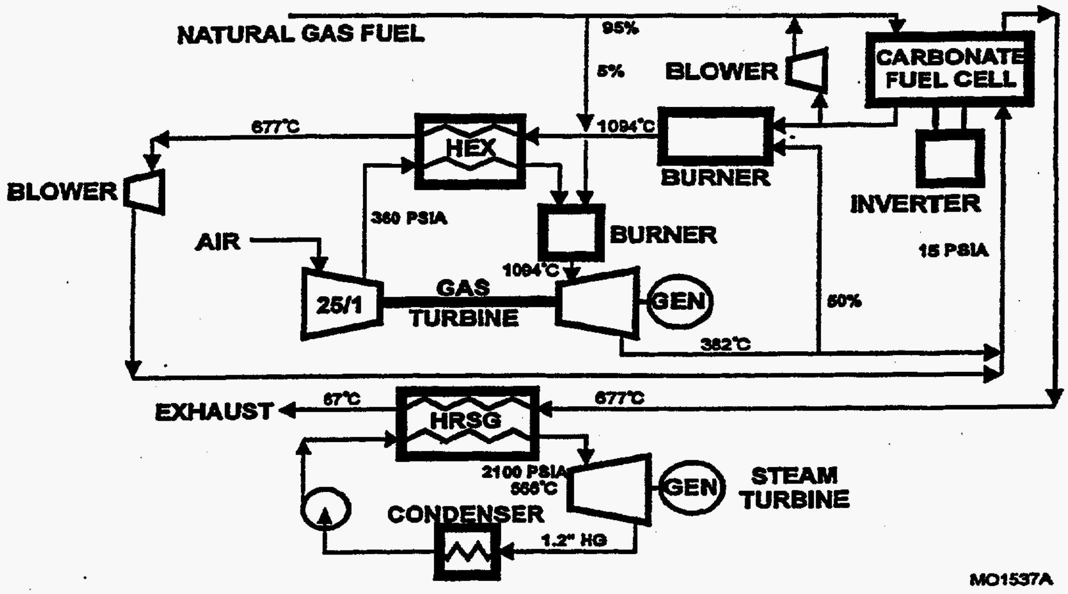

FIGURE 3. SYSTEM SCHEMATIC OF HYBRID POWER CYCLE:
Important State Points are Indicated

TABLE 1.
200 MW HYBRID POWER CYCLE PERFORMANCE:
Over 70% Efficiency is Projected

	WATER FROM STEAM SYSTEM	WATER BY ANODE RECYCLE
POWER GENERATION, MW		
GAS TURBINE	28.9	27.1
FUEL CELL	159.4	157.6
STEAM TURBINE	26.6	32.8
PARASITIC POWER	-11.6	-11.1
TOTAL	203.3	206.4
NET AC LHV EFFICIENCY, %		
FUEL CELL	58	55.1
FUEL CELL + GAS TURBINE	62	61.7
STEAM SYSTEM	32.5	34.1
OVERALL	70.2	72.6

As ambient temperature goes up from 15°C to 35°C and to 49°C, the fuel cells, which produce 70% of the power, have a relatively constant output. There is a 7-11% increase in the gas turbine compressor work and gas turbine net output is reduced 14-22%. More fuel cell waste heat is transferred in the high temperature heat exchanger and the gas turbine raw fuel flow is reduced 35-56%. A higher fraction of the gas turbine exhaust flows directly to the fuel cell for cooling and the exhaust recycle blower has 4-13% less parasitic loss. The net result is 3-4% less power output and 2-3 % less fuel flow. The result is a reduction in efficiency of only 1-1.3%, as shown in Table 2.

TABLE 2.
EFFECT OF AMBIENT TEMPERATURE ON HYBRID POWER CYCLE PERFORMANCE:
The Hybrid Cycle is Insensitive to Ambient Conditions

AMBIENT TEMP., °C	15	35	49
NET POWER, MW	206.4	200.6	197.8
EFFICIENCY, %	72.6	72.0	71.7

A comparison of the hybrid power cycle performance at temperatures above 15°C against a typical gas turbine combined cycle[5,6] is shown in Figure 4. A combined cycle is expected to have a 15% reduction in power rating at 49°C, compared to only 4% reduction in power rating with a hybrid power cycle.

The effect of elevation on the performance of the hybrid power cycle was also investigated and showed that the performance is relatively insensitive to site elevation with power rating reduction of only 2.1% between sea level and 5,000 foot site elevation.

200 MW HYBRID POWER CYCLE PLANT EMISSIONS

Although the hybrid power cycle has about 70% of its power generated by the fuel cells, there is an anode exhaust combustor and a gas turbine burner which can generate nitrous oxides, NO_x. A comparison of the NO_x between a hybrid power cycle and a gas

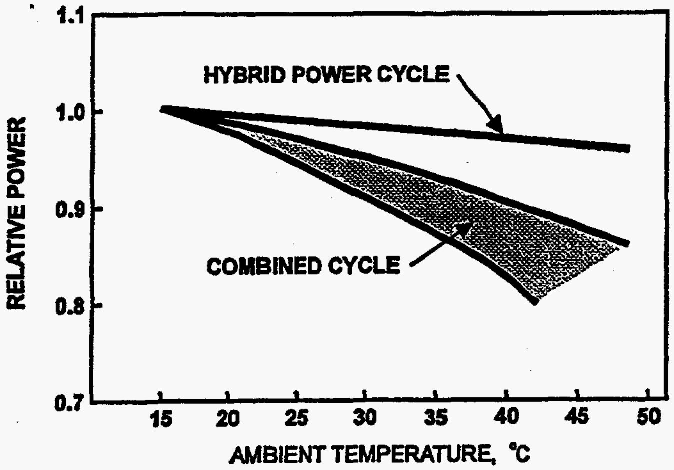

FIGURE 4. PERFORMANCE SENSITIVITY TO SITE TEMPERATURE:
Hybrid Cycle Has Significant Advantage Over Combined Cycle

turbine combined cycle was made on the basis of equilibrium levels predicted from the combustors in the two systems at their respective operating conditions. The results showed that the hybrid power cycle is expected to generate 75% less NO_x than a gas turbine combined cycle.

The emission of sulfur dioxide, SO_x is expected to be only about 1% of the level from a gas turbine combined cycle because the fuel is desulfurized as a first step in the process (not shown on the simplified system schematic Figure 3). The contribution of carbon dioxide, CO_2, to the atmosphere is expected to be about 25% lower than a gas turbine combined cycle due to the higher efficiency.

200 MW HYBRID POWER CYCLE PLANT COST OF ELECTRICITY

The 30 year levelized cost of electricity for the 200 MW plant with a hybrid power cycle was estimated at 45.8 mills/kWh, without inflation, using methods recommended in EPRI TAG[3]. This includes a levelized plant cost of 12.5 mills/kWh, operating and maintenance (O&M) cost of 11.9 mills/kWh, and levelized fuel cost of 21.4 mills/kWh.

The 30 year levelized plant cost is based on a capital cost of 974 $/kW in 1995 dollars. This overall plant capital cost includes 1000 $/kW for the fuel cell system based on projections by ERC. The capital cost for the gas turbine was estimated at 450 $/kW[4], and the steam system at 620 $/kW[4]. The cost of the system high temperature heat exchanger was estimated at 53 $/kW[7].

The O&M cost includes the fuel cell system estimated at 9.2 mills/kWh including five year fuel cell stack replacement. The O&M costs for the gas turbine and steam system are 1.7 mills/kWh and 0.9 mills/kWh, respectively.

The levelized fuel cost of 21.4 mills/kWh is based on a first year fuel cost of $3/MMBTU and a capacity factor of 0.91. The calculated levelizing factor is 1.37[3], an interest rate of 5.3%, no inflation and a fuel escalation rate of 2.5% per year.

COMPARISON WITH A 200 MW GAS TURBINE COMBINED CYCLE

For perspective on the commercialization prospects for a 200 MW plant with a hybrid power cycle, a comparison was made with a 200 MW gas turbine combined cycle. The comparison addressed issues of performance and cost of electricity. The gas turbine combined cycle selected for the comparison is a Siemens Kraftwerk Union GUD 1S84.3 rated at 227 MW. This system[4] has a single V84.3 gas turbine rated at 166 MW and a 83 MW steam turbine. The published heat rate is 6285 BTU/kWh LHV (54.3% efficiency). Although manufacturers of larger combined cycle plants with more advanced technology are advertising efficiencies approaching 60%, this model reflects presently available units for which comparison information is available.

The 30 year levelized cost of electricity for the 227 MW combined cycle was estimated at 38.8 mills/kWh, without inflation, using EPRI TAG[3]. The 30 year levelized plant cost is based on published cost of the 227 MW combined cycle[4] and estimates of installation and project cost. The O&M cost[2] is in 1995 dollars. The levelized fuel cost of 28.6 mills/kWh is based on the same assumptions as used to estimate the fuel cost for the hybrid power cycle. A breakdown of cost of electricity is shown in Table 3 in comparison with the hybrid power cycle. Although the hybrid power cycle fuel cost at $3/MMBTU is significantly less, the difference is not enough to offset higher plant and O&M cost, which result in higher COE at this fuel cost.

TABLE 3.
LEVELIZED COST OF ELECTRICITY COMPARISON, mills/kWh:
COE for Hybrid System is Greater Due Primarily to Higher Capital Cost

	HYBRID POWER CYCLE	COMBINED CYCLE
FUEL	21.4	28.6
PLANT	12.5	4.8
O&M	11.9	5.4
TOTAL	45.8	38.8

The effect of first year fuel cost on the comparison is shown in Figure 5. The hybrid power cycle is competitive with the combined cycle for 200 MW installations in which the first year fuel cost is above $5.8/MMBTU.

The first year fuel cost at which the hybrid power cycle is competitive with the combined cycle is significantly influenced by fuel cell system cost. An increase in the fuel cell system cost from 1000 $/kW to 1250 $/kW increases the first year fuel cost at which the hybrid power cycle is competitive from 5.8 $/MMBTU to 7.5 $/MMBTU. A decrease in fuel cell system cost of 100 $/kW decreases the first year fuel cost at which the hybrid power cycle is competitive by 0.7 $/MMbTU.

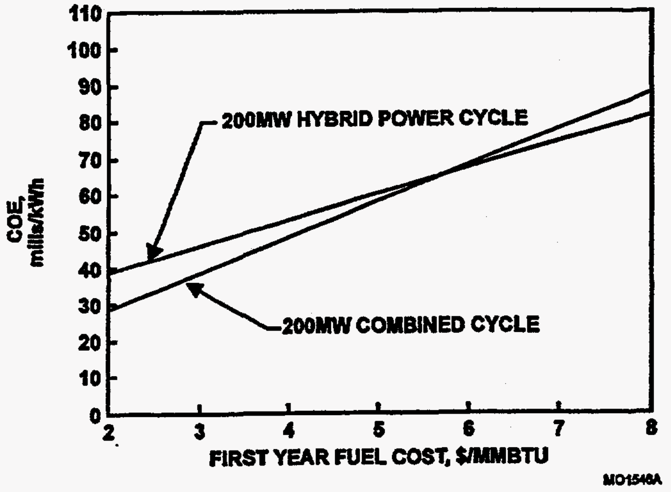

FIGURE 5. COST OF ELECTRICITY:
Hybrid Cycle Will Be Competitive Above
~6$/MMBTU Fuel Cost

200 MW HYBRID POWER CYCLE TECHNICAL CHALLENGES

Hybrid power cycle commercialization for application in 200 MW installations with high fuel cost requires that a number of technical challenges, identified below, be addressed.

Performance of the fuel cells under hybrid power cycle conditions must be verified. These conditions include the composition of gas to the anode which corresponds to the use of anode recycle as a means of providing water for the reforming process. In addition, relatively lean oxygen concentrations at the fuel cell cathodes were assumed which must be verified.

An anode recycle blower with a temperature capability of 650°C and seals that minimize fuel gas leakage under a pressure differential of about 3 psi must be found/developed.

The heat exchanger that transfers heat from the anode exit burner to the compressed air from the gas turbine must be designed for a temperature of 1094°C and a design pressure of 400 psig. High temperature heat exchangers are presently under development by METC for application to coal gasification. A detailed understanding of this technology and its application to the hybrid power cycle is needed, particularly to meet the cost projections for this equipment.

The gas turbine in the hybrid power cycle has a relatively low power output. In addition, the compressor air is heated external to the gas turbine and then returned to the gas turbine burner for supplementary heating before passing through the turbine. Gas turbine technology must be reviewed in detail with suppliers and the design modified to accommodate the hybrid power cycle integration requirements.

CONCLUSIONS

A hybrid power cycle which includes direct carbonate fuel cells operating at near atmospheric pressure, a gas turbine and a steam system, is capable of generating power at a net LHV efficiency above 70%. These results corroborate those published by DOE/METC [8]. The performance is relatively insensitive to ambient temperature and site elevation. This new power cycle requires a high temperature heat exchanger to transfer heat from the fuel cell system to the gas turbine.

Studies of the hybrid power cycle for a 200 MW plant, in which the system includes advanced heat exchanger technology indicate an efficiency of 70%. Required heat exchanger development is a design that operates at 1094°C and 400 psia. The additional development of a fuel cell anode exit recycle compressor would result in a plant efficiency of 73%. Emissions from the plant are expected to be well below existing or proposed standards. The NO_x emission level is 75% below the level from a combined cycle. A 200 MW plant with a hybrid power cycle is competitive with a gas turbine combined cycle for installations where the fuel cost is above $5.8/MMBTU.

Technical challenges include verification of fuel cell performance at the system conditions chosen, development of a high temperature heat exchanger and an anode recycle blower. In addition, design integration of the cycle gas turbine is required.

FURTHER STUDIES

Studies of a near term high efficiency direct carbonate fuel cell/turbine hybrid power cycle have also been completed and are the subject of a paper to be presented at the Fuel Cell Seminar in Orlando, Florida in November 1996. These later studies were focused on a 20 MW hybrid power cycle for near term application. A more moderate, 815°C heat exchanger, and with steam provided from the steam system rather than anode recycle were assumed. This hybrid power cycle has an estimated LHV efficiency of 65%. The NO_x emissions are 80% lower than a 20 MW gas turbine combined cycle. The estimated cost of electricity for the near term 20 MW plant with a hybrid power cycle is 50 mills/kWh, which is competitive with a 20 MW combined cycle for installations where the fuel cost is above $2.5/MMBTU.

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REFERENCES

1. CHEMCAD Version 3.0, Chemstations Inc., Houston, Texas.
2. EPRI-P-6571-L Technical Assessment Guide Vol. 1, Electrical Supply, Rev. 6, Sept. 1989.
3. EPRI-TR-100281 Technical Assessment Guide Vol. 3, Fundamental & Methods - Electrical Supply, Rev. 6, December 1995.
4. *Gas Turbine World Handbook*, 1995 Edition.
5. Umberto Desideri, "Performance Analysis of Gas Turbines Operating at Different Atmospheric Conditions", Institute di Energetica di Perugia Italy, IGTI Vol. 9, ASME Cogen Turbo 1994.
6. Izumi Ushiyama, "Theoretically Estimating the Performance of Gas Turbines Under Varying Atmospheric Conditions", Ashigawa Institute for Technology, Japan, ASME Transactions Gas Turbine Conference, March 1975.
7. Communication with Paul Micheli, METC , June 1995.
8. Micheli, Paul L., "High Efficiency MCFC Bottomed Cycle", Fuel Cells '95 Review Meeting, U.S. DOE METC, Aug. 9-10, 1995.