9950-803

Contract No. JPL-956252

EVALUATION OF SOLID OXIDE FUEL CELL SYSTEMS FOR ELECTRICITY GENERATION

Final Report

Prepared for:

A. W. Pappano
JPL Technical Manager
California Institute of Technology
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109

Authors:

D. Q. Hoover, Westinghouse Project Manager;
E. V. Somers, E. J. Vidt, R. E. Grimble, Principal Investigators

December 1982

Westinghouse R&D Center
1310 Beulah Road
Pittsburgh, Pennsylvania 15235

"This work was performed for the Jet Propulsion Laboratory, California Institute of Technology sponsored by the National Aeronautics and Space Administration under Contract NAS7-100."

TABLE OF CONTENTS

1. INTRODUCTION

As a result of advances in fabrication techniques, cell geometries and generator configurations for solid oxide electrolyte fuel cells (SOFC), the DOE and Westinghouse are cost sharing a technology development program (Contract No. DE-AC-2080ET17089). The primary goal of that program is the commercialization of SOFC in coal pile to busbar power plants that include gasification of the coal and utilization of the SOFC by-product heat in thermal conversion cycles.

Under this contract (JPL 956252), which resulted from an unsolicited proposal to JPL, we studied and evaluated attractive combinations of coal gasifiers, SOFC and heat engines. The overall objective was to identify additional research and development projects that would facilitate the commercialization of SOFC.

The four combinations selected for evaluation were:

1. Air blown (low BTU) gasification with atmospheric pressure SOFC and Rankine bottoming cycle.
2. Oxygen blown (medium BTU) gasification with atmospheric pressure SOFC and Rankine bottoming cycle.
3. Air blown gasification with pressurized SOFC and combined Brayton/Rankine bottoming cycle.
4. Oxygen blown gasification with pressurized SOFC and combined Brayton/Rankine Bottoming cycle.

In all cases the gasifiers were of the fluidized bed type and operated at pressure levels above 20 atmospheres. The Rankine cycles were 2400 psi/1000°F reheat steam cycles typical of current utility practice. The Brayton cycles were 11.2:1/2200°F which is state-of-the-art combustion turbine practice. The operating pressure of the SOFC was 1.1 atmospheres for cases 1 and 2 and 11.2 atmospheres for cases 3 and 4.

The selection of these cycles was based on previous studies and experience and was made in consultation with the JPL technical manager.

2. CONCLUSIONS

Based on the evaluation of performance and estimates of energy costs the following conclusions were reached:

A. The combination of pressurized SOFC with an air-blown fluidized bed coal gasifier, high temperature sulfur removal and combined Brayton-Rankine bottoming cycles has the potential to achieve coal pile to busbar efficiencies of 58 percent.

B. System efficiencies of 52 percent are achievable with unpressurized SOFC and a Rankine bottoming cycle.

C. The combination of air blown (low BTU) gasification and pressurized operation of the fuel cell has the lowest calculated energy cost (59 mils/kWh) and is, therefore, the most attractive for commercialization.

D. Further research is needed to verify the SOFC tolerance to the levels of sulfur (and other impurities) that are achievable by hot cleanup of the gasifier product.

E. Development of SOFC generators for pressurized operation is needed to achieve the highest system efficiencies.

3. RECOMMENDED RESEARCH AND DEVELOPMENT PROJECTS

As described in other sections of this report, the inclusion of SOFC in coal gasification power plants has the potential to achieve overall efficiencies of 52 and 58 percent with atmospheric and pressurized operation of the SOFC generator respectively. The corresponding reductions in coal consumption for a 675 MW plant operating at a 65 percent load factor are 269 and 440 thousand tons per year compared to a plant with a 40 percent efficiency. This reduction of coal consumption is one of the major benefits of SOFC commercialization.

Much of the R&D required for the commercialization of SOFC is ongoing as part of the DOE-Westinghouse cost shared program (DOE Contract No. DE-AC-0280ET17089). However, the systems described in this report require operation of the cells under conditions that are not being directly addressed under that program and additional R&D projects would facilitate SOFC commercialization.

3.1 Impurity Tolerance

The system performance and costs presented in other sections of this report are based on cleanup of the fuel gas at elevated temperature. The use of cold gas cleanup would reduce efficiencies by about 2 points and increase equipment cost and complexity(1). Theory and some experiments performed at Westinghouse R&D indicate that, if sulfur levels of 100 ppm or lower can be achieved, there will be no significant reduction in cell life and the reduction in cell performance will be small and reversible at atmospheric pressure(2). However, this has not been conclusively demonstrated for the current cell designs or in an environment that included all of the other trace impurities that will exist in coal gas. Furthermore, the effects of elevated pressure operation have not been investigated.

A research project to verify the tolerance of SOFC to fuel impurities and evaluate the effects of pressurized operation on cell performance and life would facilitate commercialization. A one year project to determine likely impurity levels, test cells at atmospheric pressure with appropriate fuels and analytically investigate the effect of elevated pressures would provide the needed information. For budgetary purposes, such a project would require funding of approximately $300,000.

3.2 Carbon Deposition

The compositions of fuel gases shown in other sections of this report are such that solid carbon would occur at thermodynamic equilibrium. Such operation is common in the chemical process industry and has been demonstrated by operation of the Westinghouse FBG (fluidized bed gasifier) at higher sulfur levels and pressure. Based on the FBG experience we feel that carbon deposition will not be a problem for the atmospheric pressure fuel cell and that it is unlikely to be a problem at the pressure levels used in this study. However, due to the exposure the fuel cell community has had to this problem in the virtually sulfur and ammonia free fuel of the MCFC, a project to verify the ability of these to inhibit deposition would facilitate the SOFC acceptance and commercialization.

We recommend a one year project to explore the effects of sulfur and ammonia on carbon deposition. The project would include collection, collation and evaluation of the information available on the effects of scale, pressure level, gas composition and construction materials on the kinetics of carbon deposition and bench scale tests at atmospheric and elevated (∿10 atm) pressures. Our budgetary estimate for this project is $300,000.

3.3 Pressurized SOFC Generator Development

The systems incorporating pressurized SOFC with combined Brayton/Rankine bottoming cycles have the highest efficiencies and lowest energy costs (revenue requirements). The solid state SOFC should be capable of operation at elevated pressure and, in fact, can tolerate pressure differentials across the electrolyte better than MCFC or PAFC. However, the on-going generator development effort is focused on atmospheric pressure operation. A project to develop a SOFC generator design for pressurized operation should be initiated soon to ensure commercialization of the most attractive system.

The initial efforts to develop a pressurized generator should be a definition of the operating requirements (e.g., pressure levels (8-12 atm), steady state pressure differentials, transient pressure differentials). This could be carried out in a six-month program for an estimated cost of $100,000.

Subsequent efforts would include:

1) Cell tests under the expected conditions to verify their performance characteristics.
2) Coordinated analyses and tests to develop design concepts for a pressurized generator.
3) Further process and materials developments if needed.
4) Design fabrication and operation of a demonstration generator at the anticipated operating conditions.

These would span a time of approximately 2 years and would have a budgetary estimate of $1,000,000.

4. PERFORMANCE AND ECONOMICS OF SELECTED SYSTEMS

4.1 Description of Systems Evaluated

Early in the study four systems were selected for evaluation. These systems comprised combinations of two gasification systems (air and oxygen blown) and two power cycles (atmospheric pressure SOFC and 11.2 atmosphere pressure SOFC). Schematic diagrams for the four systems are shown in Figures 1 through 4 and brief descriptions of the four cases are given in the Introduction (Section 1) of this report.

4.1.1 Gasification System

The gasification system selection was primarily based on the results of a previous study carried out by the Westinghouse R&D Center for the Morgantown Energy Technology Center (1). The factors considered in this selection are summarized in Section 5 of this report. The systems selected comprised air and oxygen blown versions of fluidized bed gasifiers (FBG) with hot gas cleanup. The gas compositions, flow rates, etc., at statepoints 6 and 3 in the schematic diagrams are given in Tables 1 and 2 respectively for the air and oxygen blown versions. These compositions are based on experimental data obtained on the Westinghouse Process Demonstration Unit gasifier, but are typical of those of other FBG.

4.1.2 Power Cycle

The consideration of the two power cycles was primarily based on the decision to evaluate and compare systems based on atmospheric pressure and elevated pressure operation of the SOFC. The ongoing SOFC development efforts have been focused on the former. Previous evaluations have indicated that such systems have attractive performance and economic characteristics and the generator is a simple conservative design. However, in the months preceding this contract effort, a full appreciation of the synergism of the SOFC with a combustion turbine/steam turbine combined

ORIGINAL PAGE IS
OF POOR QUALITY

Dwg. 5604C52

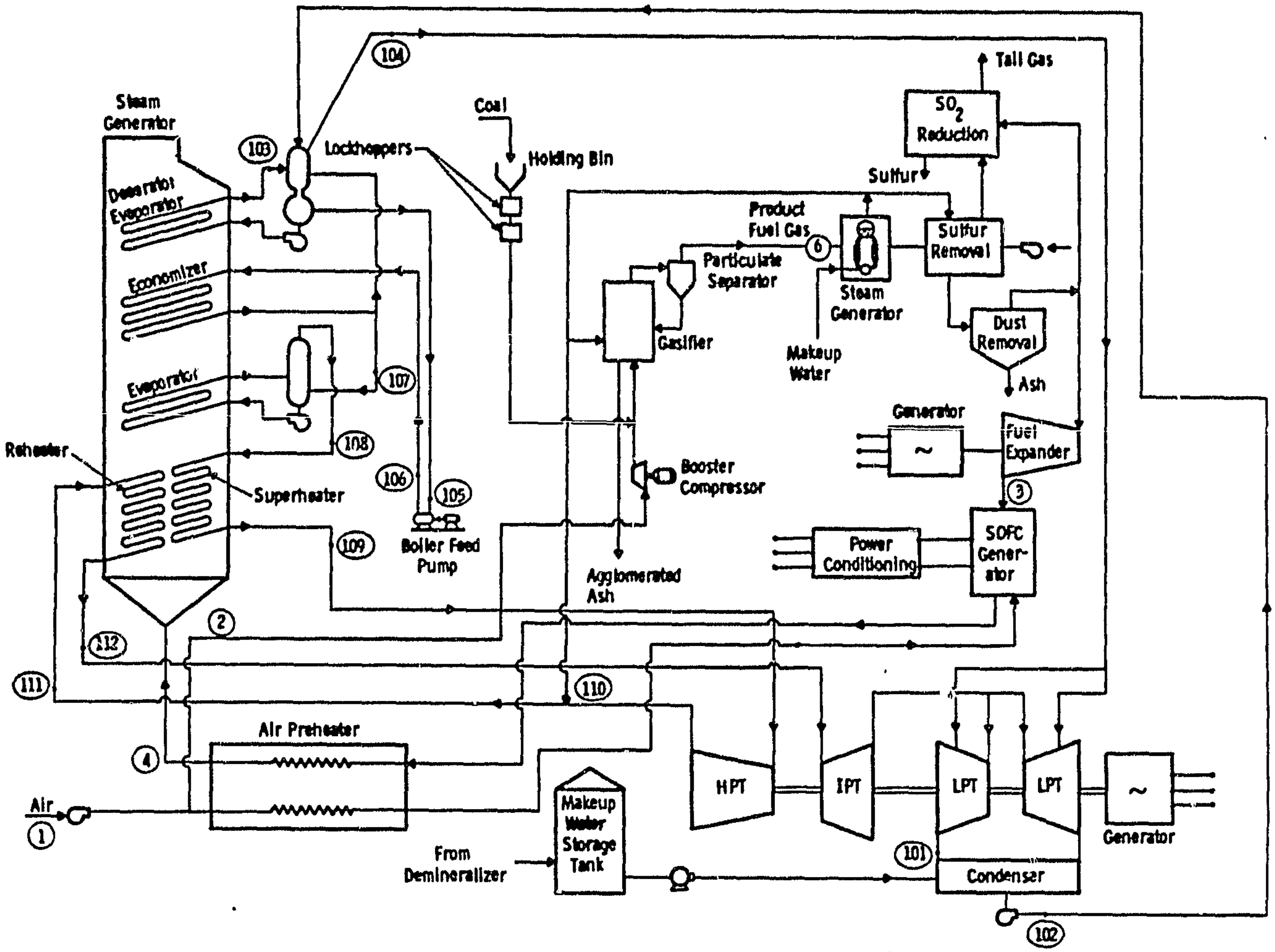

Fig. 1 – Atmospheric pressure SOFC plant with air blown gasification (case 1)

Dwg. 5604C53

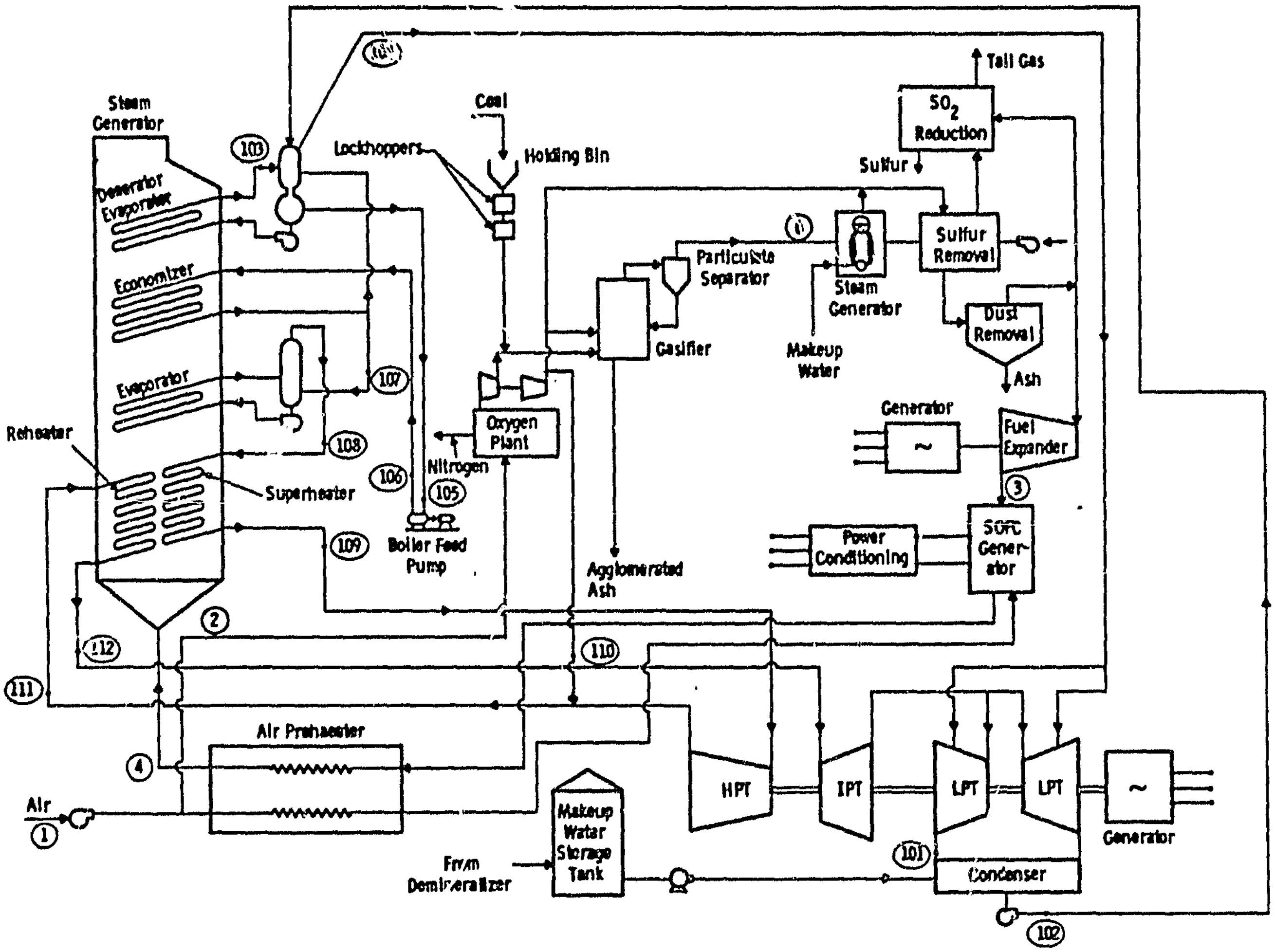

Fig. 2 – Atmospheric pressure SOFC with oxygen blown gasifier (case 2)

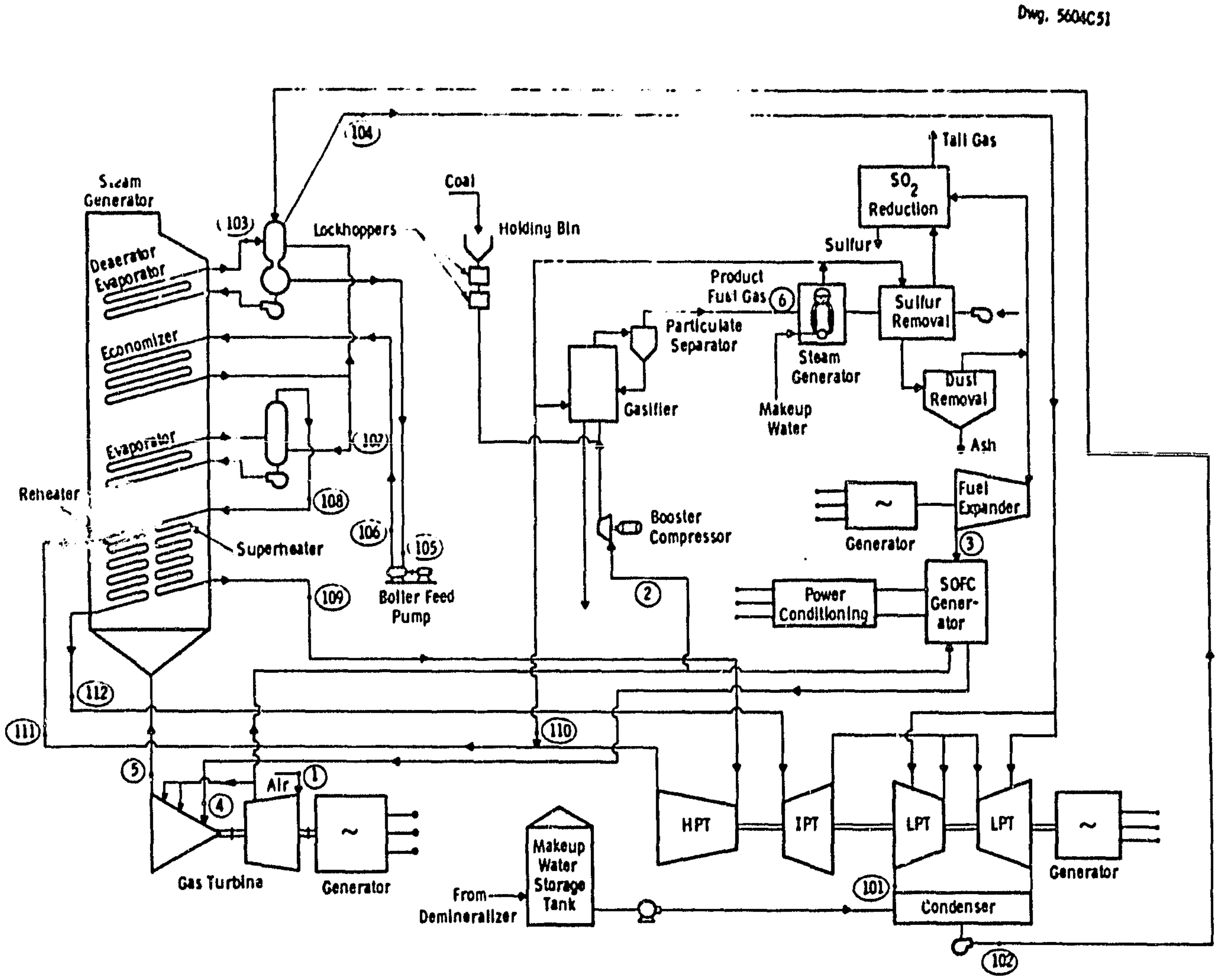

Fig. 3 – Pressurized SOFC topping of combined cycle with air blown gasifier (case 3)

ORIGINAL PAGE IS
OF POOR QUALITY

Dwg. 5604C54

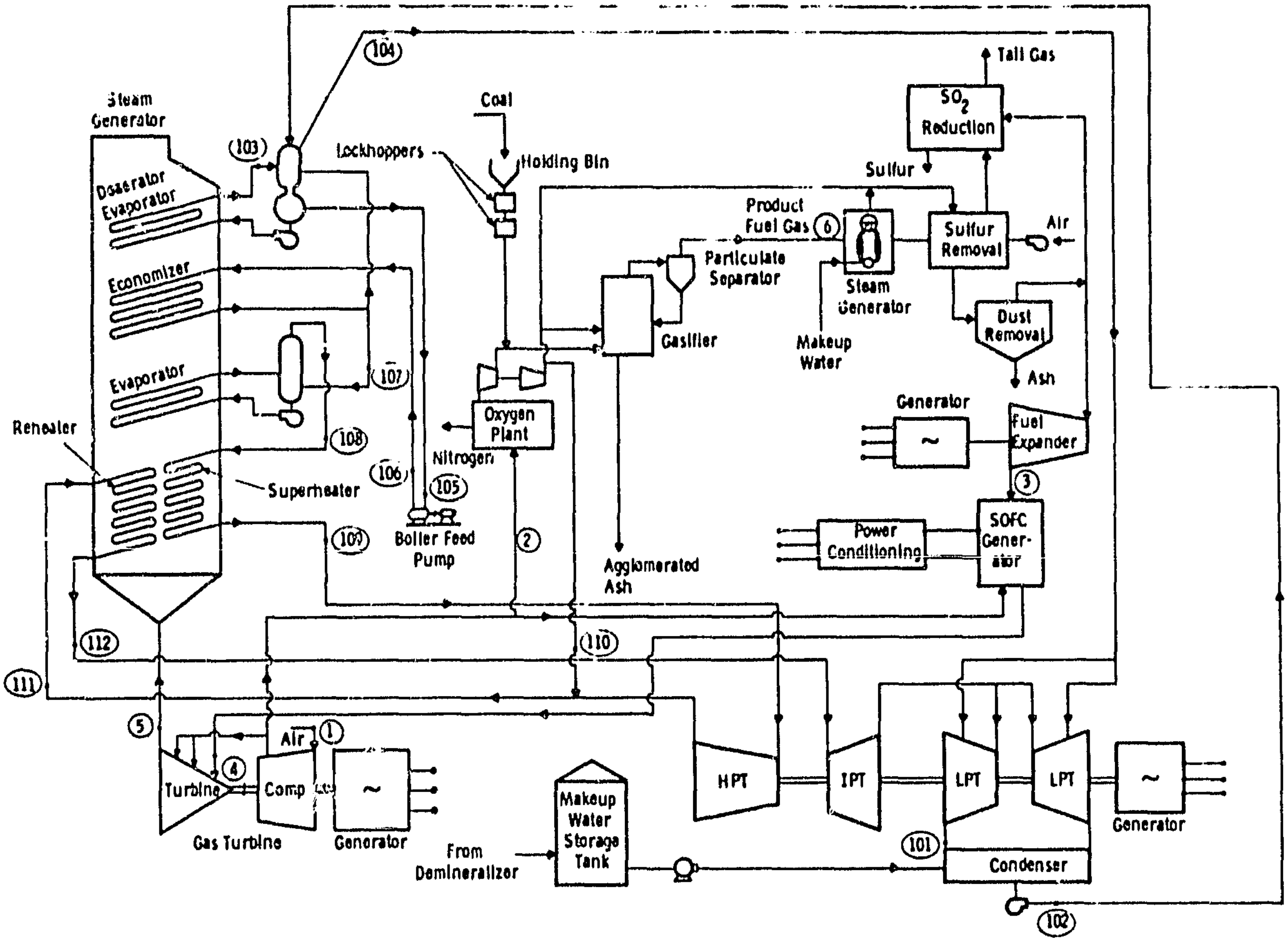

Fig. 4 – Pressurized SOFC topping of combined cycle with oxygen blown gasifier (case 4)

Table 1
Fuel Gas Characterisitics for Air Blown Gasification (Cases 1 and 3)

State Point	⑥	③
Composition (mole %)		
H_2	16.8	17.0
CO	27.9	28.1
CH_4	1.8	1.8
CO_2	2.8	2.9
H_2O	3.8	3.8
N_2	46.0	46.3
NH_3	0.16	0.16
H_2S	0.68	30 ppmv
COS	0.02	20 ppmv
Flow rate (moles/lb coal)	0.169	.166
HHV Product/HHV coal	.859	.839

Table 2
Fuel Gas Characteristics for Oxygen Blown Gasification (Cases 2 and 4)

State Point	⑥	③
Composition (mole %)		
H_2	29.4	29.8
CO	38.0	38.4
CH_4	4.0	4.0
CO_2	9.5	9.6
H_2O	17.3	17.5
N_2	.54	.58
NH_3	.24	.24
H_2S	1.07	30 ppmv
COS	.02	20 ppmv
Flow rate (moles/lb coal)	.107	.105
HHV Product/HHV coal	.864	.844

cycle was obtained through a series of calculations by and private communication among several Westinghouse divisions and utility and EPRI representatives. The basis of the synergism is the ability of the SOFC to provide exhaust products at the state-of-the-art combustion turbine temperature levels (2200F). Thus, the SOFC becomes a "combustor" for the combustion turbine which is also capable of directly converting some of the fuel into electricity.

The power cycle conditions corresponding to state points of Figures 1 through 4 are given in Table 3 through 6 respectively. The flow rates given correspond to a net plant output of 675 MW.

The combustion turbine and steam cycle configurations, state points and performances are based on combined cycle results of the Westinghouse ECAS study (3) and represent the performance of commercially available equipment.

4.2 Results

The performance of the four systems evaluated are summarized in Table 7. These were obtained using the parameters and methodology specified in the Base Case (4) (i.e., coal composition, inverter efficiency, capital charge rate, etc.

The revenue requirements and cost of energy for the four cases are summarized in Table 8. The unit cost estimates on which the revenue requirements are based are summarized in Tables 9 through 12 for the four cases respectively.

The levelizing factors, calculation methods, fuel and water costs, etc., outlined by JPL for their Base Case (5) were used in calculating the revenue requirements and cost of energy. The method used calculates a short-term, 10 year levelized cost of energy which has been adopted by EPRI as a utility preferred method.

Where feasible, the costs provided by JPL in their Base Case (i.e., coal handling, oxygen plant, accessory electrical equipment, fuel cell piping and inverters) were used in calculating the unit costs. Since the fuel cell costs used by JPL were approximately 10% higher than our estimates for the SOFC of Case 4, we used the JPL value of 133 $/kW for Case 4 and scaled the cost by the inverse of power density for the

State Point* (-)	Pressure (psia)	Temp. (°F)	Flow (lb/sec)	Enthalpy (B.T.U./lb)
1	14.7	59	2229	-
2	15.4	59	281	-
3	15.4	352	388	-
4	15.4	1101	2335	
6	320.0	1850	395	
101	2" Hg abs.	101	-	1009.5
102	-	101	320	69.1
103	-	-	112	-
104	30	250	75.4	-
105	30	250	-	-
106	2980	-	-	-
107	2683	673	245	742.0
108	-	678	245	1070.0
109	2415	1000	245	1461.2
110	556	478	60.4	1203.8
111	556	607	305	1298.4
112	500	1000	305	1519.6

Table 3
State Point Conditions for Atmospheric Pressure
SOFC Plant with Air Blown Gasifier (Case 1)

---

*Numbers correspond to points on Figure 1.

State Point* (-)	Pressure (psia)	Temp. (°F)	Flow (lb/sec)	Enthalpy (B.T.U./lb)
1	14.7	59	2534	-
2	15.4	59	343	-
3	15.4	352	217	-
4	15.4	1073	2408	
6	380	1900	350	
101	2" Hg abs.	101	-	1009.5
102	-	101	330	69.1
103	-	-	115	-
104	30	250	77.9	-
105	30	250	-	-
106	2980	-	-	-
107	2683	673	253	742.0
108	-	678	253	1070.0
109	2415	1000	253	1461.2
110	556	478	2.9	1203.8
111	556	642	255	1320.4
112	500	1000	255	1519.6

Table 4
State Point Conditions for Atmospheric
Pressure SOFC Plant with Oxygen Blown Gasifier (Case 2)

---

*Numbers correspond to points on Figure 2.

State Point* (1)	Pressure (psia)	Temp. (°F)	Flow (lb/sec)	Enthalpy (B.T.U./lb)
1	14.7	59	1551	-
2	165.4	600	252	-
3	165.4	978	348	-
4	165.4	2200	1405	606.4
5	165.4	1166	1646	274.8
6	320.0	1850	354	
101	2" Hg abs.	101		1009.5
102	-	101	226	69.1
103	-	-	79.0	-
104	30	250	53.4	-
105	30	250	173	-
106	2980	-	173	-
107	2683	673	173	742.0
108	-	678	173	1070.0
109	2415	1000	173	1461.2
110	556	478	54.2	1203.8
111	556	599	227	1293.5
112	550	1000	227	1519.6

Table 5
State Point Conditions for SOFC Topping of Combined Cycle with Air Blown Gasifier (Case 3)

---

*Numbers correspond to points on Figure 3.

State Points* (-)	Pressure (psia)	Temp. (°F)	Flow (lb/sec)	Enthalpy (B.T.U./lb)
1	14.7	59	1777	-
2	165.4	600	315	-
3	165.4	911	199	-
4	165.4	2200	1412	619.5
5	15.4	1073	1661	264.2
6	380.0	1900	203	
101	2" Hg abs.	101		1009.5
102	-	101	229	69.1
103	-	-	79.7	-
104	30	250	53.9	-
105	30	250	175	-
106	2980	-	175	-
107	2683	673	175	742.0
108	-	678	175	1070.0
109	2415	1000	175	1461.2
110	556	478	2.8	1203.8
111	556	641	177	1319.6
112	500	1000	177	1519.6

Table 6
State Point Conditions for Pressurized SOFC Topping of Combined Cycle with Oxygen Blown Gasifier (Case 4)

---

*Numbers correspond to points on Figure 4.

Table 7. Summary of Performance for 675 MW SOFC Power Plants

Case Number	1	2	3	4
1.0 Power Output (MW)	675	675	675	675
1.1 Fuel Cell	387	423	279	307
1.2 Combustion Turbine Set	0	0	226	226
1.3 Steam Turbine	212	184	153	127
1.4 Fuel Gas Expender	88.8	81	26.6	24.9
1.5 Inverters	-7.8	-8.3	-6.2	-6.6
1.6 BFW Pump	-5.0	-4.7	-3.4	-3.3
2.0 Coal Flow (1000 lbs/hr)	359	383	322	351
3.0 Coal HHV* Heat Rate (Btu/kWh)	6513	6951	5841	6366
Coal HHV* Efficiency (%)	52.4	49.1	58.4	53.6
4.0 Cell Performance				
Exit Nernst Potential (mV)	780	810	920	930
Voltage (mV)	600	600	660	660
Fuel Utilization† (%)	83.7	85.4	61.7	61.5
Oxygen Utilization (%)	25.5	25.4	31.5	30.6
Current Density (mA/cm^2)	238	224	294	271
Inlet Air Temperature (°F)	940	890	900	870
Outlet Air Temperature (°F)	1660	1650	1620	1600
Outlet Fuel Temperature (°F)	1640	1580	1610	1530
5.0 Gasifier Performance Using Illinois 6 Coal				
Carbon Conversion (%)	98.5	98.5	98.5	98.5
Steam Use (lb steam/lb coal)	.253	.566	.253	.566
Oxygen Use (lb oxygen/lb coal)	0	.644	0	.644
Air Use (lb air/lb coal)	2.82	0	2.82	0

---

*12235 Btu/lb

†All electrochemically active species are assumed to be utilized equally

Table 8. Summary of Revenue Requirements and Cost of Energy for 675 MW SOFC Power Plants

	Case Number	1	2	3	4
1.0	Total Capital Requirement (MM$)	824.8	975.2	678.1	819.9
	1.1 Total Plant Cost (on-site)	756.3	896.3	620.0	751.8
	1.2 Allowance for Funds During Constr.	28.2	33.4	23.1	28.0
	1.3 Prepaid Royalties	3.5	4.5	2.9	3.5
	1.4 Preproduction Costs	23.8	27.2	20.2	23.6
	1.5 Inventory Capital	10.4	11.2	9.36	10.34
	1.6 Catalyst & Chemical Charge	1.7	1.7	1.7	1.7
	1.7 Land	.9	.9	.9	.9
	Capital*Related Revenue Requirement (MM$/yr)	148.5	175.5	122.1	147.58
2.0	Variable Operating Costs (MM$/yr)	42.63	45.39	38.19	41.87
	2.1 Fuel	41.36	44.09	37.05	40.37
	2.2 Water	.53	.47	.39	.33
	2.3 Ash Disposal	.49	.52	.44	.47
	2.4 Catalysts & Chemicals	.31	.31	.31	.31
	Levelized*Variable Revenue Requirement	65.72	69.98	58.88	63.96
3.0	Fixed Operating Costs (MM$/yr)	22.14	25.03	20.32	23.00
	3.1 Operating Labor	3.74	3.74	3.74	3.74
	3.2 Maintenance Costs	15.42	18.01	13.80	16.19
	3.3 Overhead	2.97	3.28	2.78	3.07
	Levelized*Fixed Revenue Requirement	32.94	37.11	30.2	34.22
4.0	Levelized*Fuel Cell Replacement (MM$/yr)	26.07	30.2	15.3	18.05
	Total Levelized*Revenue Requirement (MM$/yr)	273.19	312.8	226.5	264.38
	Levelized*Cost of Energy ($/kWh)	.07108	.0814	.0589	.0688

*Levelized for first 10 years of operation using factors from References 4 and 5.

Table 9. UNIT COST ESTIMATES FOR AIR BLOWN ATMOSPHERIC PRESSURE CASE (No. 1)

UNIT	Plant Size	Costing Scale Expn.	Total Constructed Mid 81 Cost Note (1)(2) $MM	Process (On-Site) Costs $MM	E.H.O. Ovhd. + Fees Note (3) $MM	Process Cont. $MM	Proj. Cont. $MM	Total Plant Cost $MM	$/kW
Coal Handling	4311 TPD	.78	18.1			-0-	5.4	23.5	34.8
Gasification & Ash Handling Zn Ferrite Treatment Sulfur Recovery & Tail Gas	4311 TPD 60650 mph 1092 mph	.6	86.3			21.6	25.9	133.8	198.2
Fuel Processor Sub-Totals			104.4			21.6	31.3	157.3	233.0
Fuel Cells	387 MW	1.0	58.2			29.1	17.5	104.8	155.3
Fuel Cell Piping, etc.	387 MW	1.0	82.3			41.3	24.7	148.3	219.7
Fuel Cell Sub-Totals			140.5			70.4	42.2	253.1	374.9
Steam Bottoming Cycles: Expans. Turbine Air Preheater Steam Turbine	296 MW		153.3			-0-	46.1	199.4	295.4
Inverters	379 MW	1.0	38.3			3.8	11.5	53.6	79.4
Accessory Elect. Equip. Step Up & Transmission	675 MW	1.0	28.2			-0-	8.5	36.7	54.4
Power Cycles Sub-Totals			360.2			74.2	103.8	542.8	804.1
Process (On-Site) Sub-Total			464.6	422.4	42.2	95.8	139.6	700.1	1037.2
General Facilities [≈10% of Process (On-Site) Costs]			42.2				14.0	56.2	83.2
Total			506.8			95.8	153.6	756.3	1120.4

Notes:
1. Constructed Costs include Engineering and Home Office Overhead plus Fees.
2. Time Esc. Factor from Mid '76 to Mid -81 = 1.54.
3. E.H.O. Ovhd. + Fees = Engineering and Home Office Overhead plus Fees.
4. Process Contingencies used as follows: Gasif. & Ash Handling = 25% Fuel Cell = 50%; Inverters = 10%.

Table 10. UNIT COST ESTIMATES FOR OXYGEN BLOWN ATMOSPHERIC PRESSURE CASE (No. 2)

UNIT	Plant Size	Costing Scale Expn.	Total Constructed Mid 81 Cost Note (1)(2) $MM	Process (On-Site) Costs $MM	E.H.O. Ovhd. + Fees Note (3) $MM	Process Cont. $MM	Proj. Cont. $MM	Total Plant Cost $MM	$/kW
Oxygen Plant & Delivery	2964 TPD	.75	75.4			-0-	22.6	98.0	145.2
Coal Handling	4602 TPD	.78	19.0			-0-	5.7	24.7	36.7
Gasification & Ash Handling	4602 TPD								
Zn Ferrite Treatment	40645 mph	.6	87.7			21.9	26.3	135.9	201.3
Sulfur Recovery & Tail Gas	894 mph								
Fuel Processor Sub-Totals			182.1			21.9	54.6	258.6	383.2
Fuel Cells	423 MW		67.3			33.7	20.2	121.2	179.6
Fuel Cell Piping, etc.	423 MW		96.6			48.3	29.0	173.9	257.7
Fuel Cell Sub-Totals			163.9			82.0	49.2	295.1	437.3
Steam + GT Bottoming Cycles: Expans. Turbine Comb. Turbine Steam Turbine	261 MW	0.7	142.8			-0-	42.8	185.6	275.1
Inverters	414 MW	1.0	41.9			4.2	12.6	58.6	86.8
Accessory Elect. Equip. Step Up & Transmission	675 MW	1.0	28.2			-0-	8.5	36.7	54.4
Power Cycles Sub-Totals			377.5			86.2	113.1	576.0	853.6
Process (On-Site) Sub-Total			558.9	508.1	50.8	108.1	167.7	834.7	1236.6
General Facilities [=10% of Process (On-Site) Costs]			50.8				10.8	61.6	91.3
Total			609.7			108.1	178.5	896.3	1327.9

NOTES:
1. Constructed Costs include Engineering and Home Office Overhead plus Fees.
2. Time Esc. Factor from Mid '76 to Mid '81 = 1.54.
3. E.H.O. Ovhd. + Fees = Engineering and Home Office Overload plus Fees.
4. Process Contingencies used as follows: Gasif. & Ash Handling = 25% Fuel Cell = 50%; Inverters = 10%.

Table 11. UNIT COST ESTIMATES FOR AIR BLOWN PRESSURIZED CASE (No. 3)

UNIT	Plant Size	Costing Scale Expn.	Total Constructed Mid 81 Cost Note (1)(2) $MM	Process (On-Site) Costs $MM	E.H.O. Ovhd. + Fees Note (3) $MM	Process Cont. $MM	Proj. Cont. $MM	Total Plant Cost $MM	$/kW
Coal Handling	3867 TPD	.78	16.6			-0-	5.0	21.6	32.0
Gasification & Ash Handling Zn Ferrite Treatment Sulfur Recovery & Tail Gas	3867 TPD 54380 mph 979 mph	.6	77.8			19.5	23.3	120.6	178.7
Fuel Processor Sub-Totals			94.4			19.5	28.3	142.2	210.7
Fuel Cells	279 MW	1.0	34.1			17.1	10.2	61.4	91.0
Fuel Cell Piping, etc.	279 MW	1.0	54.3			27.2	16.3	97.8	144.9
Fuel Cell Sub-Totals			88.4			44.3	26.5	159.2	235.9
Steam + GT Bottoming Cycles: Expans. Turbine Comb. Turbine Steam Turbine	26.6 226 153	1.0	150.9			-0-	45.3	196.2	290.7
Inverters	273 NW	1.0	27.6			2.8	8.2	38.6	57.2
Accessory Elect. Equip. Step Up & Transmission	675 MW	1.0	28.2			-0-	8.5	36.7	54.4
Power Cycles Sub-Totals			295.1			47.1	88.5	430.7	638.1
Process (On-Site) Sub-Total			389.5	354.1	35.4	66.6	116.8	572.9	848.7
General Facilities [=10% of Process (On-Site) Costs]			35.4				11.7	47.1	69.8
Total			424.9			66.6	128.5	620.0	918.5

NOTES:
1. Constructed Costs include Engineering and Home Office Overhead plus Fees.
2. Time Esc. Factor from Mid '76 to Mid '81 = 1.54.
3. E.H.O. Ovhd. + Fees = Engineering and Home Office Overhead plus Fees.
4. Process Contingencies used as follows: Gasif. & Ash Handling = 25% Fuel Cell = 50%; Inverters = 10%.

OF POOR QUALITY

Table 12. UNIT COST ESTIMATES FOR OXYGEN BLOWN PRESSURIZED CASE (No. 4)

UNIT		Plant Size	Costing Scale Expn.	Total Constructed Mid 81 Cost Note (1)(2) $MM	Process (On-Site) Costs $MM	E.H.O. Ovhd. + Fees Note (3) $MM	Process Cont. $MM	Proj. Cont. $MM	Total Plant Cost $MM	$/kW
Oxygen Plant & Delivery		2714 TPD	.75	67.5			-0-	20.2	87.7	129.9
Coal Handling		4214 TPD	.78	17.8			-0-	5.3	23.1	34.2
Gasification & Ash Handling		4214 TPD								
Zn Ferrite Treatment		36682 mph	.6	84.8			21.2	25.3	131.3	194.5
Sulfur Recovery & Tail Gas		809 mph								
Fuel Processor Sub-Totals				170.1			21.2	50.8	242.1	358.7
Fuel Cells		307 MW	1.0	40.8			20.4	12.2	73.4	108.7
Fuel Cell Piping, etc.		307 MW	1.0	65.8			32.5	19.5	117.0	173.3
Fuel Cell Sub-Totals				105.8			52.9	31.7	190.4	282.1
Steam + GT	Expans. Turbine	24.9 MW								
Bottoming	Comb. Turbine	226 MW	1.0	140.6			-0-	42.2	182.8	270.8
Cycles	Steam Turbine	127 MW								
Inverters		300 MW	1.0	30.3			3.0	9.1	42.4	62.8
Accessory Elect. Equip. Step Up & Transmission		675 MW	1.0	28.2			-0-	8.5	36.7	54.4
Power Cycles Sub-Totals				304.9			55.9	91.5	452.3	670.1
Process (On-Site) Sub-Total				475.0	431.8	43.2	77.1	142.3	694.4	1028.7
General Facilities [=10% of Process (On-Site) Costs]				43.2				14.2	57.4	85.0
Total				518.2			77.1	156.5	751.8	1113.8

NOTES:
1. Constructed Costs include Engineering and Home Office Overhead plus Fees.
2. Time Esc. Factor from Mid '76 to Mid '81 = 1.54.
3. E.H.O. Ovhd. + Fees = Engineering and Home Office Overhead plus Fees.
4. Process Contingencies used as follows: Gasif. & Ash Handling = 25% Fuel Cell = 50%; Inverters = 10%.

other 3 cases. Gasification system costs were based on estimates prepared by the Westinghouse Synthetic Fuels Division for similar systems. The combustion turbine and steam cycle costs are the same as those used by the Westinghouse Combustion Turbine System Division for similar studies.

5. FUEL GAS FROM COAL FOR HIGH TEMPERATURE SOLID OXIDE ELECTROLYTE FUEL CELLS

Two principal questions must be addressed in the supply of fuel cells with coal derived gas:

1. Which coal gasification process is most effective (economic, efficient, and operable)?
2. What level of purification is required for the coal derived gas (sulfur compounds, halogens, heavy metals, and dust are contaminants present in all coal gas)?

5.1 Gasification System Characteristics

To address the first question, we find that a number of coal gasification processes are available with varying degrees of energy efficiency and overall cost effectiveness. In order to select a particular gasification process, one is required to evaluate its characteristics in the framework of the following decision factors.

The coal-derived fuel gas must be compatible with the fuel cell so as to maximize cycle efficiency. Although data are unavailable, "tolerance is expected to be low" for light oils and tars, which could hinder system performance. The coal gas water vapor content should be low to obtain high cell voltage and gasification efficiency.

Cold gas efficiency is usually defined as the ratio of the heating value of the product gas to the heating value of the coal. This cold gas efficiency is a measure of the useful fuel input to the SOFC and a high value indicates lower equipment cost (higher output per unit throughput) and lower heat rate for the integrated power plant.

The reliability of a coal gasifier is largely determined by its ability to withstand off-design operating conditions, such as interruptions in coal feed, loss of oxidant and/or steam flow, and blockage in the ash withdrawal port. The controllability is determined by its turndown ratio and the speed of its response to load changes on the power plant.

The fuel cell commercialization will realize maximum benefit by applying the most cost-effective coal gasification technology. The technical feasibility of the gasifier should have been demonstrated in a facility capable of direct scale-up to a commercial plant. Process know-how and, more importantly, information on the reliability of various hardware components and materials of construction must be available for scale-up purposes within the time frame of the proposed program.

In the final analysis the success of an integrated fuel cell power plant will be dictated by capital and operating costs. Table 14 presents the characteristics judged to be desirable in terms of gasification economics, along with the economic effects of these characteristics and the necessary operating conditions.

All gasifier types -- fixed bed, fluidized bed, entrained bed, and miscellaneous types such as the molten salt reactor -- are applicable for the SOFC.

5.2 Gas Cleanup System Characteristics

Hot, raw, product gas leaving the gasifier can contain tars, char, particulate matter, and small quantities of sulfur compounds and ammonia. Other elements, such as alkali and heavy metals, hydrogen cyanide, and halogen compounds, appear in trace amounts. There is little information on the removal of particulates or trace elements by gas cleanup systems. Although there is little data on their effect, related experience and thermodynamics indicate that the trace elements present no problem for the SOFC.

Table 14

Dwg. 4251B98

DESIRABLE CHARACTERISTICS OF ADVANCED GASIFICATION PROCESSES FOR PRODUCING COAL GAS

Desirable Characteristics	Economic Effects	Process Conditions Leading to Desirable Characteristics		
		Temperature	Pressure	Other Conditions
1. High specific gasification rate	Fewer gasifiers, decreased investment*	High	High	High heat and mass transfer rates
2. Minimum gasification by-products	Decreased investment in recovery facilities possibly increased gasification efficiency+	About 816°C (1500°F) or greater	Little effect	–
3. Maximum flexibility in coal size	Decreased investment for coal grinding, no loss of fines	No effect	No effect	Minimum carry-over of fines, high heat and mass transfer rates
4. Ability to process caking coals	Reduced coal pretreatment losses, decreased investment, increased gasification efficiency	High, to prevent caking	Little effect	Stirring of fixed beds and jet injection into fluidized beds
5. Minimum oxygen or air requirements	Decreased investment, increased gasification efficiency, increased methane content in product gas	Low	High	Countercurrent flow of coal and oxygen (air)
6. Minimum gasifier steam requirements	Decreased investment in waste heat or auxiliary boilers	High	Depends on process	–
7. Minimum loss of unreacted carbon	Increased gasification efficiency	High	High	Molten bath advantageous
8. Minimum compression power	Decreased investment, possibly increased gasification efficiency	Low	Slightly higher than that desired for product gas	Use of oxygen rather than air if gasification pressure greatly exceeds 690 kPa (100 psia)

---

*Decreased investment resulting from desired characteristic alone. Method of achieving the particular characteristic may add enough investment to result in a net increase in investment.

+Increased gasification efficiency will usually result in decreased investment because of the reduced amount of coal being handled and gasified.

Sulfur compounds have been identified as critical contaminant for fuel cell applications. These compounds can adversely affect fuel cell performance and life expectancy. H_2S is the primary sulfur compound and COS is the secondary sulfur compound in the raw gas stream. As much as 95% of the total sulfur compounds appear as H_2S with the remainder being COS. For typical coals approximately 1 vol% of the raw fuel gas is COS and H_2S. Reduction to about 100 ppm is believed to be adequate for SOFC. These levels can be achieved by the regenerable zinc ferrite sorbent(6) which operates at high temperature (about 650°C). Since hot gas cleanup is attractive for fuel cell power plants, the zinc ferrite system was selected for this study.

6. SOLID OXIDE FUEL CELL COMBINED POWER CYCLES

The high temperature solid oxide fuel cell performs well in both pressurized and atmospheric combined power generation cycles. In each case, the fuel cell is used as a topping unit to permit effective conversion of the fuel cell byproduct heat to electricity. The byproduct heat results from the difference between the enthalpy and free energy of the cell reaction, from electrical losses within the fuel cell, and from fuel that is not utilized by the cell. In each case the heating value of the unused fuel is reacted by mixing the anode exhaust with the cathode exhaust at high temperature. The sensible heat of the resultant product stream is used to preheat the cell air supply and in the bottoming cycles. Air flow rate and temperature of the air supplied to the cathode are adjusted to satisfy the electrolyte material temperature limit of 2010°F (1100°C). In all cases, the fuel gas is expanded from gasifier pressures to fuel cell pressure. Hence, the temperature of the fuel gas entering the fuel cell differ significantly between the pressurized and atmospheric pressure cycles.

Tables 3 through 6 in combination with Figures 1 through 4 show the integration of the fuel cell generator into each of the 4 systems and give the stream temperatures and pressures. Performance of the four plant configurations are given in Table 9. The compositions of the fuel for the fuel cell generator are given in Tables 1 and 2 for the low BTU (air blown gasifier) and high BTU (oxygen blown gasifier) respectively.

6.1 Fuel Cell Characteristics

In the pressurized cases, the products of the reacted cathode and anode exhausts go to the combustion turbine inlet. An inlet temperature level of 2200°F was selected as being close to the state-of-the-art. This established a relatively low fuel utilization (62%) in the fuel cells which permits better cell electrical performance (higher voltage with higher current density) than that of the atmospheric pressure cases where higher utilizations (~85%) are required for good system efficiency. Lower combustion turbine inlet temperatures would establish higher fuel utilizations (and poorer cell electrical performance); thus reducing the advantages gained by incorporating the pressurized system while returning the additional complexity.

The differences between the low BTU (air blown) and high BTU (oxygen blown) fuels do not markedly affect electrical performance. A slightly more favorable combination of local internal and polarization resistances and the local Nernst voltages along the cell length produce a somewhat higher average current density with the lower BTU fuel. Information on the internal and polarization resistance is available in a Westinghouse report to DOE on its solid-oxide fuel cell contract work(7). The overall cell operating and performance characteristics (e.g., air utilization, current density) are summarized in Table 7.

6.2 Bottoming-plant

The bottoming plant thermal performance is better with air-blown fuel than with oxygen-blown fuel for both atmospheric and elevated pressure cases because:

- considerably more steam is available for induction into the steam turbine since less is used in the gasifier
- more total gas flow is available for the bottoming plant since the nitrogen is carried along in the fuel
- more fuel gas flow is available for the fuel gas expander.

6.3 Combined-plant Discussion

The thermal efficiency of the two power plants fueled with air-blown fuel is better than that for the two respective power plants fueled with oxygen-blown fuel. This is due to slightly better performance of the fuel cell and much better performance of the bottoming plant as described above.

7. REFERENCES

1. Vidt, E. J., et al, "Evaluation of Gasification and Gas Cleanup Processes for Use in MCFC Power Plants - Task D Topical Report, Summary Analyses," Contract No. DE-AC21-81MC16220, June 8, 1982.
2. Feduska, W., et al, "Thin Film Battery/Fuel Cell Power Generating System - Final Report of the Continuation Contract (Tasks 1-4) Covering the Period April 1, 1978 - March 31, 1980," Contract No. DE-AC-0379ET11305, June 30, 1980.
3. Beecher, D. T., et al, "Energy Conversion Alternatives Study (ECAS) Westinghouse Phase I Final Report. Volume V - Combined Gas-Steam Turbine Cycles," Contract No. NAS 3-19407, February 12, 1976.
4. "Base Case Reference Design and Economic Assumptions for a Coal-Based Fuel Cell Power Plant," JPL reference AP: jb-FCE-345-82-52, August 1982.
5. "Economics for Base Case Reference Design," JPL reference JF/ep-FCE-345-82-64, October 1982.
6. Grindley, T., Steinfeld, G., "Development and Testing of Regenerable Hot Coal Gas Desulfurization Sorbents," Proceedings of Second Annual Contractors Meeting on Contaminant Control in Hot Coal Derived Gas Streams, DOE, February 1982.
7. Feduska, W., et al, "High Temperature, Solid Oxide Electrolyte Fuel Cell Power Generation System - Annual Report Covering the Period June 1, 1981 to May 31, 1982" Contract No. DE-AC-0280ET17089, June 28, 1982.